# BUILDINGS' CARBON FOOTPRINT CALCULATIONS FROM CONSTRUCTION COMPANY'S PERSPECTIVE

Determining carbon footprint for building with Finnish national method

Lappeenranta–Lahti University of Technology LUT

Master's Programme in Circular Economy, Environmental Technology Master's Thesis

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ABSTRACT

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Finland's upcoming climate law implementation will be effective from the beginning of 2025, and this shall set limits for buildings' carbon footprints and make carbon footprint calculations mandatory for new construction projects. One of the objectives of the thesis is to evaluate construction company NCC Suomi Oy's pilot phase carbon footprint calculation tool's results of building material emissions. Literature research will be carried out to determine the status of Finland's carbon footprint calculation of buildings to discover how the company's pilot phase carbon footprint calculation tool corresponds for requirements of the future law. The carbon footprint calculation tool's results are analyzed with help of reference cases and process identifies development targets for the piloted tool. As the construction industry is a major user of material resources, the potential of circular economy to reduce the carbon footprint is also identified through both a literature review and a case study. Furthermore, other carbon reduction solutions potential for buildings is reviewed and means to lower carbon footprint level is presented in the thesis. The case study reveals that circular economy products can easily provide about 10% carbon reduction potential to product phase emissions in typical concrete structured residential building if low carbon circular products are targeted to the major structures are like precast wall and flooring elements. In addition, more impressive carbon reduction can be gained by combining selection of different carbon reduction choices as applying design optimization, low carbon design solution and circular low carbon materials and by additional utilization of demolition and refurbishment projects' materials this would provide the most significant carbon reduction potential.

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Suomen tuleva ilmastolain täytäntöönpano astuu voimaan vuoden 2025 alusta asettaen rajat rakennusten hiilijalanjäljelle tehden hiilijalanjälkilaskelmat pakollisiksi uusissa rakennushankkeissa. Yhtenä opinnäytetyön tavoitteena on arvioida rakennusliike NCC Suomi Oy:n pilottivaiheessa olevan hiilijalanjälkilaskentatyökalun tuloksia rakennusmateriaalien päästöistä. Kirjallisuustutkimuksella selvitetään Suomen rakennusten hiilijalanjälkilaskennan tilanne, jotta saadaan selville, miten yrityksen pilottivaiheen hiilijalanjälkilaskentatyökalu vastaa tulevan lain vaatimuksiin. Hiilijalanjälkilaskentatyökalun tuloksia analysoidaan vertailutapausten avulla ja prosessissa tunnistetaan kehityskohteita pilottityökalulle. Rakennusteollisuuden ollessa merkittävä materiaaliresurssien käyttäjä työssä tunnistetaan myös kiertotalouden mahdollistama potentiaali hiilijalanjäljen pienentämiseksi molempien kirjallisuustutkimuksen ja tapaustutkimuksen avulla. Lisäksi työssä käydään läpi muita rakennusten hiilidioksidipäästöjen vähentämismahdollisuuksia ja esitellään keinoja hiilijalanjäljen tason alentamiseksi. Tapaustutkimus paljastaa kiertotaloustuotteiden tarjoavan helposti noin 10% hiilidioksidivähennyspotentiaalin tuotevaiheen päästöihin tyypillisessä betonirakenteisessa asuinrakennuksessa jos vähähiiliset kiertotaloustuotteet kohdennetaan tärkeimpiin rakenteisin kuten lattia- ja seinäelementteihin. Hiilidioksidi päästöjä voidaan vähentää vaikuttavammin yhdistämällä erilaisia hiilidioksidipäästöjen vähentämisvaihtoehtoja, kuten suunnittelun optimointi, vähähiiliset kiertotalousmateriaalit, sekä hyödyntämällä purku- ja kunnostushankkeiden materiaaleja, jolloin hiilidioksidi päästöjen vähentämispotentiaali on merkittävin.

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SYMBOLS AND ABBREVIATIONS

Subscripts

| | |
|---|---|
| kg | kilogram |
| km | kilometre |
| $m^2$ | square metres |
| g-$m^2$ | gross floor area in square metres (bruttoala, $brm^2$) |
| n-$m^2$ | heated net floor area in square metres (YM2021 method) |
| nr- $m^2$ | net room area (huoneala, $hum^2$) |

Abbreviations

| | |
|---|---|
| ARA | Housing Finance and Development Centre of Finland |
| BIM | Building Information Model / Modelling |
| BREEAM | Building Research Establishment Environmental Assessment Method |
| CE | Circular economy |
| CF | Carbon footprint |
| CH | Carbon handprint |
| $CO_2$ | Carbon dioxide |
| $CO_2$-eq | Carbon dioxide equivalent, *"a metric measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential"* (Eurostat, 2017). |
| DS | Design stage |
| EEA | European Environment Agency |
| EPD | Environmental product declaration |
| EoL | End of Life |

| | |
|---|---|
| EU | European Union |
| FiGBC | Finnis green building council |
| GHG | Greenhouse gas |
| GBP | Green building partners |
| GWP | Global warming potential |
| ISO | International Organization for Standardization |
| HVAC | Heating, ventilation, and air conditioning |
| LCA | Life cycle assessment |
| LEED | Leadership in Energy and Environmental Design |
| OCL | One Click LCA software |
| OECD | Organization for Economic Co-operation and Development |
| PCR | Post construction |
| REM | Finnish building life cycle meters analysis guideline (Rakennusten elinkaarimittarit) |
| RTS | Rakennustietosäätiö, Building information foundation in Finland |
| UN | United Nations |
| VN | Valtioneuvosto, Government of Finland |
| YM | Ympäristöministeriö, Ministry of the Environment, Finland |

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# 1 Introduction

Finnish building sector is responsible for 30% of the greenhouse gas (GHG) emission and almost 40% of energy consumption in Finland (RT, 2022; TEM 2020, p. 92). Burden is similar for environment also at European Union (EU) level. Thankfully GHG emissions in EU have been decreasing since 2005 according to European Environment Agency (EEA). In Finland GHG emissions have decreased 40% between years 2005 and 2019. Still, to achieve the targeted emission reduction of United Nations (UN) Agenda 2030 EU's building sector needs to gain roughly 60% reduction of GHG emission compared to current level. (EEA, 2022).

To achieve the target emission reduction of UN Agenda 2030, the Finnish government has been taking action with their climate policy programme from 2019 aiming to achieve Carbon Neutral Finland by 2035. This means also that the Finnish building sector has started to shift towards more sustainable future. (Rakennuslehti, 2021; YM, 2022a). Currently the Finnish building sector has no regulations to control GHG emissions, but this is about to change. According to the Finnish Ministry of the Environment buildings' life-cycle carbon dioxide ($CO_2$) emission regulation was planned to take place at latest by 2025 (YM, 2022). The Reform of the Land Use and Building Act proposition aiming to this was presented at fall of 2022 to parliament (VN, 2022) and recently beginning of March 2023 this motion was accepted, meaning that this law reform comes in force at 1.1.2025 (VN, 2023). This new act will enable the regulators to direct construction industry towards more sustainable future. As has been stated by the Finnish government a major part of the reform is that climate change controlling is integrated in this law (VN, 2023). This political decision will strengthen emission reductions during buildings whole life cycle and enable circular economy with i.e., requirements for buildings life span, adaptability, also for refurbishment and end-of-life actions and data of utilizable materials (YM, 2023).

One part of the Finnish new building law reform is related to carbon footprint (CF), which is sustainability indicator, informing the $CO_2$ emissions caused during buildings' life cycle and forthcoming regulation reform allows to set limits for different type of buildings' CF at 2025 (Bionova, 2017, p. 2, 11, 24; YM, 2022b; VN, 2023). In 2017 the low-carbon road map of Finnish construction predicted that with the planned implementations, if building material

distribution remains the same, the CF development of built environment could have 66% decrease and with the innovative solutions full potential this reduction could be up to 78% by 2035 (TEM, 2020, p. 95-96)**.**

Building's developers act as influencers, enablers, and executors of projects and have key role in value chain of the whole built environment. The upcoming climate revised building law impacts on the construction company's operations has been recognized by construction industry and stakeholders have started to prepare for change. The construction company NCC has set a target to be climate neutral by 2045 with other emission reduction aims to meet EU's and Nordic Countries national policy initiatives and global climate change challenge (NCC, 2023). This study is made for NCC Nordic's Building Finland department (NCC Suomi Oy) and funded by residential unit of the company. The transformation towards low-carbon society, vision of Carbon Neutral Finland 2035 and upcoming Reform of the Land Use and Building Act set new demands for construction company's operations, so study for buildings CF calculation from company perspective is topical. Research about the CF's reduction possibilities and integration to business operations answering to the low-carbon demands is important and can be pilot environment for new innovations that could significantly drop the sectors carbon intensity.

## 1.1 Background

The so called "green transition" aiming to more sustainable future has been driven by EU regulation and Finnish climate policy's Reform of the Land Use and Building Act will establish limits for buildings GHG emission by 2025 (Bionova, 2017, p. 2; YM 2022b; VN, 2023). Buildings life cycle's GHG emissions informing carbon footprint is divided to product stage (A1-3), construction process (A4-5), use stage (B) and end-of-life stage (C). Figure 1 presents these stages as part of Finnish Ministry of the Environment methodology for the whole life carbon assessment of buildings. As presented (Figure 1) the assessment is also dependent on materials, energy, transportation, and construction activities (YM, 2019).

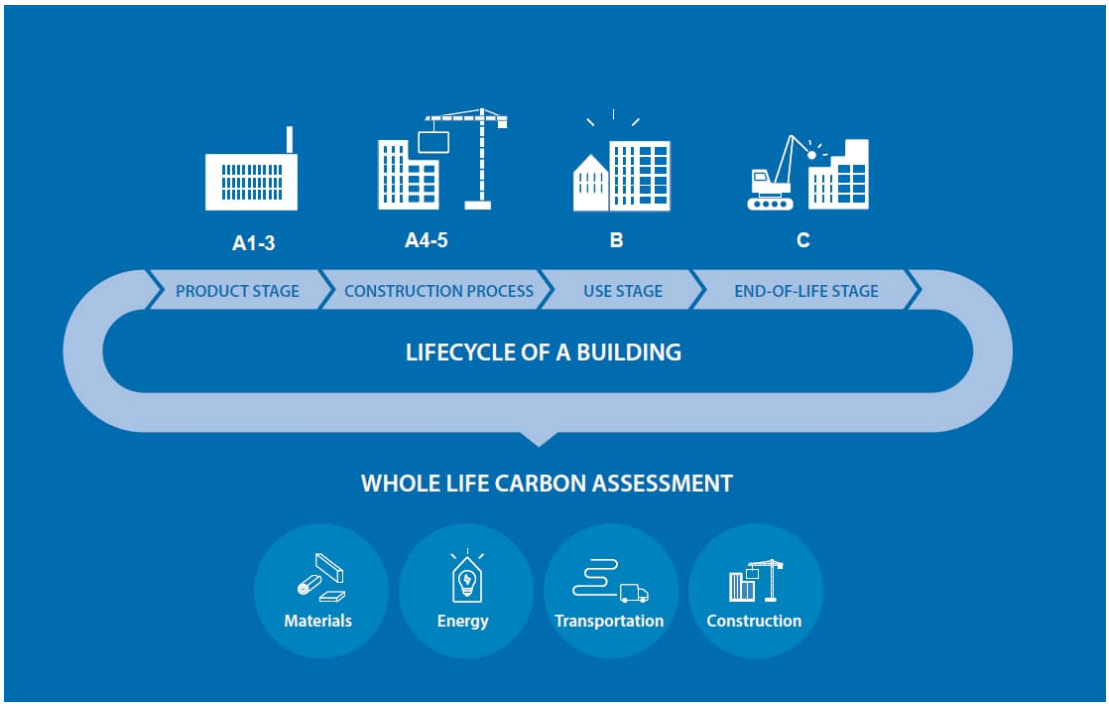



Figure 1. Methodology for the whole life carbon assessment of buildings by Finnish Ministry of the Environment (YM, 2019).

Buildings CF calculations can be executed with different means, but currently in NCC Building Finland's projects fair amount of those are done with One Click LCA software, EN-15978 tool (NCC Suomi Oy, 2022a). One Click LCA tool is commercially available and advertised to be the leading LCA tool of buildings (One Click LCA, 2022). There are also other tools available for companies and NCC Suomi Oy has integrated the building materials CF calculation section to company's own space-based cost estimation tool in September 2021. After the law will change carbon footprint limits and cost of building project are both information that needs to be estimated beforehand. The buildings cost estimation and carbon footprint calculation both are based on the amount and properties of building materials and these in future these will together determine viability of the whole building project.

At this stage NCC Suomi Oy has carried out some projects' pilot CF calculations and piloting of the tool is currently on going. As both building project's budget and CF calculation are based on the quantities of construction materials the integration seems promising. The company's integrated CF calculation feature is based on the Finnish Ministry of the Environment's "*Method for the whole life carbon assessment of buildings*"- guide (YM, 2022) as this shall be the mandatory CF evaluation method in Finland. The same calculation

method is also available in One Click LCA's CF calculation tool. The most significant difference is that the company's own software considers the construction materials, so only production stage (incl. A1-A3) carbon footprint can be evaluated. The other calculation tools like One Click LCA can be used for whole life cycles $CO_2$ emissions assessment (incl. A1-A5, B4-B5 and end-of-life).

If comparing the product stage CF results, the company's own CF calculation tool's results of pilot phase and the results calculated with prevalent building CF calculator One Click LCA tool, the results are differing. At pilot stage company's tool seems to give higher CF estimations when comparing to CF results calculated by experts with One Click LCA tool. In response to this observation research and analysis is needed to evaluate the company's CF calculation's integration to cost estimation software more deeply. (NCC Suomi Oy, 2022a).

There are several studies concerning low-carbon building and carbon footprints calculation of buildings. NCC Suomi Oy has been part of ARA (Housing Finance and Development Centre of Finland) funded project that examined building emissions reduction possibilities during its life cycle in affordable way. This study established some possible target levels for carbon footprint of the apartment buildings and how different solutions impact on results but has not yet set a focus on circular economy possibilities. (Ahola and Liljeström, 2018).

Kuittinen, and Häkkinen (2020) assessed the Finnish standards and CF assessment methodology for buildings. Bionova Ltd's (2021) study for Finnish Ministry of Environment analysed hundreds of building projects' data to establish CF limits for common building types as a base study for forthcoming regulations. These projects and reports have established basis for carbon footprint regulations and piloted CF calculation of actual case projects. The building projects' CF limits will in future affect to construction company's operation through design solutions and project development, material selections and are in relation to costs, building techniques and solutions.

In addition to being a major contributor to GHG emission formation the building sector utilises about 50% of the natural resources globally. Circular economy is one solution to mitigate the resource use challenge and at this the construction business has a key role. (YM. 2022c). Also, the circular economy (CE) is directly linked to demolition and refurbishment project's operations and new buildings' low-carbon targets through the materials production

stage impacts. For example, the company NCC Suomi Oy's refurbishment unit has recently had high CE targets set for the projects and have managed to answer the customers material recovery objectives (NCC, 2022d). Furthermore, research that considers the circular economy of building sector has recently been increasing. Leising et. al. study (2018) established that to shift building sector towards CE new process design, co-creation of innovative visions, new business models and involving entire value chain is needed. Eberhardt et al. (2021) studied the environmental design guidelines for circular building components and states that open design structure buildings have lowest global warming potential (GWP) over 200 years period. This resulted when comparing the open design structure to eco-efficient, bio-structure and design for disassembly design methods. In addition, the significant differences in GWP of the different design types appears after 70 years life span of a building. The open design structure in the study is structure that has space design, which is more flexible allowing better adaptability, chosen materials are durable and is designed more leaner than in business-as-usual scenario. These different structural design variants are presented in Appendix 2 in details. (Eberhardt et al., 2021).

## 1.2 Objectives of the study

As previous studies have assessed the current stage of regulation regime and assessed the preparation of future law the information in those studies has already partly outdated due to new Reform of the Land Use and Building Act draft and other more recent CF calculation methods published for the piloting period. This thesis research Finnish building sector's $CO_2$ emission calculation methods and demands now and for future. These methods and demands effects on CF calculations from construction company's perspective and to their operations are examined. Furthermore, one aspect is to discover what are the carbon footprint control manners and solutions of a building project used among the construction companies and how those effect on buildings CF calculation and results. As, different circular economy (CE) solutions and targets for the construction projects are likely to become more common in the future, the construction industry's circular economy solutions are to be investigated, trying to discover different solutions impacts on the buildings CF results. Aim is to reveal the CE solutions potential from the CF perspective as other studies haven't yet widely investigated this potential. One target of this study is to discover could the actualized carbon footprint of building be predicted in forehand, so CF results of building cases shall be analysed. These

carbon footprint results will be analysed by investigating case projects CF calculations, aiming to discover possible reasons that are influencing on the CF results. Also, the company NCC's own CF calculation tool will be evaluated as a part of case studies CF analysis. The case studies of carbon footprint calculations are narrowed down to project's were the company NCC Suomi Oy has been involved. The company's Metropolitan area building projects where the CF has been estimated with Finnish Environmental ministry's CF calculation method by expert authority are researched and targeted. Furthermore, study's CF analysis tries to recognize the possible challenges and opportunities of used calculation method and company's CF estimation tool. The company's own CF estimations are limited to building materials product stage (A1-A3) $CO_2$ emissions so analysing of the results will be limited to that part of the CF.

In this study building is considered as OECD (2002) defines it: "*any independent free-standing structure comprising one or more rooms or other spaces, covered by a roof, enclosed with external walls or dividing walls which extend from the foundations to the roof, and intended for residential, agricultural, industrial, commercial, cultural, etc., purposes*". There are different type of buildings which can be categorized by use purpose i.e., apartment, office, commercial, and this study deals only with the larger multi floor apartment and office type of buildings and excludes the small residential buildings, row house type apartment buildings, and commercial, school, healthcare, service, and educational buildings.

List of the aimed objectives of the study:

- *reveal CE solutions potential from CF perspective*
- *discover could the actualized carbon footprint of building be predicted in forehand*
- *discover possible reasons that are influencing on CF results*
- *company's own CF calculation tool will be evaluated*
- *CF analysi's recognizing the possible challenges and opportunities of used calculation method and company's CF estimation tool.*

Based on the aimed objectives of the study the research questions were formulated:

- *What factors affects most on the buildings CF calculation results?*

- *How the construction company's own CF calculation tool estimates the carbon footprint in comparison to the buildings CF calculation methods in Finland?*
- *How accurately could buildings' actualized commissioning phase's CF be determined at design phase of construction project?*
- *What kind of impacts the circular economy solutions have on buildings carbon footprint?*

Limitations of the research:

- *Limited to the Finnish construction business area's residential and office buildings*
- *Building's CF results evaluation focused to the product stage (A1-A3)*
- *Case study focused on the company's internal CF estimation tool's calculation analyses*
- *Concentration only to the carbon footprint perspective.*

## 1.3 Research process and materials

This thesis is consisted of two main parts, the theory-based literature research and the empirical case study about buildings' carbon footprint calculations. The literature research includes Finnish current state of buildings GHG emission regulations and dives into the carbon footprint calculation principles and methods. Also, an overview of the emission reduction potential and the solutions for it is researched including a circular economy aspect.

Materials of this study are from public and company's internal data sources. The public materials used for literature research are gathered from most recent studies, articles, conferences, and news of the building sector. Fair number of materials is collected from the company NCC Suomi Oy's Metropolitan area projects, data bases and company's partner experts. For the case study's reference purposes, the company's building projects CF footprint calculations available are researched and investigated. Summary of the company's CF calculation projects is compiled to Appendix 1. The cases are listed and named alphabetically, from A to S and referred as such through this thesis. Also, the most recent

information is gathered from the company experts with semi-structured interviews that are targeted to expert's own field. In these semi-structured interviews, an open question has been formulated before-hand and the respondent could have responded freely for the questions. The list of experts interviewed is presented in Appendix 3, but no full interviews are published as the information is partially confidential.

The empirical study part deals with the case buildings carbon footprint calculation in set scope to answer the research questions. Firstly, the case buildings data collection and selection of the handled CF calculation results are presented and compared. This is followed by a CF analysing part that evaluates the calculations and the company's pilot CF calculation tool (Esti Model) properties and logic with case example. Furthermore, also the circular economy potential is discovered with help of case examples found from company.

The case building projects' CF calculations will be handled as material of literature research and to provide reference background for the empirical study part. The case buildings' CF research and analysis follows the process that is presented in Figure 2. The first two phases (1.-2.) including data collection and case buildings' CF report interpretation of the process are part of the literature research. The phases 3.-7. are included in the empirical study of this thesis and consists of an evaluation and analysis of the cases CF results leading up to results and recommendations.

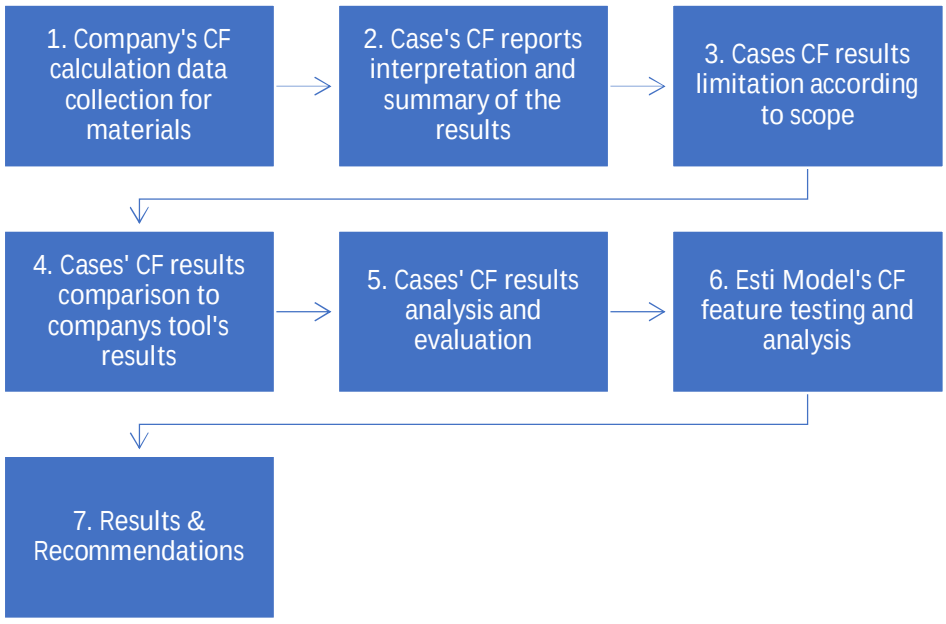



Figure 2. Case buildings' research and analysis process.

This study utilises two different CF calculation tools for in the empirical study part. The company NCC Suomi Oy's own product phase CF calculation tool Esti Model and commercial One Click LCA software are both used in the study to create buildings CF calculations. The Esti Model software is provided by the company NCC Suomi Oy for study's use. The One Click LCA software's provided student license is used mainly in this study, but also software's personal commercial licence's free period is utilized for testing CF calculation with YM2021 method that is limited out from the student licence.

# 2 Buildings GHG emission regulations and controlling

The Finnish national CF calculation methodology development has been launched in 2017, but currently no law yet regulates the building's life cycle's GHG emissions in Finland. Before the Finnish national CF evaluation method development there has already been other methods (i.e., Level(s)) to calculate carbon footprint of building, that are still in use. Earlier the CF calculation of building has been assessed as part an optional ecolabelling of buildings (LEED, BREEAM, Swan Label and RTS) or in pilot cases. (Bionova, 2017; VN, 2022).

Finnish government has proposed Reform of the Land Use and Building Act draft and related law for parliament 15.09.2022. These laws are aiming to better restrain climate change, enhance circular economy and to enable buildings data and digitalized decision making in national level. This future new law reform is intended to come into force at 1.1.2025. The carbon footprint levels will be regulated later after the law proposition has come in force. Furthermore, also carbon handprint of buildings should be evaluated alongside with carbon footprint. (VN, 2022). Figure 3 presents buildings' $CO_2$ emission controlling development of recent years and currently phase 2 is ongoing (YM 2022b).

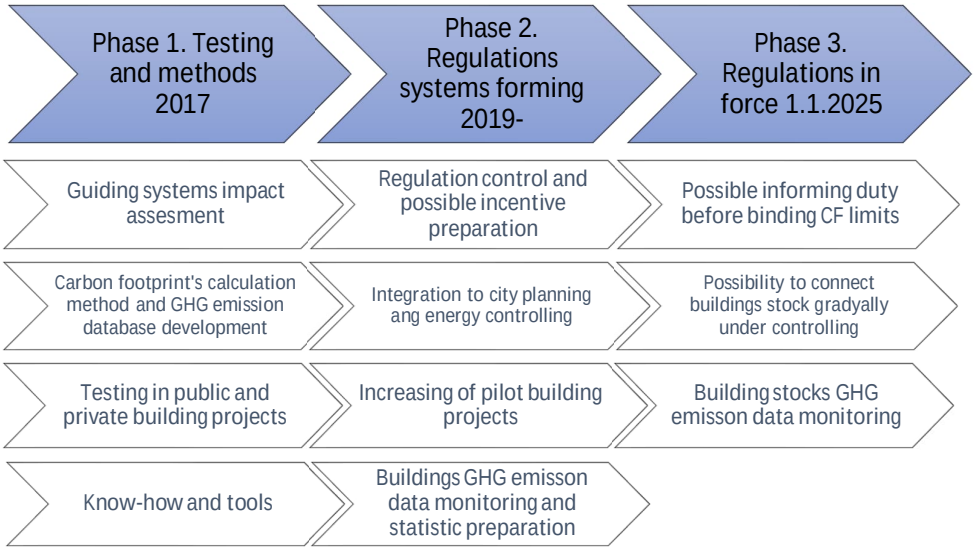



Figure 3. Buildings' $CO_2$ emission regulation's development in Finland during 2017-2025 (YM 2022b; VN 2023).

## 2.1 Buildings' CF calculation methods in Finland

One of the challenges, as Finland does not have the regulations set in place yet, is that the national method to calculate CF of a building has been updated few times. At least three different calculation methods or guides have been available for buildings and now new regulation proposition is supplementing those (Table 1). Latest information regarding of CF calculation methodology is presented by *Finnish Environmental Ministry's Reform of the Land Use and Building Act proposition 9/2022* that is part of climate act. (KEKRI, 2022, p. 2). Finalised methodology based on this new law reform is intended to be published when statements have been given for it (YM, 2021). This set's challenge to compare calculation results as there are some variations between the methods which is reflected on the results (result reporting and content of CF results).

Table 1. Different carbon footprint calculation methods used in Finland.

| Method | Based on | Purpose | Life-cycle phases included |
|---|---|---|---|
| **Level (s)- Green building council of Finland's (FIGBC) calculation guide** [1] | FIGBC life cycle meters guide, based on CEN/TC 350 Sustainability of Construction Works and EN-standard EN 15978 | EU commission's method for unified reporting of buildings GHG contribution | A1- A5, B1-2 (B3*), B4, (B5*), C1-C4 + D |
| **YM 2019:22 - Method for the whole life carbon assessment of buildings** [2] | EU Commission Level(s) method and EN- standards EN 15643-series, EN 15978 and EN 15804 | Meant only for testing period starting at 2019 – intended to be update before official regulations forced based on the feedback | A1- A3, A4-A5, B3-4, (B5*), B6, C1-C4 (+ additional D) |
| **YM 6/2021 draft of Method for the whole life carbon assessment of buildings** [2] | YM 2019:22 - Method for the whole life carbon assessment of buildings | Draft for pilot use. Meant to be used in line with forthcoming Reform of the Land Use and Building Act proposition – the new regulation act will be considered firstly and draft secondly. ** | A1-A3, A4-A5, B4, (B5*) B6, C1-C4 + separately informed D |
| **Reform of the Land Use and Building Act proposition 9/2022** [4] | YM 6/2021 Method for the whole life carbon assessment of buildings | Control buildings GHG emissions in Finland, over rules some YM6/2021 drafts guidelines | A1-A3, A4-A5, B4, (B5*) B6, C1-C4 + separately informed D |

** Renovation not applicable for new buildings, ** Will be published with some corrections for use when new law has been forced, 1) FIGBC,2022; 2) YM, 2019; 3) YM, 2021; 4) VN, 2022*

At the beginning of 2021, emission database combining climate impacts, carbon footprint and handprint information for Finnish building materials was launched (Ympäristö, 2022). This national generic GHG emission database called "$CO_2$ emission data base" was created for to be used in line with the YM6/2021 draft method (YM, 2021). Finnish national method requires that if the specific product is not known (i.e., manufacturer not selected) the generic conservative GHG emission data of $CO_2$ emission data base is to be used in CF calculations. Also, product specific environmental product declarations (EDP) inform the $CO_2$ emissions of product and has been used in carbon footprint calculations if the used product is selected and specified. But due to Reform of the Land Use and Building Act proposition 9/2022 the EDP alone is not enough and Rakennustieto foundation will launch new RTS- climate document (in compliment of EN15804 standard) at beginning of 2023 that informs products carbon footprint, carbon handprint and other material information accordingly Reform of the Land Use and Building Act categorization. The EPD compliance gap seems to be in the carbon handprint's aggregate value as it needs to be reported by modules. The other problem in EPD's directs use is the material description's requirements according to the new law reform. (Rakennustieto, 2022). The construction law reform also fulfils the forthcoming EU levels regulations that will require climate reporting at 2027, GHG emission removal reporting, reporting of products climate impacts and embodied carbon storage reporting (Kuittinen, 2023).

## 2.2 GHG emission demands for buildings

The new Reform of the Land Use and Building Act will demand that climate declaration will be drawn up for all new building projects aiming to almost zero energy level (some small renovations, vacation use and smaller 50 $m^2$ buildings would be excluded). (VN, 2022, p. 158). Furthermore, larger renovation projects will also have at least CF informing obligation (Kuittinen, 2023).

Bionova (2021) research established embodied carbon reference and limit values for typical building types in Finland from 482 existing projects. Table 2 presents their study's CF results for apartment and office buildings (excluding the building place and foundations) as normalized reference CF category per n-$m^2$ and per year. (Bionova, 2021, p. 35).

Table 2. Proposed preliminary embodied carbon reference and CF limit values for apartment and office buildings by Bionova (2021).

| Embodied carbon level | Residential | Office |
|---|---|---|
| **Variance adjusted reference carbon footprint (current level)** | 15.1 kg $CO_2e/m^2/a$ | 12.8 kg $CO_2e/m^2/a$ |
| **Proposed preliminary CF limit value*** | 11.5 kg $CO_2e/m^2/a$ | 10.0 kg $CO_2e/m^2/a$ |

**Only for building, building site is excluded*

The limit and reference values presented in Table 2 are variance adjusted by authors. Their recommendation to the CF limit value target 11.5 $kgCO_2e/m^2/a$ for residential buildings is 25% lower than current embodied carbon level (15.1 $kgCO_2e/m^2/a$) of buildings established in their study. (Bionova, 2021). The suggestion (Table 2) is based on YM2021 method and current default values of the moment, default table value level has been estimated to be 1.5 $kgCO_2e/m^2/a$ in 2021. These default values shall be updated later which will affect on these proposed limit values. (One Click LCA, 2021).

Meeting the forthcoming regulations CF limits shall be condition for construction permit (VN, 2022). Notable is that the demands will not consider building lot, foundations, parking structures, ground pole structures and other external structures (One Click LCA, 2021; KEKRI 2022; YM, 2021) as they can remarkably affect building projects CF with increase between 12-20% (Ahola & Liljeström 2018; Bionova 2021). These system boundaries of $CO_2$ emission controlling for building are presented in Figure 4.

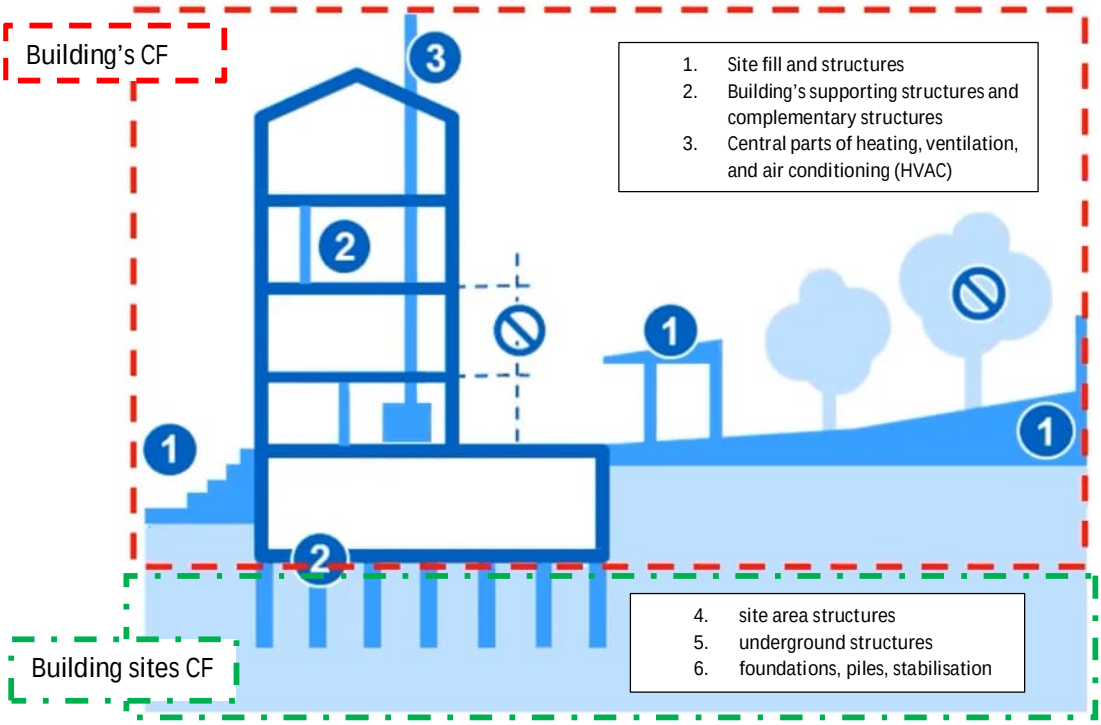



Figure 4. System boundaries for buildings $CO_2$ emission controlling adapted from One Click LCA (2021) (One Click LCA, 2021; YM,2021).

The excluded parts of building's CF like foundations shall be informed separately as part of building site's CF (YM, 2021), but due to high variation these will not be regulated with limit values (One Click LCA, 2021).

From Nordic countries the Denmark has already climate regulation in force (1.1.2023) and limits are planned to be tightened every two year (Appendix 4). Currently, new buildings over 1000 $m^2$ have $CO_2$ limit value that has been set for 12 $kgCO_2e/m^2/a$ until year 2025 and new lower limit value shall be decided at end of 2023. (Bolig- og planstyrelsen, 2022). In other Nordic countries Sweden and Norway has law requirements about climate reporting and in Sweden carbon footprint limits are planned to be in force by 2027.

The Finnish government has drafted tentative regulative scenarios about GHG emission reductions for low-carbon buildings. Figure 5 presents these different scenarios and who moderate regulation could lead up to 41% emission reductions, but it's not in line with Paris agreement scenario which would mean 71% reduction. (VN, 2023).

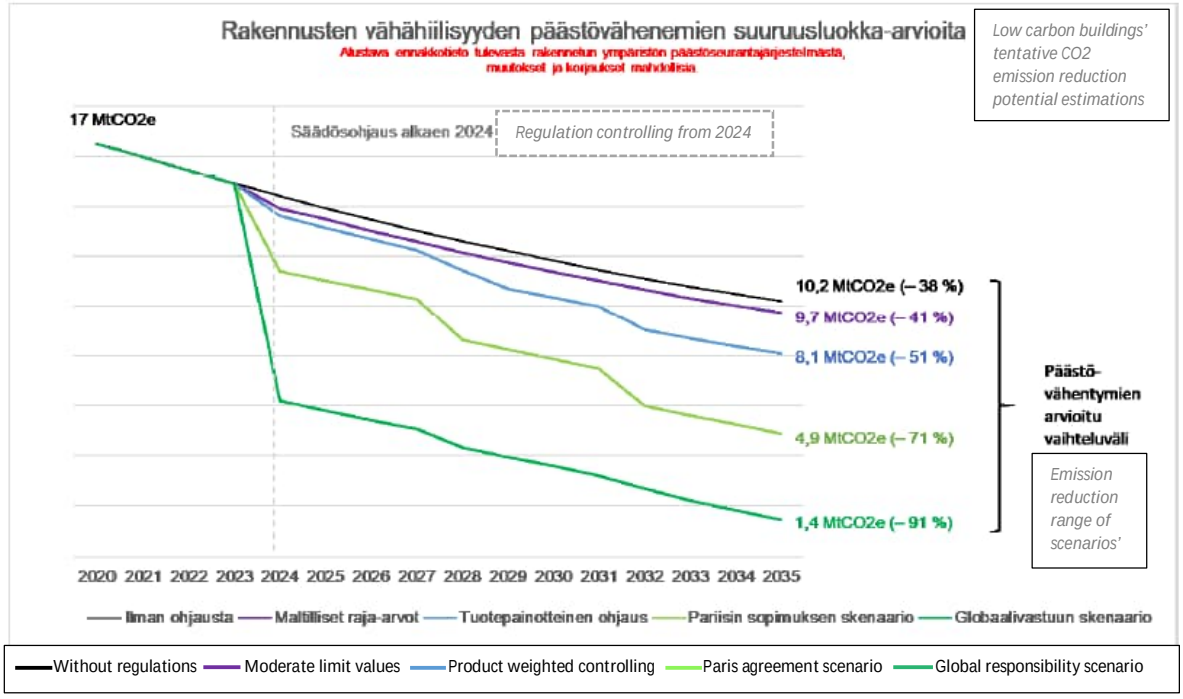
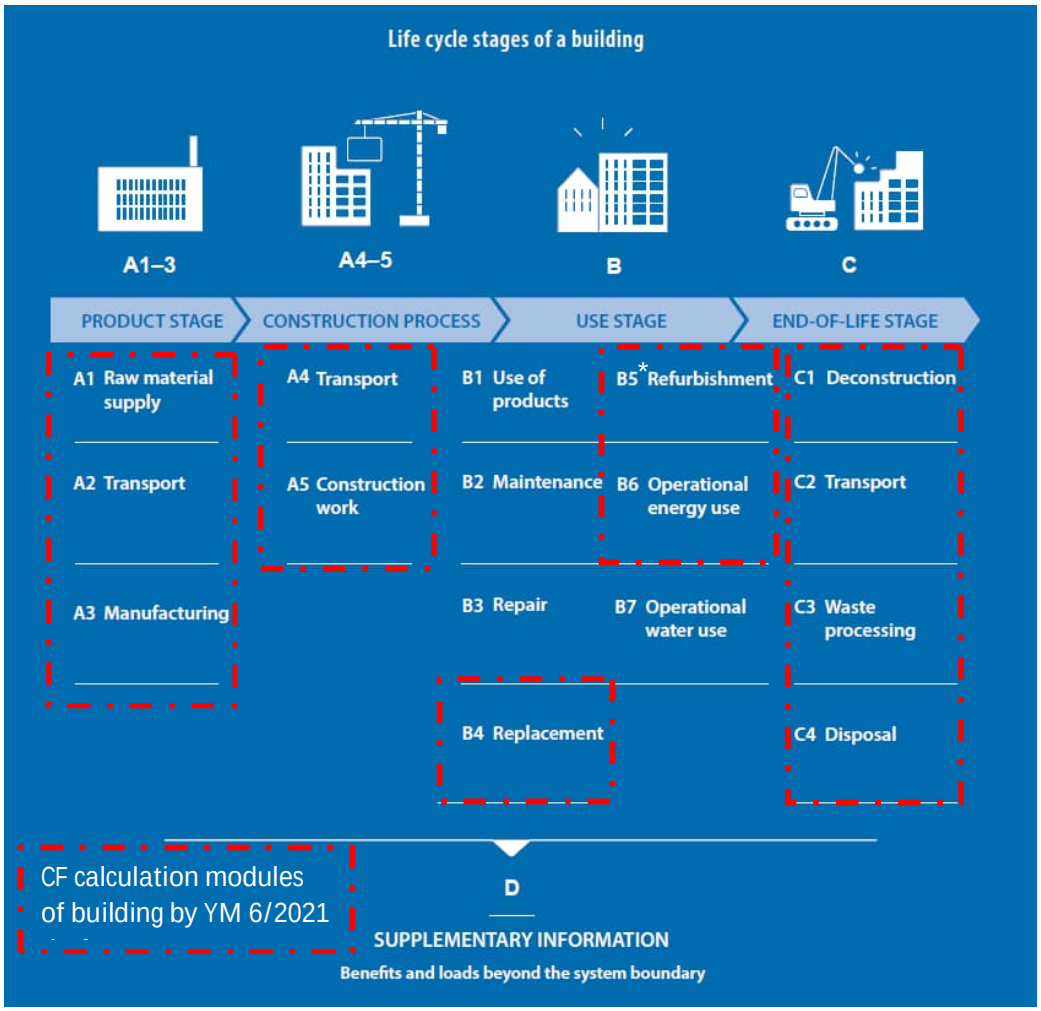



Figure 5. Low carbon buildings tentative $CO_2$ emission reduction potential estimations by Finnish government with added translations (VN, 2022 p. 85).

The presented scenarios illustrate the potential that different regulative decrees could have on Finnish level and as moderate limits are not align with Paris agreement or global responsibility scenario more strict limits are probable. The forthcoming regulation and the statutes according to it will set the direction for this development. The Danish climate regulation model (Appendix 4) of gradually lowering $CO_2$ limit seems advisable that industry can progress to the desirable level of emission reduction.

# 3 Status of buildings' carbon footprint calculation

In general carbon footprint calculation process is quite simple as it is a total sum of GHG emissions that are linked to the whole life cycle of building (YM, 2021, p. 8, 16). Figure 1 previously presented the categories that are included in the life cycle by different calculation methods YM 2019:22 and YM 6/2021 draft. So, for example calculating CF for certain material in building the amount of material is multiplied with the emission factor to get the results and this is done for all parts of building that are included in CF calculations system boundaries (Figure 4) and finally all GHG emission stages are summed up to get the whole buildings CF. (YM, 2019; YM, 2021). The Finnish Method for whole life cycle carbon footprint assessment of buildings 2019:22 considers life cycle stages of building to be the process stages from A1-5, B and C (YM, 2019, p. 12) usually called as cradle to gate. The Figure 6 presents the phases and the subcategories of these stages, but not all subcategories are included to the Finnish CF evaluation (see Table 1). As, carbon footprint is the sum of GHG emission during buildings life cycle, the carbon handprint presents the positive climate impacts that would not be created without building project (YM, 2021, p. 8).




*Included modules of CF evaluation; *B5 used in larger renovations only*

Figure 6. Life cycle stages of building according to the Finnish Method for whole life carbon assessment of buildings 2019:22 and included modules of CF evaluation CF by YM6/2021 draft presented with red frames (YM, 2019; YM, 2021)

Figure 7 presents building information model-based illustration of building and its main parts on rough level. The main structural components are building's foundations, interior and exterior walls, base and other layers flooring, roofing, windows and related heating systems and their heat recovery.

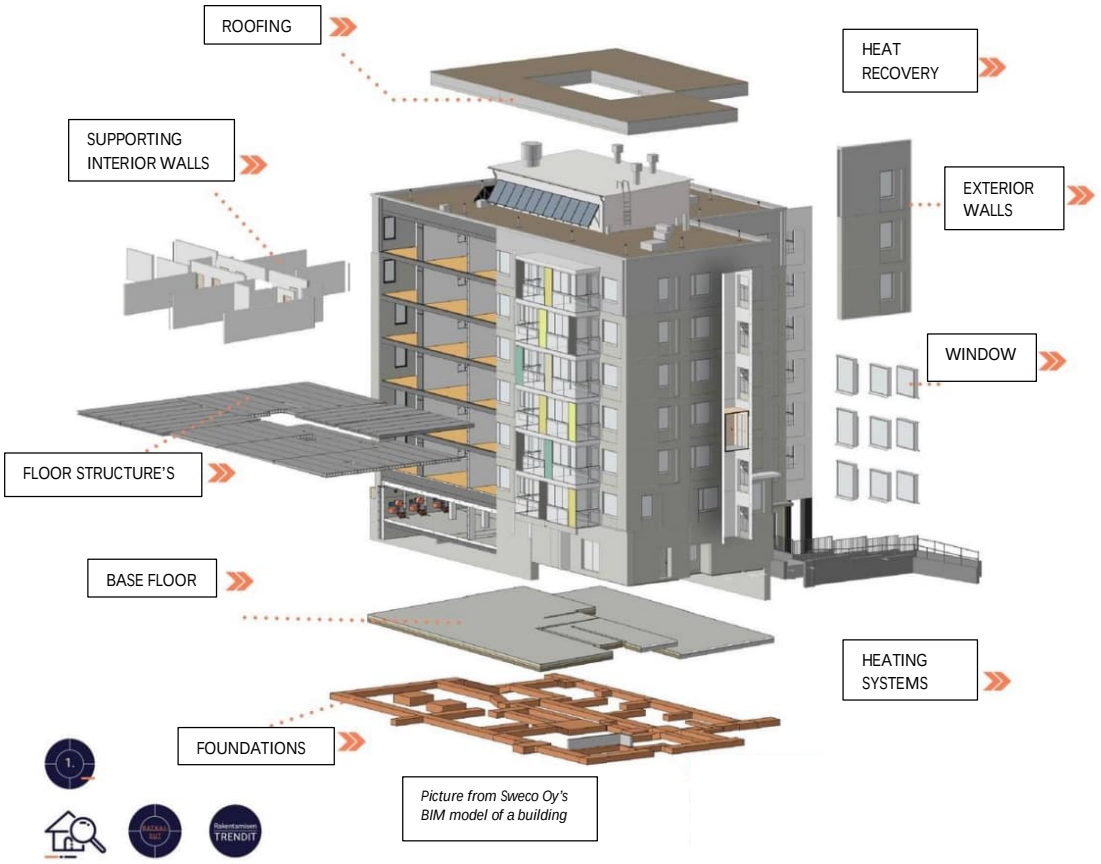



Figure 7. Building information model (BIM) by Sweco Oy and an illustration of building parts from NCC Suomi Oy's low-carbon and resource efficient unit's marketing platform brochure, adapted to English (NCC, 2022d)

Ahola & Liljeström (2018) studied the carbon footprint of a buildings, and it was found out that largest effect on the carbon footprint (CF) of building during its lifetime fell upon the energy use (B6, 62-68%). At that time building materials had second largest effect on CF (A1-A3, 20-23% including foundations). The Figure 8 presents the average of four residential building's carbon footprint by study of Ahola & Liljeström (2018) and in 2020 by one residential house (Optiplan, 2020) informed and calculated by Level (s) method. Level (s) is European framework, a method to assess and report the sustainability performance of building's life cycle that includes the carbon footprint assessment (European Commission, 2023).

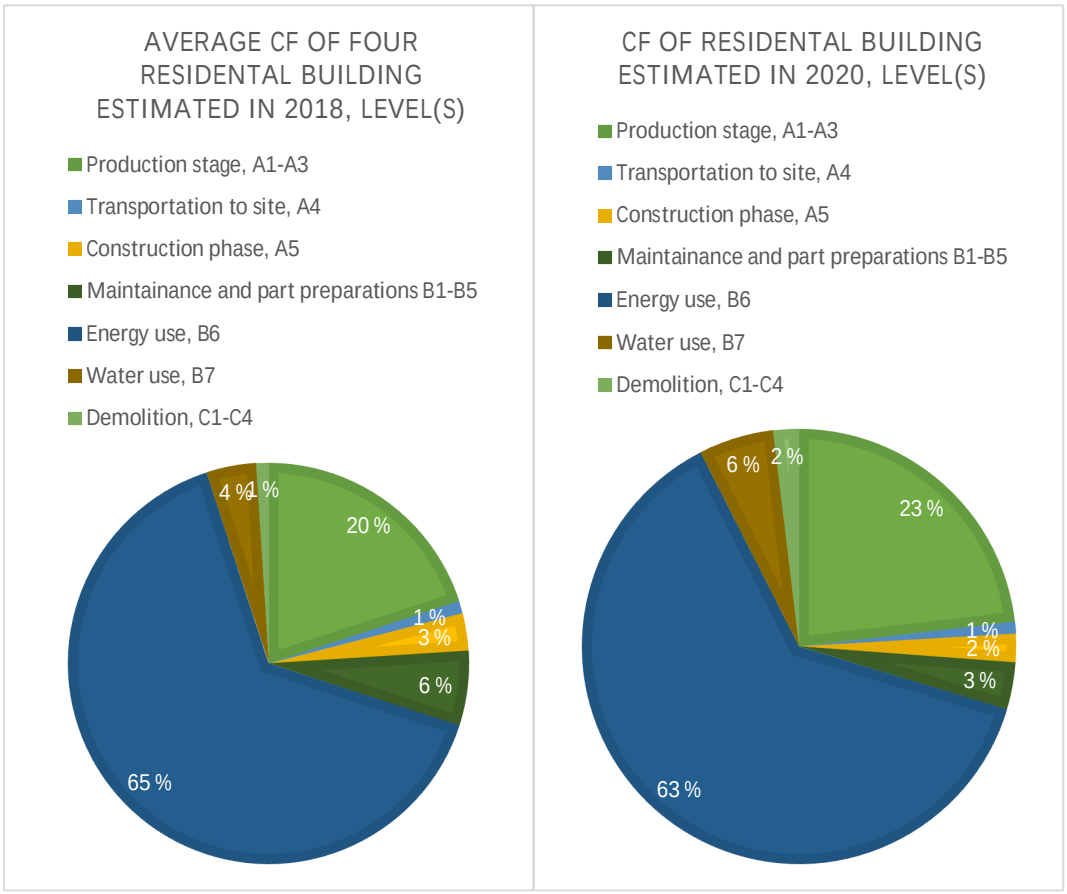



Figure 8. Residential buildings carbon footprint distribution to different life cycle stages at 2018 average of four projects (Ahola & Liljeström, 2018) and in 2020 by one residential house at construction permit phase (Optiplan, 2020) with Level(s) method

The calculation method has great affect to the CF distribution and on the CF results as the content, categories included, and emission factors of energy use differ by method. Figure 9 shows the difference of the CF results distribution with YM2021 and Level(s) method from a same residential building. If calculation has made with Level(s) method the energy use category still dominates the share of building's carbon footprint from all the CF categories (Figure 6). In comparison, if YM methodology is applied the CF shares are totally different (Figure 9). The energy use category's share is dependent of the emission factors and the LCA calculation methods emission factors and possible future prediction scenario about energy's emissions. YM2021 method has significantly lower assumption for future energy emissions factors as renewable energy share can lower the energy production GHG emission intensity. Despite this future energy scenario development difference between YM2021 and

Levels(s) methods, the production stage emissions are calculated both according to EN 15978 -standard. In Figure 9, the energy use (B6) of building and production stage (A1-A3) category shares are nearly opposite when different methodology is applied. Notable is also that YM2021 does not include the same categories and water use (B7) is excluded.

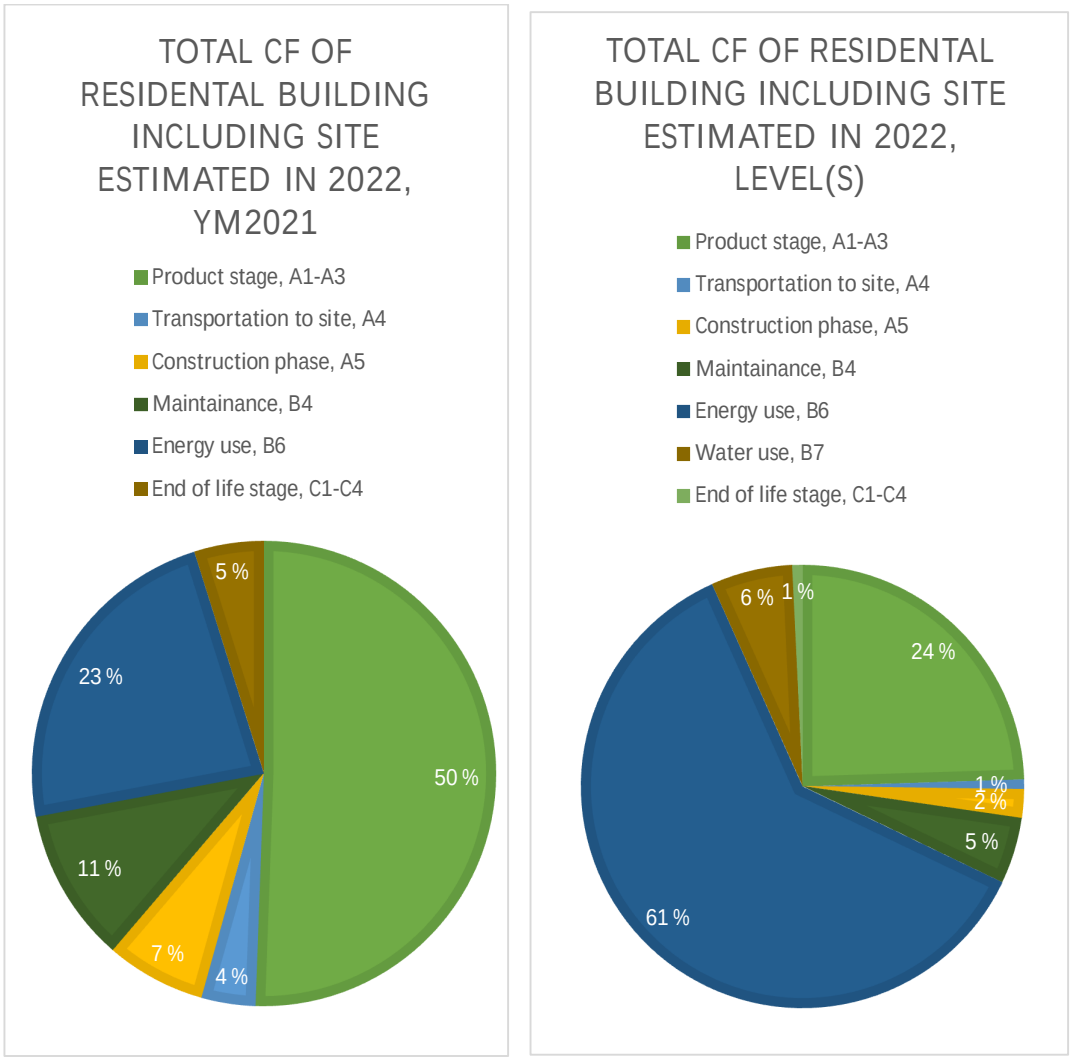



Figure 9. Residential buildings carbon footprint distribution to different life cycle stages with YM2021 and with Level(s) methods of same residential building at construction commissioning phase with Level(s) method (Sweco, 2022a).

In one office development project (later Case L/M) the consultant company Sweco Oy compared wood and concrete structure options for case office building and low-carbon materials were considered in separate scenarios as alternative for both. (Sweco, 2021a).

Appendix 5 presents in Figure 1 the CF scenarios of regional energy production emission factors with Helen Oy (Helsinki city area energy producer and distributer), and in Figure 2 of Appendix 5 the scenario with environmental ministry's national energy emission factors (CO2data.fi). In Sweco's regional energy scenario that also consider energy optimization solutions and wind power utilization up to 100% in electricity use (improved scenario of Appendix 5, Figure 1) the emission reduction potential reaches up to 91% better performance in CF results when comparing environmental ministry's national energy emission factors (CO2data.fi). It is to be noted that this regional energy scenario is by case and dependent about the regional energy provider's emission factors. According to YM 6/2021 draft method the regional energy emission factors can be used as additional information, but these can't replace the national energy emissions factors in calculation. If in future the new regional energy emission factors are taken into consideration the production stage (A1-A3) share of the building's whole life cycles CF increases more than was presented in Appendix 5 in Figure 2.

Based on the CF results for the case building in Figure 9, the carbon footprint share of building materials (A1-A3) is more dominant when using the Finnish national building life cycle methodology (YM2021). With this YM2021 method, the material and structural selection is the one that affects most to whole life cycle CF results. In future manufacturing emissions are likely to reduce which this will further decrease absolute carbon footprint level.

## 3.1 Carbon footprint calculation with YM2021

The carbon footprint calculation of YM2021 methodology is based on standards EN 156 43, EN 15978, EN 15804, ISO 14067 and EU's Level(s) methodology. The carbon footprint of a building is calculated as a sum of building's lifecycle's phases global warming potential (GWP) (Figure 10). The Figure 10 illustrates the CF calculation equation for building and the data use possibilities of the different phase of calculation. For some phases the specific project data is required, but for the other phases default table values usage is allowed also. (Kuittinen, 2023)

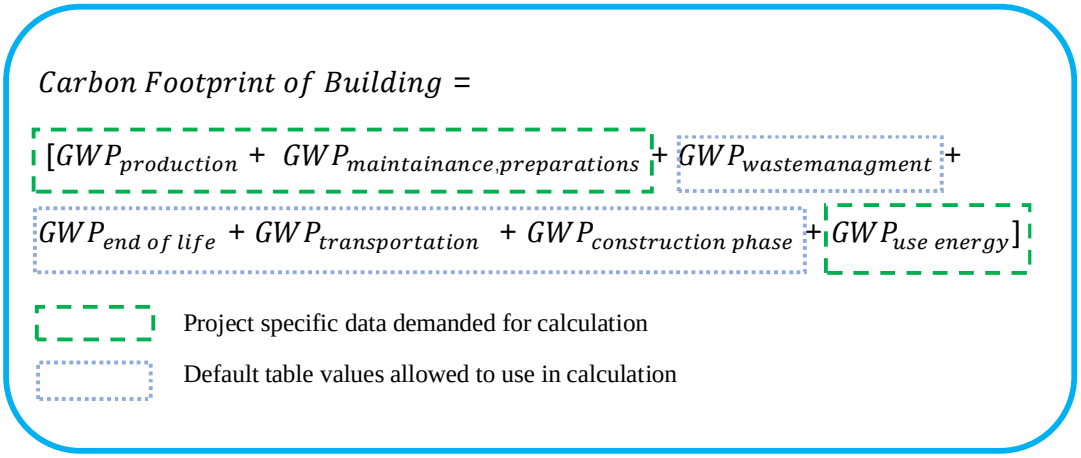



Figure 10. Illustration of carbon footprint equation and the calculation data source demands of CF calculation by Finnish YM2021 method, based on Kuittinen (2023).

Production includes all building materials GHG emissions from acquisition (A1), materials transportation (A2) to materials production (A3). Maintenance and preparations (B4) include material part swaps. Waste management includes construction phase (A5), maintenance (B4) and demolition (C3) activities waste management GHG emissions. The end of life (EOL) includes construction and demolition waste management's GHG emissions. Transportation includes the material transport from production to construction site (A4) and waste management operations' transportation emissions (C2). Construction phase includes the energy use of construction operations (A5), maintenance (B4) and demolition (C1) emissions. Use of energy covers building's life cycle's energy consumptions emissions (B6). (YM, 2021).

## 3.2 Content of building's CF calculation with YM2021

YM2021 method separates the building and building site from one another as building site conditions can highly vary between locations. The included parts in YM2021 CF calculation content of building and building site is listed mainly to Table 3. More detailed, up to date content with Talo 2000 (House 2000) categorisation is available at CO2data.fi under *"use age"* -section. (YM, 2021; SYKE, 2022).

Table 3. Included buildings parts of carbon footprint calculation, divided between building and building site (YM, 2021; SYKE, 2022).

| Included building parts/content* | Building | | Building site |
|---|---|---|---|
| **Site elements** | - | | Ground elements<br>Soil stabilization and reinforcement elements:<br>Paved and green areas<br>Site construction |
| **Building elements** | Ground floors<br>Structural frame<br>Façades<br>External decks<br>Roofs | | Foundations |
| **Internal space elements** | Internal dividers<br>Space surfaces<br>Internal fixtures<br>Other internal space elements<br>Box units | | - |
| **Building services**** | Residential building:<br>Water fixtures<br>Air handling units<br>Lighting fixtures<br>Cooling system<br>Extinguishing system, sprinklers | Office:<br>Water fixtures<br>Room heating units<br>Ventilation system<br>Cooling system<br>Sprinkler system<br>Lighting fixtures | HVAC system parts that are not serving the building itself but serves the building site, i.e., area lighting, or exterior canopy electrical systems |
| ** The full and up to date content is available at CO2data.fi*<br>***The information presented in Table 3 limits out other building types of HVAC content, only residential and office buildings have been included to this table* | | | |

As the carbon footprint of production phase is sum of the emissions associated with the production of the materials, the primary data of mass quantities used in the CF calculation is key factor influencing the result. To evaluate the carbon footprint calculation results several factors are needed be considered. If target is to compare different calculation tool results it is vital to understand the calculation tool operating principles, possible differences in initial material mass data and included content for calculation. What is selected for primary initial data and for system boundaries limiting the content will have major impact on the result. As a result of this the plain carbon footprint results are rarely if ever comparable

directly itself alone. This illustrates the need for standard calculation in order to get comparable results.

### 3.2.1 Material description of building

Currently the initial data used in the CF calculation can be obtained from Building Information Model (BIM), other 2D building plans (architectural and structural) and energy certificate and report of building. Calculation author can utilize the data from building plans and other initial data available like mass listing if provided by quantity survey experts. (NCC Suomi Oy, 2022c).

The new building law reform aims that all buildings will have material description in future (or declaration of building products). This will also act as basis for the low carbon evaluation and is basic part of regulations directing buildings to carbon reductions. It is intended that the digital BIM model information could be exploited in this material description. Therefore, digitalisation is part of the building law reform, and it aims that BIM based construction planning is to be mandatory and integrated to construction permit process. The BIM model of building shall be updated as part of construction process and actual material and mass information should be up to date when buildings commissioning takes place. This dimension shall elevate circular economy as realized building material and mass information's shall be heritage for buildings use, maintenance, renovation, refurbishment, and demolition phases. (Parliament, 2022, sections 3.2.2, 3.2.3). This materials description proposition (Parliament, 2022) makes the embodied carbon (integrated carbon within material) that has been evaluated as part of CF calculation more transparent. To addition, the transparency with material description of building makes the buildings' carbon footprint calculation more congruence for comparison purposes.

## 3.3 Carbon handprint calculation

Carbon handprint calculation is indicator of buildings' whole lifecycle's possible climate beneficial factors that would not be created without the building project. Carbon handprint (CH) results are informed separately and shall not be subtracted from carbon footprint results. CH includes following parts according to YM 2021 draft (YM, 2021):

- D1: via building materials reuse or through material recycling avoided GHG emissions
- D2: materials utilization through recycling fuel or energy
- D3: In building or at building sites produced surplus energy
- D4: Embodied biogenic or technic carbon of long-life span building products
- D5: Atmospheres carbon dioxide that bonds through carbonisation to cement products.

## 3.4 CF calculation tools

In general, there are several different CF calculation tools for building sector's use like EPIC, One Click LCA, Green Building Partners (GBP) tool, Build Carbon Neutral, Pathfinder online software and other Excel based calculation tools like The Environment Agency Carbon Calculator and Finnish Environmental ministry's tool etc. Moreover, there are professional LCA softwares like GaBi, SimaPro and Open LCA that can be used to construct fully customizable LCA models. (Circular Ecology, 2022; Carbon Leadership Forum, 2022; YM, 2019; Raksystems 2020). In 2021, company NCC Suomi Oy integrated the CF calculation of production phase (A1-A3) to their own cost estimation tool Esti Model.

One target of the study was to establish how company's CF calculation tool estimates buildings CF so research about the central calculation tools was made. Later at the empirical part the case buildings CF calculation that are to be used as material for CF results analysing are created with Esti Model, One Click LCA or Green Building Partners tools, so these tools and their features are researched further.

### 3.4.1 Esti Model

Company's own Esti Model tool (Excel based) is created for early-stage cost estimation purposes, and it will model the building materials of project based on space specific information by creating its own mass list of the building materials (Figure 11). The actualized detailed mass lists are created later for the projects, so the tool is more intended

for cost estimations at development stage. Nevertheless, this tool is utilized on projects' cost estimations when drawing up the actual first budget version of project to compare the differences. In addition, the Esti Model calculations are conducted for comparison also to other projects to reveal possible calculation mistakes. (NCC Suomi Oy 2022a; NCC Suomi Oy 2022f).

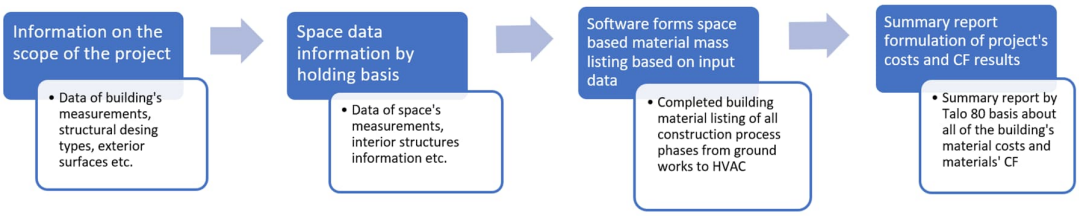



Figure 11. Esti Model's operation process description (NCC Suomi Oy 2022f).

Esti Model uses the Finnish national emission data base, CO2data.fi, to estimate the CF of building project's materials with typical emission values. This open $CO_2$ database is provided by Finnish Environmental centre (SYKE), and it presents objectively the conservative and the typical values for different building products. Notable is that the conservative values of CO2data.fi are meant for building permit phase in Finland when products are not specified, and these conservative values are 20% higher than the typical GWP values of products in this database and higher than manufacture specific EDP information (One Click LCA, 2021; YM 2019, p. 45; SYKE, 2022). This conservative value factor 20% can be added to the final Esti Model result manually.

### 3.4.2 One Click LCA

One Click LCA software (web-based) is a commonly used worldwide CF calculation tool that considers the whole life cycle emissions of building. One Click LCA database is checked and reviewed firstly by the software provider and integrated to One Click LCA database after quality checking. This database uses freely available data from the environmental performance declarations (EPD) of construction sector products globally. One Click LCA also includes public LCA data, and generic data of the key construction materials. In addition, the software has generic region or country specific data for processes like energy

production. The software's full feature use licences are fee-based, but some of software's features are available free for students or provided with free license period. (One Click LCA, 2020; One Click LCA, 2022).

One Click LCA also has rough pre-project stage strategic design tool, the Carbon Designer where different solutions carbon footprints can be compared when the accurate initial data of the mass amounts is still lacking from a building project. The basic information of a planned project is required like building type and size. (One Click LCA, 2021).

### 3.4.3 Green Building Partners tool

Green Building Partners (GBP) have their own excel based LCA calculation tool that informs the CF calculation results according to Finnish building life cycle meters analysis guideline called REM (Rakennusten elinkaarimittarit) method. REM method is based on EN 15978 – standard (Assessment of environmental performance of buildings – Calculation method) and is resulted from Finnish Green Building Council's Värkki project of 2013. The CF results are informed nowadays also according to YM2019 or YM2021 and REM together in same results reporting. The emission data sources used include EPDs and Finnish national emission data base and environmental statements of construction products, and European products supplementary data. The GBP tool reporting also differs as it applies detailed sufficient data division categorised with Finnish Talo (Building) 2000 classification to make the CF calculation more transparent and revealing comparable figures. (Raksystems, 2020; Raksystems, 2023; FIGBC. 2022).

### 3.4.4 Main differences of considered calculation tools

The CF calculation tools differ quite much from another starting from initial data source, main purpose of tool, the different functions, and the differing operation environment. Table 4 presents the main differences of OCL and Esti Model.

Table 4. Differences of considered CF calculation tools (NCC Suomi Oy, 2023b; OCL, 2023; Raksystems, 2020).

| | **Esti Model** | **One Click LCA** | **GBP** | One Click LCA – Carbon designer [3] |
|---|---|---|---|---|
| Method | YM 6/2021 | YM 6/2021, YM2019:22, Level(s), Planetary Finland, etc. | YM6/2021, YM2019:22, REM | Carbon designer |
| Purpose | Strategic planning phase of building projects cost estimations and product stage CF estimations | Planning phase of building projects and accurate CF calculations of selected life cycle stages | Planning phase of building projects and accurate CF calculations of selected life cycle stages | Strategic planning phase of building projects when lacking mass information |
| Life cycle stages | Product stage A1-A3 | Whole life cycle methods: A1-A5, B1-2, B3, B4, B5, C1-C4, D [2] | Whole life cycle methods: A1-A5, B1-2, B3, B4, B5, C1-C4, D | Product stage A1-A3 |
| Initial emissions data | Finnish national emission data base [1] – typical product GWP values | Finnish national emission data base, EPD, OCL own database of product emission factors | Finnish national emission data base, EPD | Finnish national emission data base, EPD, OCL own database of product emission factors |
| Initial mass data | Creation of the program based on space information | Mass data from mass lists, import from BIM models, mass quantity listings | Mass data from mass lists, import from BIM models, mass quantity listings | Creation of the program based on 3D model information |

*1) is CO2.data.fi; 2) Life cycle stages that can be included with the tool and included stages are depending on method selected; 3) Tool not used in this study or to create this study's results*

The Esti Model tool is focused on the strategic planning phase of the building projects costs and CF estimations according to Finnish YM 6/2021 method. Esti Model is also limited to product stage (A1-A3) and does not consider whole life cycle of a building. In turn, the One Click LCA (OCL) software offers several different methods to be used in calculation basis.

OCL software also has different features to compare the scenarios and the low-carbon solutions are proposed by the software (expert business licence). The building's whole life cycle CF calculation differs between researched tools as the modules are different and the initial data is different. Major difference on OCL's CF calculation and between CF estimation of Esti Model is that Esti Model creates its own mass list of building materials based on space information (Figure 11). OCL tool on other had uses the mass data imported from BIM model or completed mass lists or input data can also be added manually. Even if the results were narrowed down to product stage (A1-A3) the Esti Model and OLC the results are not comparable because the initial mass data (input data) differs in calculations. Furthermore, the Esti Modell uses by default only the national generic emission data base and therefore the emission can be higher when compared to product specific emission factors of the EPD's. The use of conservative, typical or the product specific emission values can impact on total carbon footprint and significance varies by project. In the Esti Model the emission value can be altered by calculating author if for example specific product's EDP values is needed to utilize. As an additional feature, OCL has a feature meant for the building projects strategic planning phase when mass lists are not completed that creates simple 3D model according to building type and shape (OCL, 2023). The GBP excel based tool suits for multiple method purposes at ones and it considers more detailed reporting that complies for both REM and YM method at same time. The differences between the tools used must be taken into account when comparing CF results, as the choice of tool can affect the results through the input data, the emission factors and the calculation method used.

# 4 Overview of buildings GHG emission reduction potential and solutions

GHG emissions reduction potential of buildings differs among the project development stages. Figure 12 presents that the planning and design phase has the largest carbon reduction potential and after that the construction phase can only utilize different efficient building solutions. (One Click LCA, 2021).

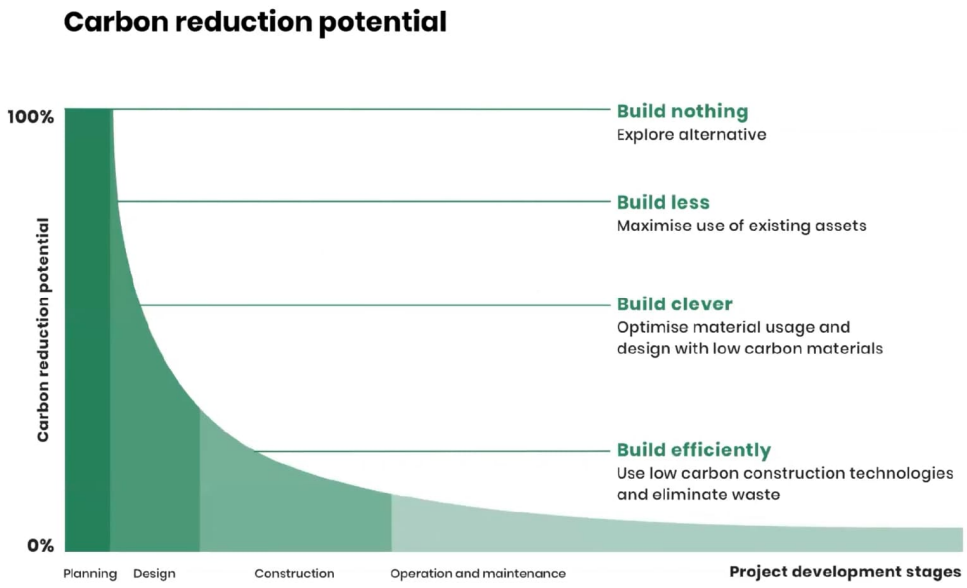



Figure 12. Carbon reduction potential of a building project stages (One Click LCA, 2021).

Carbon footprint can be affected mostly by material and design solutions that alter the energy consumption of buildings. It is likely that building companies cannot continue the business-as-usual practices to reach the planned carbon footprint limit levels. Therefore, different control methods and design and optimization solutions needs to be introduced for projects. (One Click LCA, 2021).

## 4.1 CF reduction solutions

Design choices, material selections and low-carbon alternative products can have major impact on buildings CF results when targeted at the primary parts of the building. Primary parts of the building are the structural parts (Figure 7) that constitute the largest mass like building's structural frame (bearing walls and flooring). Different solutions have been studied widely and according to Ahola & Liljeström (2018) the highest $CO_2$ emission of their case buildings materials occurred from heating, ventilation, and air conditioning (HVAC) design, second largest from horizontal structures and third highest exterior wall structures. (Ahola & Liljeström 2018, p.30-31). Study revealed that the investigated exterior wall solutions CF result per floor gross area in square metres (g-$m^2$) vary a lot according to selected design:

- Supporting exterior wall CF varies between 87-107 $kgCO_2$/g-$m^2$ in case projects
- Non-supporting exterior wall CF varies between 20-104 $kgCO_2$/ g-$m^2$ in case projects
    - If recycled bricks would be used the highest CF of brick façade wall would drop to level 73 $kgCO_2$/ g-$m^2$ (-31 $kgCO_2$/ g-$m^2$)
    - If steel supports would be replaced with wood supports, then lowest Cf would drop to level 17 $kgCO_2$/ g-$m^2$ (-3 $kgCO_2$/ g-$m^2$)

Also, horizontal structures had different solutions and was established that base floor CF results were 84-90 $kgCO_2$/ g-$m^2$ and roofing structures options CF 115-138 $kgCO_2$/ g-$m^2$ (diagonal sheet metal roofing smallest 115 $kgCO_2$/ g-$m^2$ and flat light gravel roofing the largest). It was established in the study that of horizontal structures the light gravel roofing solution had high impact on CF results as this material have larger emissions than sheet metal coated ridge roof design. In the study HVAC design was only estimated according to buildings flooring area at this study and no comparison of solutions was available. This study's emissions have been assessed with 2016 levels energy emissions factors and no development scenario of future emission factors have been considered (major difference when comparing the Finnish YM2021 method). Also, emission factors align with EN15804 or ISO14040 and product specific information has been utilized or similar product info used, region Finland, Northern countries, or EU area typical product information. Other solutions to lower CF regarding the building materials selection are window glass and frame solutions

that can lower use phase energy consumption, but the window solar control glass that responds to the heat conditions are still expensive products. Study's comparison of different structural design solutions shows that selecting certain designs can have major effect to CF result when choosing design solution that have a lower carbon footprint content like the diagonal sheet metal roofing or the plaster surfaced façade. (Ahola & Liljeström, 2018)

In addition to design solutions the product specific selection can have a major effect on CF results as i.e., low-carbon in-situ used concrete can have 15-60% lower emissions compared to the regular concrete products manufactured from the virgin raw materials (Rudus, 2021). In addition, if the design solution can be modified to include a timber frame in combination with a timber cladding, this combination can reduce the CF by about 20%, thus reducing the impact on the CF results (A-insinöörit, 2021). It is to be noted that the wood material selection also has other impacts on the total design of the building and the structural design varies from concrete buildings, for example the steel structures are likely to be added.

Renewable energy solutions and energy efficiency of a building possess significant impact on the building's whole life cycles CF reduction. When choosing the energy classification for a building step from second best category (B) to best category (A) can have 30% reduction impact on the CF. If geothermal heat pump systems have been selected for heating solution together with best energy efficiency performance (A) this can have over 60% reduction to CF results over the building's life cycle (A-insinöörit, 2021).

NCC Suomi Oy has utilized the Ahola & Liljeström 2018 study's results when developing Case F-H apartment building projects (case description will follow in chapter 5) and the targeted carbon footprint level for that cases are based on that research (NCC Suomi Oy, 2022c). The CF targets' set for the Case F-H (Appendix 1) was 1250 $kgCO_2$/ g-$m^2$ (Level(s) -method). Figure 13 presents the CF development of Cases F/G/H and for two older reference level cases which were part of Ahola & Liljeström (2018).

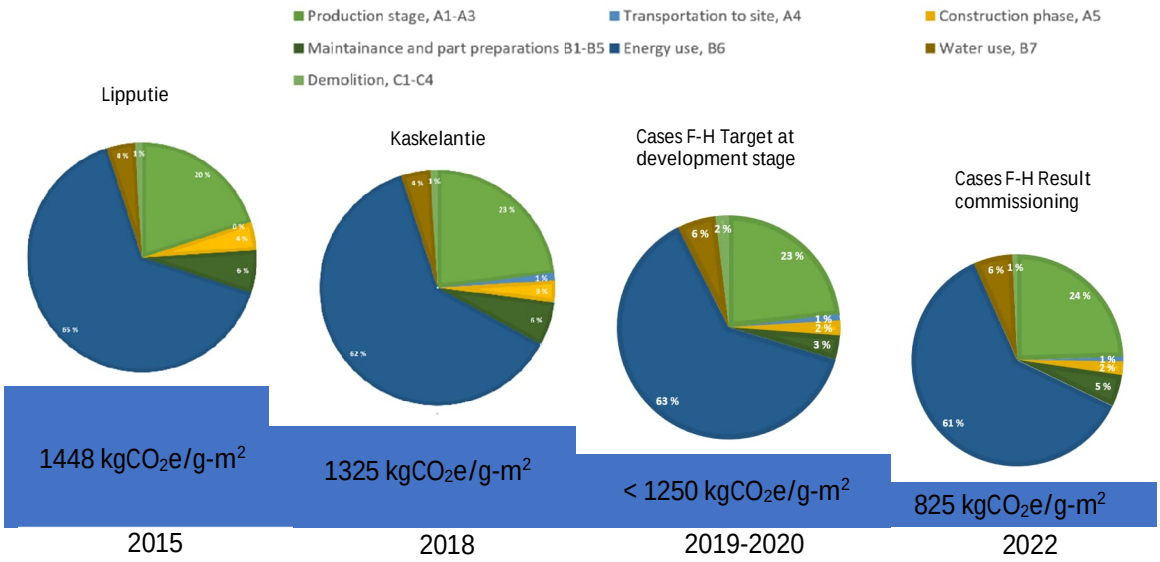



Figure 13. CF target level setting with Levels method for Case projects F-H, based on Ahola and Liljeström study (2018, p. 24) projects Lipputie and Kaskelantie and Cases F-H CF calculations' by Sweco (NCC Suomi Oy 2022c; Optiplan, 2019; Optiplan, 2020; Sweco, 2022).

The CF results of Case F-H are resulted from Swan labelling's high energy efficiency targets, previous study of Ahola & Liljeström (2018) results utilization of different structural design choices and geothermal heat pump solution selection and straight-forward design of building (NCC Suomi Oy 2022c).

## 4.2 Circular economy potential

Nordic Networks for Circular Construction (2023) consortium defines the circular economy in construction business to be "*maintaining and increasing the value in the built environment*". The actions required to enable this include enhanced productions, digital tools, new business models and lifestyle actions. Enabling circular economy engagement, re-thinking, and co-operation through whole vale chain of build environment will be needed. (NNCC, 2023; Leising et. al, 2018). Figure 14 presents the circular economy systems diagram demonstration for construction business by architects of INARO (2021) circular city block project based on Ellen MacArthur Foundation's (2019) CE systems diagram. Figure 14 illustrates circular economy activities for construction business aiming to minimize the systemic leakage of value and negative externalities.

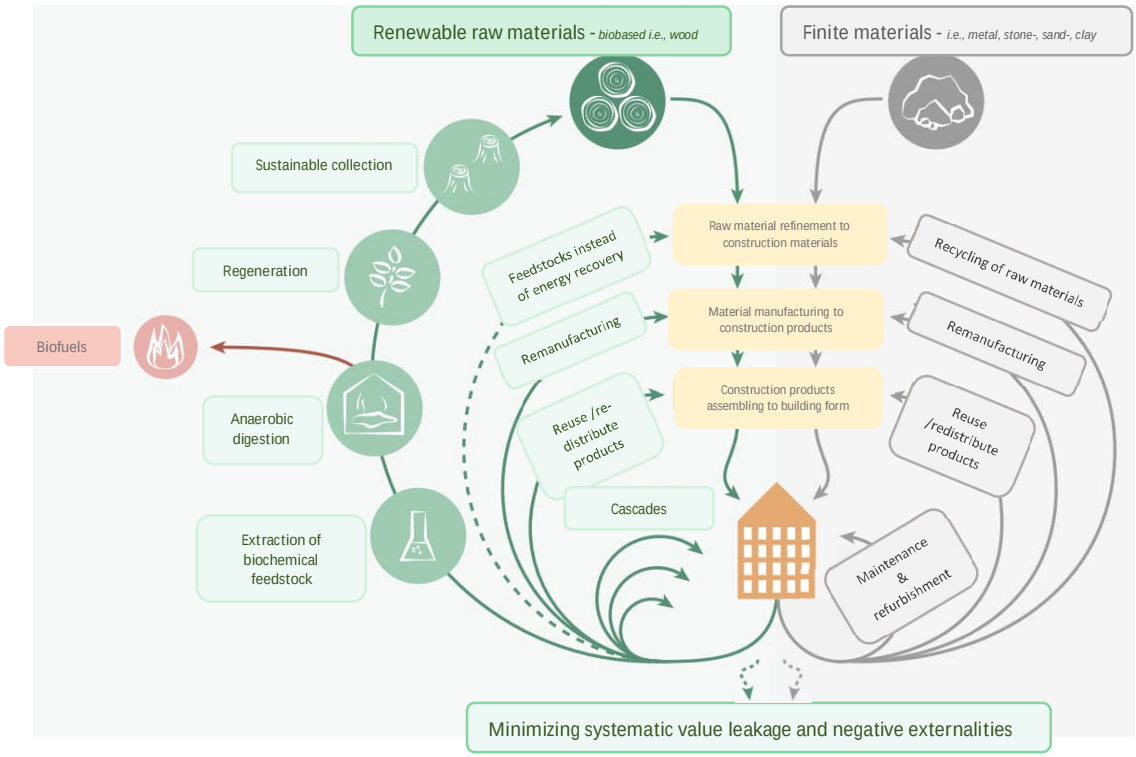



Figure 14. Illustration of circular economy model in construction business, adopted from INARO (2021) based on Ellen MacArthur Foundation's (2013) CE systems diagram.

The circular economy process described in Figure 14 also presents some of the R-hierarchy activities that describes the value preservation degree aiming almost closed loop of material utilization. The study of Reike et. al. (2018) presents the 10R hierarchies of material value retention options "*R0 - Refuse, R1 – Reduce, R2 - Re-sell/Re-use, R3 - Repair, R4 - Refurbish, R5 - Re-Manufacture, R6 - Re-purpose (Rethink), R7 - Recycle, R8 - Recover (Energy), R9 - Re-Mine*" which can be applied also for building sector. (INARO, 2021; Ellen MacArthur, 2019; Reike et. al. 2018).

The construction companies can adopt these principles in their operations and strategy and all the actions can have huge impact on carbon reduction of building sector. Refusing (R0) can be applied for avoiding new building by selecting refurbishment instead if developing projects. Reducing (R1) can be applied in planning and development phase by optimizing the building solutions and resource use. (INARO, 2021). Furthermore, from the whole life cycle perspective the designing building applying CE principle so that buildings spaces are

flexible adjustable for different purposes (R6, R5) i.e., open design structure, structures are maintainable (R3, R4) and suitable for disassembly for reuse and redistribution (R2). In addition, to these the materials selection should be focus on materials that can be recirculated (R5), recycled (R7) and recovered (R8, R9) for further use in value chain or as feedstock for some other valorisation purpose. (INARO, 2021; Reike et. al. 2018; Ebenhart et al. 2021).

### 4.2.1 Circular economy's impacts on CF

The reuse of materials possesses great potential to decrease $CO_2$ emissions of buildings (Bionova, 2021, p. 17) and different studies have estimated the circular economy (CE) impacts on carbon footprint reduction.

According to following studies materials reuse (R2) possess the highest impact on CF reduction:

- Reused concrete structures are estimated to have 98% smaller CF (Järvelä, 2021) and reused hollow core slabs can results 89% emission savings estimated by NTNU master students Høydahl and Walter at 2020 (Entra ASA, 2023 p. 54)
- Reuse of concrete elements and thermal window with reused double glazing has estimated to be 96% lower GHG emissions than similar new building products (Andersen et. al 2020, 385-386).
- Reused window CF (A1-A4) has been estimated be 13 kg/ $CO_2$e/piece as in for new windows can be 161.5 kg/ $CO_2$e/piece (Entra ASA, 2023 p. 15)
- Reused brick to façade cladding 75-79% lower GHG emissions (Andersen et. al 2020, 385-386)
- With reused façade panel and interior ceiling panels in general can result 97-98% emission savings (Entra ASA, 2023 p. 18, 30)
- Recycled brick façade element 59-62% lower impact on GHG emissions (Andersen et. al 2020, 385-386).

The reusability and adaptability of a building is a key element enabling the circular economy for buildings. As previous examples of the emission saving potential of reused materials show, the emission saving potential is significant if products can be reused for the same

value-added purpose. Instead of the demolition, refurbishment options should be explored and, if demolition is chosen, the utilization of material resources should be planned and thoroughly mapped to identify potentially dismantled and reusable materials. From construction business perspective the profitability counts. In KA13 Case evaluation revealed that reused window products had about 60% and chilled 65% beams lower purchase prises when comparing to new products. But in turn ceiling panels and steel structures were 50-60% more expensive than the new products. The KA13 Case new building utilizing reused hollow core slabs, steel structures and façade panes emission reduction of 36% was estimated to achieve and for refurbished building 78% GHG emission reduction occurred when planning preservation structures and materials carefully. (Entra ASA, 2023 p. 85, 94, 100-101).

Before the new Reform of the Land Use and Building Act there has been only one way to prove material approval for reused materials, the building project specific approval (YM 2021). According to Finnish Environmental Ministry *"European Commission has launched a process to clarify the Construction Products Regulation to allow the use of recycled materials in future"* (YM 2022b). When actualizing this will ease the reuse and "recycling" of materials in their higher value form.

Also, some products are considered improved products or CE products that have positive effect to CF as the recycled materials are used in product manufacturing (as feedstock) to lower carbon and virgin material intensity of products when compared to conventional products (Sweco, 2021a). Mostly known CE products at the business are low-carbon concrete products and reinforcement products that have high recycled steel content. Currently, new low-carbon solutions (CE products) can be found for major central parts of building materials like precast concrete elements. The hollow core slabs and columns possess reduction potential of CF up to 50%, and wall-elements CF reduction potential reaches up to 40%. The reduced carbon footprint impact is based on recycled content of cementitious and non-cementitious binders and concrete crush and recycled reinforcement materials. (Parma, 2023a; Parma 2023b; Parma, 2023c). Also, steel products can be found from low-carbon category and major steel beams can have up to 50% lower CF than regular products (Peikko, 2023). If recycled content products and reuse of building materials could be integrated into building sectors normal operation this could have significant impact on the new buildings CF results.

## 4.3 Carbon distribution of building

When developing and planning the building it is crucial to identify CF reduction potential of different solutions, design choices and products. The materials' carbon footprint in building is significant factor of CF as by YM method it can represent over 50% share of the total carbon footprint of buildings lifecycle. Identifying the building parts that contribute most to CF is crucial aiming to reduce CO2 emissions through embodied carbon or identifying CF reduction potential of building materials. The Figure 15 presents a typical case of residential building materials' carbon footprint distribution that shows that the highest materials carbon is within structural bearing and exterior walls, building services in general, and in intermediate floors. This type of carbon footprint distribution of materials was common for all the residential building cases that was researched in this study (Appendix 1) and most variation was seen at the foundations. These are the parts that possess the most significant carbon footprint reduction potential to focus the different optimization and low carbon materials selection, to gain the most significant impact.

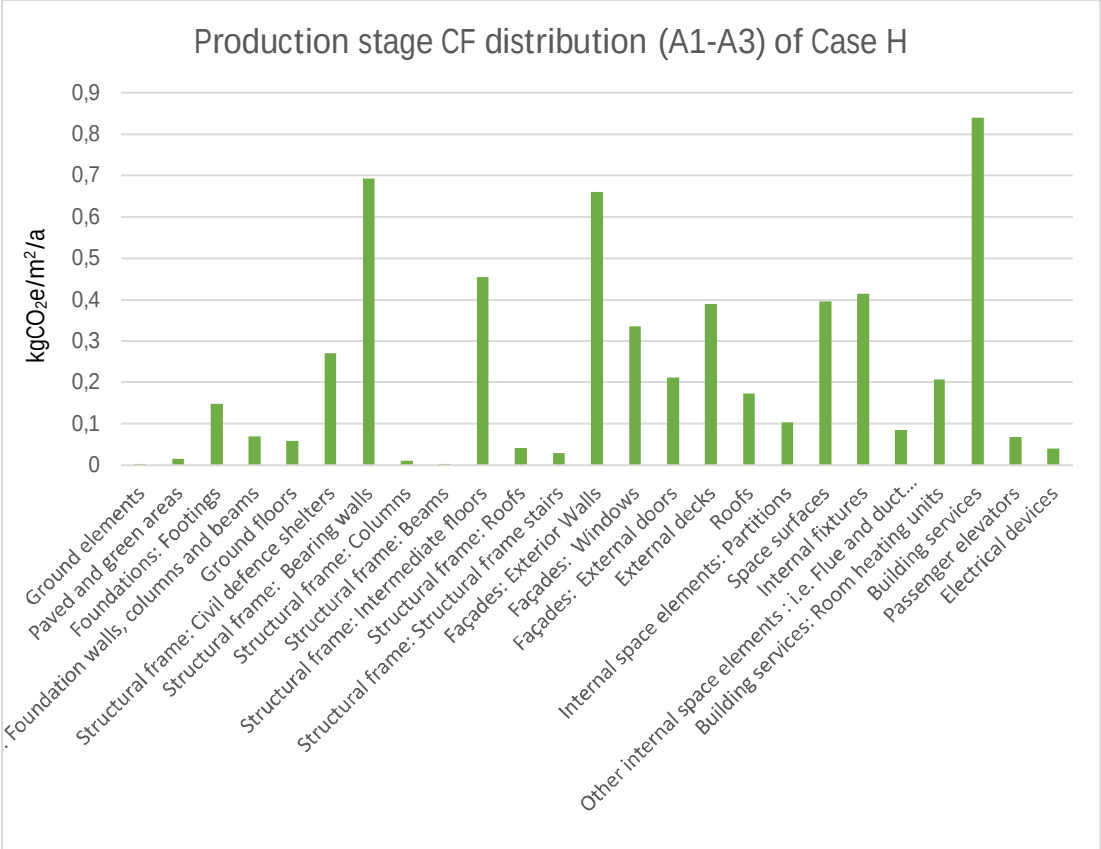



Figure 15. Productions stage CF results distribution for building Case H as $kgCO_2e/n\text{-}m^2/a$, according to YM 2021 method, formed from the data shared by Sweco (2022b).

It should be noted that identification of the most weighed and hence significant carbon footprint sources for the building should be examined by building type and by case to obtain the best added value of low carbon materials or design and optimization solutions.

# 5 Case buildings' carbon footprint calculations

One of the study's aims is to discover how construction company's own CF calculation tool, Esti Model, estimates the carbon footprint. This part will present the case building data research and CF results of the cases selected for comparison. In addition, the CF results reporting differences of the cases are compared. It should be noted that CF results are reported and reviewed based on the CF case reports.

Currently pilot use of Esti Model's carbon footprint section is ongoing, but no further analysing has yet been done for the calculation tool or results created with this tool (NCC Suomi, 2022a). Nowadays, company NCC Suomi Oy's building projects carbon footprint (CF) calculations have mostly been created with One Click LCA tool or with GBP tool by consultant companies. Respectively, these CF calculations are expert authority creations that are based on best available data and method of the moment when calculation has been created. In this study, CF calculations of case buildings prepared by experts are used for objective baseline material when analysing Esti Model' CF calculation results.

The CF calculation is affected mostly by method used that sets the content and systems boundaries, assumptions made by calculating author, primary and secondary data used in calculation. To directly compare CF results of different calculations the initial data used in the calculations and the system boundaries should be equal and methodology of calculation same or follow same principles. Furthermore, phase when the case buildings' CF calculations are done is also relevant as building plans can evolve, change, or be specified during the construction process. This more qualified or refined exact data will affect to CF calculation results via the primary data alteration in CF calculation. Primary data refining also effects the emission factors that can be utilized in the calculation. Meaning that if the specific product has been decided, then the product specific EPD data can be used in the calculation. The EDP usually presents lower emission factors than conservative CO2.fi database emission factors. (YM, 2021).

## 5.1 Case data collection

The challenge of study was to find data from company's building projects CF calculations since CF calculation data is not systematically collected to specific database. Firstly, study gathered the carbon footprint data from 19 building projects with interviews and inquiries from company's Metropolitan area building projects. Appendix 1 presents these projects where carbon footprint had been assessed by consultant companies. In Appendix 1 the Table 1 presents the residential buildings data and Table 2 presents the office buildings. From Appendix 1 can be seen that the calculation methodology varies between cases and not all initial data has been able to be found in background research of study. Due to the incomparable data and initial data availability of projects CF calculations, only some case projects were able to be selected for further analyse. Secondly, to analyse how company's own CF estimation of product phase would correlate to the actual LCA's product phase results (A1-A3), company's calculation tools (Esti Model) existing CF calculation case data of the same projects cases was collected. Currently, company does not have many Esti Model calculations done for the same cases than expert LCA calculations has been done. So, to be able to analyse the CF results data integration to the latest version of Esti Model was required. At the moment, no automatic data integration between different versions of Esti Model has been developed. Therefore, in the study data had to be derived manually from older version to the latest Esti Model version that includes CF calculation feature in selected cases.

## 5.2 Case buildings' CF calculations selection

The CF calculation data summary of NCC Suomi Oy's 19 metropolitan area case building projects is presented in Appendix 1. Appendix 1 presents the case projects CF reports data analysis with colour codes. From all these case buildings only six cases (E, H, I, J, K, M/L) had CF calculation results available according to YM2021 method. Most of the office building Cases (N, O, P, Q, R, S) had CF calculation available with Level(s) method and therefore these cases were handled separately from YM2021 method cases, but result summary was included to evaluation.

As one main goals of the study was to investigate how company's CF calculation tool (Esti model) estimates product stage (A1-A3) carbon footprint, so the cases had to be narrowed down further. The limitation from the six YM2021 method cases E, H, I, J, K and M/L to examined cases was done according to the primary data availability of the project (LCA report and input data information). The existing Esti Model CF calculation results were available from cases E and K, so these were included to selection. The scarcity of the Esti model CF results set a challenge for the comparison. So, to increase the number of Esti Model CF calculation results to be assessed, two Cases H and J was decided to be added for comparison with own Esti Model scenario creation. Therefore, the CF calculation results of Case H and J were created as a part of thesis. Decision to limit these own CF scenarios building with Esti Model to two case's was done according to highly available primary data of these cases. Finally, the 19 cases were narrowed down to the selected four residential building Cases E, H, J and K and to one office building Case M/L from all cases of Appendix 1.

### 5.2.1 Case buildings' CF calculations results reporting

Esti model's current pilot phase results reporting summary is presented in Table 5. This summary is on general level without details. Also, the results categorization according to YM2021 methods that separates the building and building place (see Figure 4) is not visible in the results reporting (resembles more YM2019 reporting). Moreover, the differences between structural parts are not specified, but this is only summary of the detailed report that can also be printed to excel from program (Appendix 6). One notable difference is that Esti Model uses net room area as divider and the expert are using heated net floor area, so area unit differs.

Table 5. Esti Model pilot phase results summary, based on Case H's space-based calculation scenario of this thesis.

| Building part category | kg $CO_2$ | nr-$m^2$ | $CO_2$/nr-$m^2$/50a |
|---|---|---|---|
| **Ground structures (row 11–18)** | 13 419 | 4.70 | 0.09 |
| **Foundations (row 21, 22)** | 36 306 | 12.71 | 0.25 |
| **Structural frame (row 23, 25, 26, 32, 33, 34)** | 367 416 | 128.65 | 2.57 |
| **Exterior frame (row 35, 36, 37, 41, 43, 51, 55)** | 373 110 | 130.64 | 2.61 |
| **Partitions and doors (row 43, 44, 45, 46, 47,48)** | 54 566 | 19.11 | 0.38 |
| **Space surfaces (row 52, 53, 54, 56, 57, 58)** | 76 662 | 26.84 | 0.54 |
| **Internal fixtures (row 61, 62, 63, 64, 67)** | 39 612 | 13.87 | 0.28 |
| **Building services (row 71, 71, 73)** | 83 616 | 29.28 | 0.59 |
| **Passenger elevators etc. (ro 74, 78)** | 9 612 | 3.37 | 0.07 |
| **Total whole building** | **1 054 318** | **369** | **7.38** |
| **Construction permit *** | **795 092** | **278** | **5.57** |
| ** Includes: structural frame, exterior frame, partitions, and doors* | | | |

The experts CF calculation results with OCL tool and GBP tool are reported separately for building and building site according to YM2021 method requires. The results provided by OCL tool are mainly reported in summary charts and figures and as total results. Unfortunately, in these cases no mass quantities were included in the OCL tool reporting documents. However, the detailed mass information and initial data can be shared in OCL tool. The OCL based cases data was granted to be used in this study via OCL sharing and could be exported to excel form from OCL tool. The OCL reporting data example is presented in Appendix 7. The data could not be worked with in OCL as this study mainly used only the student license and to work with expert created different method based (YM2019, YM 2021, Level(s)) data in OCL would have required the of commercial license.

The reporting with GPB tool includes detail data of different building part results divided between building, building place, parking hall and total. GBP reporting also informs the materials mass of different building part categories (Appendix 8).

### 5.2.2 Case E

Case E is apartment building in early stage where only draft of planning has been done so CF results is only estimation before more detailed planning phase. Case E was selected as both calculation tools' (Esti Model and One Click LCA) results were available. Total CF for building by experts was 14.61 $kgCO_2e/m^2/a$, and for building site 0.48 $kgCO_2e/m^2/a$, and estimation of production stage 6.48 $kgCO_2e/m^2/a$ (derived from YM2019 calculation result of A1-A3 as in YM2021 method this was nor reported separately). The Esti Model's CF result was 6.84 $kgCO_2e/m^2/a$ (A1-A3). Unfortunately, from this project there was not available more detailed data, and no mass or material listing of primary data was reported part of early-stage CF estimation results. Both, the expert authority calculation result, and company's internal CF results are informed for heated net floor area $3500m^2$. (Sweco 2021b; NCC Suomi Oy 2022b)

### 5.2.3 Case H

Cases F, G and H in Appendix 1 are same apartment building project where different CF calculation methods have been applied in different stages. As Case H has been calculated according to YM 2021 it was selected to be analysed further. Case has been a development case of the NCC Suomi Oy and the CF results are available from construction permit phase to commissioning with Levels (Case F & Case G) and YM2019 and the commissioning results are available by YM2021 method (Case H). Furthermore, Case H includes three separate residential buildings at same building site quite equal and for further case analysis one of the three separate buildings was selected. Cases F/G/H buildings have environmentally classified as Swan labelled buildings. The initial data for calculation have been derived from BIM modelling and construction plans. In these Cases F/G/H, the initial data availability of expert calculation were high as the original OCL calculation data was shared for research use by consultant company directly through OCL software. For this reason, also deeper initial data analysis and was possible for the Case H. (Sweco, 2022)

In Case H's CF results were calculated with YM 2021 method and whole life cycle's CF results for building was 12.32 $kgCO_2e/m^2/a$, and building site 3.15 $kgCO_2e/m^2/a$. The production stage A1-A3 results for building were 5.54 $kgCO_2e/m^2/a$. (Sweco, 2022)

However, the company's own Esti model cost calculation was originally made with older software version no CF results were available directly. Therefore space-based scenario was created as a part of this study based with Esti Model version that calculates the CF results. The created scenario CF calculation scenario of Case H's Esti Model was based on older cost estimation version's space information and structural design types. Appendix 9 presents this formed Esti Model space-listing for this scenario in Table 1. The calculated CF result for production stage A1-A3 was 7.01 $kgCO_2e/m^2/a$ when using same heated net floor area 3008 $n\text{-}m^2$ as in expert calculations.

### 5.2.4 Case J

Case J is residential building that aims to LEED Gold level environmental classification and construction permit phase CF calculation result are estimated with YM2021 method. Building height varies from 4.-10. stores and is consisted of several staircase units that have variable space quality level. Whole lifecycle CF results for building and building site together 15.1 $kgCO_2e/m^2/a$, building separately 13.25 $kgCO_2e/m^2/a$, and building site 0.5 $kgCO_2e/m^2/a$. The production stage A1-A3 results are for total 8.8 $kgCO_2e/m^2/a$, for building 6.95 $kgCO_2e/m^2/a$, and attached parking hall 1.84 $kgCO_2e/m^2/a$. Content and mass list of Case J was included to CF calculation results reporting and initial quantity listing from construction project has been provided to expert authority as calculation initial data. (GBP, 2022)

In this Case J also company's own Esti model cost calculation was made with older software version and the space-based scenario was made as a part of this thesis study based on older cost estimation version with some own variation based on further planning. Appendix 9 (Table 2) presents the formed space-listing for this Case J scenario. External wall structures were changed to match current design choices, mainly plaster covered precast concrete insulation elements. Also, to scenario variation were done: first with parking hall as original Esti Model cost calculation and second without parking hall to separate building site's and building's CF from one another. The CF result for production stage A1-A3 for building was 9.22 $kgCO_2e/m^2/a$ when converted to same heated net floor area 9653 $n\text{-}m^2$ that consultant calculation has.

### 5.2.5 Case K

Case K is residential building aiming to reach LEED Gold level environmental classification and construction permit phase CF calculation result are estimated with YM2021 method. Building height varies from 4.-10. stores and has five staircase units with different quality levels between staircase sections. Whole lifecycle CF results for building and building site together 16.02 $kgCO_2e/m^2/a$, building separately 14.05 $kgCO_2e/m^2/a$, and building site 0.65 $kgCO_2e/m^2/a$. The production stage A1-A3 results are for total 9.83 $kgCO_2e/m^2/a$, for building 7.22 $kgCO_2e/m^2/a$, and building site 1.84 $kgCO_2e/m^2/a$. Content and mass list of Case K was provided from construction project to expert authority as calculation initial data. (GBP, 2023)

In this case Esti model cost calculation by company's internal cost engineer was already available and information was used by extracting the attached parking hall results from the building. The CF result for production stage A1-A3 for building was 12.08 $kgCO_2e/m^2/a$ when converted to same heated net floor area 9 413 $n\text{-}m^2$ that consultant calculation uses. (NCC Suomi Oy 2022b)

### 5.2.6 Case L and Case M

Case L and Case M in Appendix 1 at Table 2 are the same development project that has CF results from both YM2019 (Case L) and YM2021 (Case M) methodology. It was selected for case analysis since it was one of first projects were both company's own CF calculation and reference expert calculation had both been created. Since Case M/L is office development projects and differs from other data it is handled separately from other Cases and only production stage (A1-A3) results are analysed. (NCC Suomi Oy 2022b; Sweco, 2021a; Sweco, 2022)

From this Case company has Esti model cost calculation that includes CF result, so calculation is made by company's internal expert. The CF result base case concrete scenario's production stage A1-A3 was 9.71 $kgCO_2/n\text{-}m^2/a$ when converted to same heated net floor area 16159 $n\text{-}m^2$ than consultant calculations (NCC Suomi Oy 2022b). This scenario is created at same time than Case L scenarios by consultant. Case L product stage results A1-A3 by consultant company were 7.68 $kgCO_2/n\text{-}m^2/a$ (Sweco, 2023).

## 5.3 Case buildings' CF results summary

The Case building carbon footprint results of product stage (A1-A3) with YM2021 method estimated by different calculation tools are gathered to Table 5. The CF results in Table 6 shows that the material CF results (A1-A3) are differing by calculation tool and Esti Model CF results are higher than expert calculation results. The difference is assumed to be resulted from initial data input and content variation between same Case calculations. The initial data and content included in calculation shall be evaluated further as a part of results analysis (chapter 6).

Table 6. Case building product phase (A1-A3) CF results by different calculation tool, according to YM2021 method (Sweco, 2021a; Sweco 2021b; Sweco 2022a; GBP, 2022; GBP, 2022; NCC Suomi Oy 2022b).

| Case building | Case status | Calculation method & tool | Calculating author | CF result of product phase A1-A3 | Initial data source |
|---|---|---|---|---|---|
| **Case H** | Commissioned building 2022 | YM2021, One Click LCA | Sweco | 5.68 $kgCO_2e/m^2/a$ | By Sweco (BIM, plans) |
| | | YM2021, Esti Model | Scenario as part of Thesis | 7.4 $kgCO_2e/m^2/a$* | Mass list based on space information |
| **Case J** | Under construction | YM2021, GBP tool, 50y | Green Building Partners | 6,95 $kgCO_2e/m^2/a$ | By Green Building Partners & NCC Suomi Oy mass listing |
| | | YM2021, Esti Model | Scenario as part of Thesis | 9.22 $kgCO_2e/m^2/a$* | Mass list based on space information |
| **Case K** | Under construction | YM2021, GBP tool, 50y | Green Building Partners | 7.87 $kgCO_2e/m^2/a$ | By Green Building Partners & NCC Suomi Oy mass listing |
| | | YM2021, Esti Model | Scenario as part of Thesis | 12.08 $kgCO_2e/m^2/a$* | Mass list based on space information |
| **Case M/L** | Development stage scenario | YM2021, One Click LCA | Sweco | 8.61 $kgCO_2e/m^2/a$ | By Sweco (BIM, plans) |
| | | YM2021, Esti Model | NCC internal cost estimation scenario | 10.2 $kgCO_2e/m^2/a$* | Mass list based on space information |
| **Case E** | Draft of planning stage scenario | YM2019, One Click LCA | Sweco | 5.95 $kgCO_2e/m^2/a$ | N/A |
| | | YM2021, One Click LCA | | Estimation 6.48 $kgCO_2e/m^2/a$** | |
| | | YM2021, Esti Model | NCC internal cost estimation scenario | 6.8 $kgCO_2e/m^2/a$* | N/A |

**Esti Model CF calculation result and One Click LCA results are not comparable in this table. Esti Model CF result is only converted to same unit, but no data has yet been assessed.*

*** YM2021 methods material A1-A3 CF result derived from total CF results based on CF result share of YM2019 of the Case E.*

The CF results of residential Cases E, H, J and K for building (excl. building site) by expert calculations and indicative CF estimation from Esti Model's total CF result difference is demonstrated in Figure 16. It should be noted that nor in Table 5 or Figure 16 the piloted Esti Model's total results are higher.

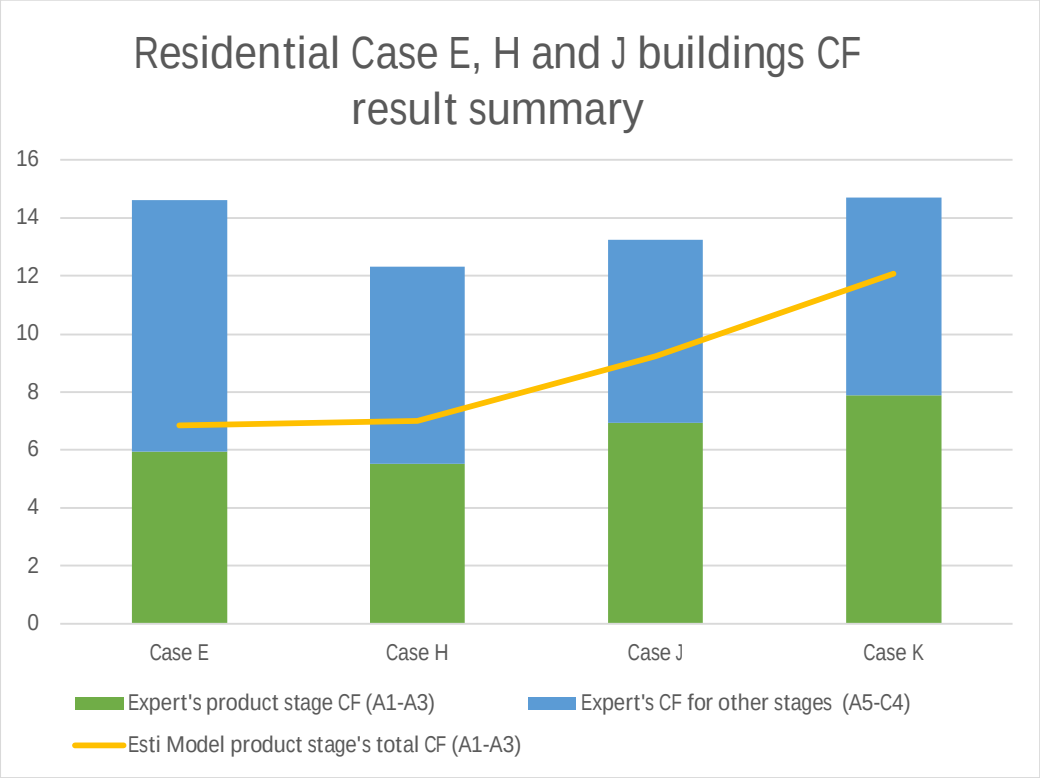



Figure 16. Residential cases CF results for buildings' as $kgCO_2e/n\text{-}m^2/a$, according to YM 2021 method. The Esti model results is not yet comparable to expert CF results (Sweco 2021b; Sweco 2022a; GBP, 2022; GBP, 2022; NCC Suomi Oy 2022b).

If comparing the expert calculation results to Esti model-based CF results directly it shows that both residential and office cases Case E and Case H which are at development or draft of planning phase obtain 8-12% lower results in expert calculations (with OCL or GBP tool) than with space-based CF estimation (Esti Model). The residential Cases H and J of permit or commissioning phases obtain 23-25% lower results with OCL by expert estimation than with company's space-based estimation tool. The direct comparison of product stage (A1-A3) results' indicates that the results created with company's early-phase tool Esti Model gives higher CF level for building materials. This comparison of one summary result number without analysing the content behind it does not yet provide answer to the research questions, but only presents case dependent indication of result variation. To understand more deeply

about the CF calculation results and to gain knowledge of the content and initial data that result is based on further analysing is needed.

### 5.3.1 Residential Case buildings' CF of whole life cycle with YM2021 method

Residential Case buildings (E, H, I, J and K) total average carbon footprint of whole life cycle results by expert made CF calculations was 15.17 kg $CO_2/m^2/a$, according to YM2021 calculation method (Figure 17). Most of the cases targets or has obtained some environmental label certification which most likely has affected on the CF results as energy classification of building usually is set in these projects to the best category (A).

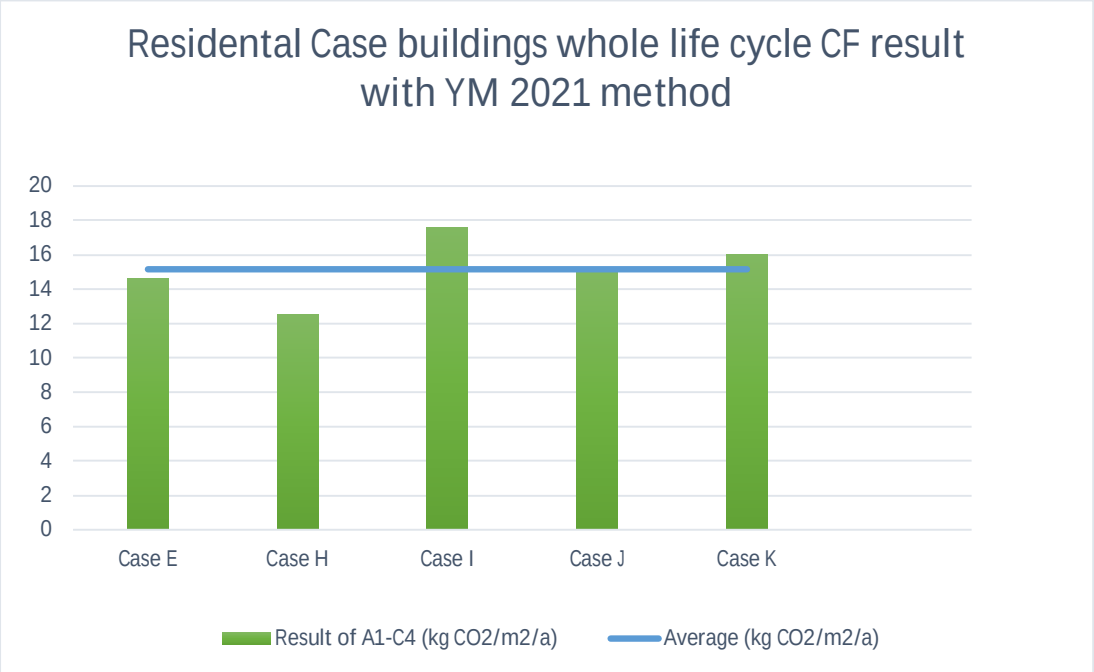



Figure 17. Residential Case buildings whole life cycles CF results calculated with YM2021 method (Sweco 2021b; Sweco 2022a; GBP, 2021; GBP, 2022; GBP, 2022).

### 5.3.2 Office Case buildings' CF of whole life cycle with Level(s) method

Most of the office building Cases (N, O, P, Q, R, S) had CF calculation available with Level(s) method. Therefore, these Cases were excluded from further result analysis, but results were examined separately. The company's office development unit had gathered the different case buildings' CF data and made estimations how CF results are varying at design

phase of building and after the construction process. In this context the design stage (DS) means the phase of building projects before construction work when the planning f project is ongoing and construction permit is not yet fixed. The post construction (PCR) is the phase of project when construction work is done, and all the material selections are locked. Figure 18 presents three office Cases N, O and P, where CF results are calculated by Level(s) method. (NCC Suomi Oy, 2023a; NCC Suomi Oy, 2023d).

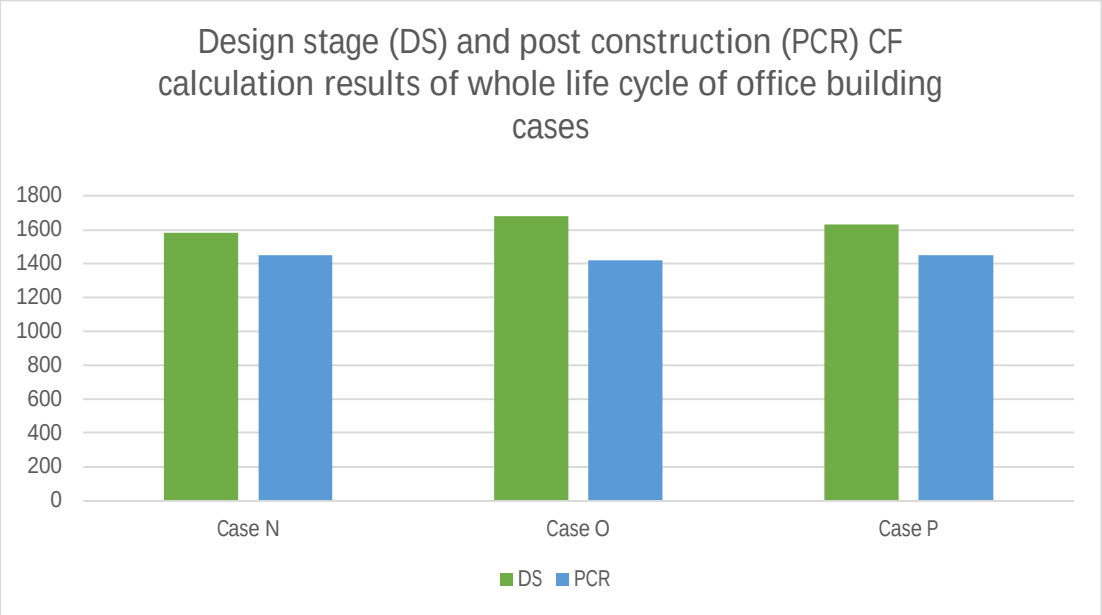



Figure 18. Office Case buildings whole life cycles CF results at design stage and post construction phase with Level(s) method (NCC Suomi Oy, 2023d).

The CF results of LCA calculations were varying from 8-15% when comparing design stage and post construction phase calculations. The difference is highly affected by the available data of building at design phase and due to some lacking initial data, more assumptions and more conservative data was estimated to have been used in design phase calculations. (NCC Suomi Oy, 2023a). The same can be seen from the apartment building Case F-H at Figure 13 that is the only project that had CF results available in different phases of the project by same method, Level(s). Unfortunately, no data were available about the same project with YM2021 method from design stage, construction permit phase or post construction (commissioning). This lacking data limits out the comparison of YM2021 methods CF results development in different phases of the project and no foretelling data could be established in this study.

Also, another interesting observation of office building Cases was that the building technology (HVAC) $CO_2$ emissions share has increasing trend in different year calculation results (Figure 19). (NCC Suomi Oy, 2023a; NCC Suomi Oy, 2023d).

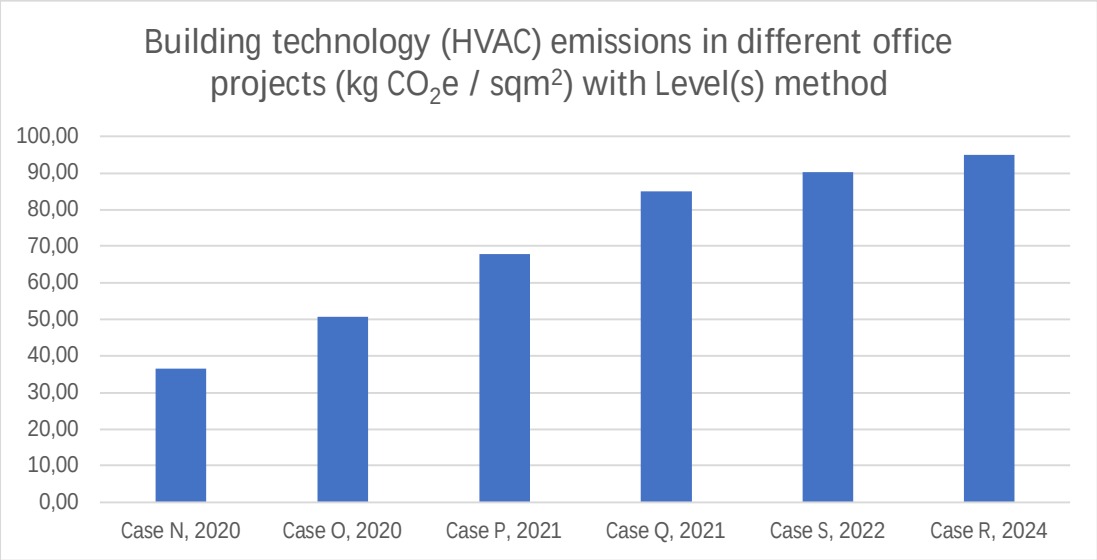



Figure 19. Buildings technology emissions development between years 2020-2024 in different office building projects with Level(s) method (NCC Suomi Oy, 2023d).

The calculations were not assessed deeply as a part of this study and further analysis is needed to conclude the causes of which this increasing trend in HVAC technology is originated. Furthermore, the impact of the selected calculation method should be analysed further as it seems that YM2021 method HVAC results are lower than Level (s) methods results (NCC Suomi Oy, 2023a). Furthermore, YM2021 method enables the table default values in HVAC's CF calculation (emission factors by building type per square meter) and it could also be assessed more detailed manner (NCC Suomi Oy, 2023a; SYKE 2022).

# 6 Building's carbon footprint analysis

Already the YM 2019:22 method stated that the CF results that are based on different methods and uses different calculation tools are not comparable (YM, 2019). For this reason, different calculation methods results are not cross compared in this work either. The main difference between Level(s) and Finnish national YM2019 and YM 2021 method calculations is in energy use category (B6) as the energy emission scenario for future has different assumptions about emission factors and its development. Second difference is in the subcategory selection of Level(s) method and both Finnish national methods. Finnish national methods YM2019 and YM2021 also differ as the emission factors of energy are updated with higher vales to YM2021 method and HVAC systems default table vales are updated. In addition, YM 2021 results reporting differs from YM 2021 as results are divided to building and building site, which was no considered at YM2019 method yet.

Also, the content of calculations initial data can be variable and is based on the best available data of calculation moment, strongly affected by the phase of project when calculation has been performed. The content of CF calculation according to YM2021 was presented before in Table 3. The content details are revised at CO2data.fi and at the moment information has already been updated several times. The Esti Model's CF results are not automatically following the updated content and data needs to be assessed further. The forthcoming Finnish building law reform will add material description to construction permit process and in future the reporting of CF calculation result should be more unified and more transparent.

Because Esti Model produces its own initial mass listing (based on space information), the comparison to experts LCA calculation results based on different initial mass data of same Case projects is reflected on results differing (Table 6, Figure 16).

To evaluate the CF results of product stage (A1-A3) analysis was targeted first to initial mass data selection of calculations to form comparable results which was the most limiting factor in the case projects selection for analysis. Secondly the content of results was analysed and categorized according to structural parts classification (Talo 80 or Talo 2000) results were compared. Thirdly, HVAC's CF calculation manner was harmonised to follow the YM2021 methods default values to have more comparable results. After these steps Esti Models calculation logic, it tested to have validation for own assumptions. Lastly the circular

economy potential will be discovered with relevant cases to set light for its potential beneficial effects.

## 6.1 CF calculation results analysis of product stage (A1-A3)

Direct comparing of the total CF results by material category was not possible as the results are informed in Esti Model CF results summary differently than YM2021 content is categorized (Table 3). Furthermore, in some expert calculation reports the CF results was not reported as detailed manner and the material mass quantity estimations were lacking from the reported information. Furthermore, when comparing OCL and Esti Model tool the material data can be grouped differently, i.e., some data by structural types or by products and units (i.e., kg/$m^2$/$m^3$, pieces) can be differing. Therefore, the input data comparison is not clearly separatable or distinct. The input data was evaluated further in Case H, as projects initial data used in OCL expert calculation was fully in use at this study thanks to collaboration of Sweco Talotekniikka Oy (Sweco, 2022b).

### 6.1.1 Case H analysis

Due to the planed results summary provided by pilot tool (Table 5) data had to be assessed from Esti model detailed report (Appendix 6) that informs carbon emissions by kg $CO_2$ for every building part (mass quantity rows) and as in Case H there were 391 total rows in the longer exact report.

First the detailed initial data content of calculations (Appendix 6's and Appendix 7's Table 1) was compared and was found out that about 80% of Esti Model's initial data was consistent to expert's OCL calculation. Confusing notion was that, in the comparison was found out that Esti Model also creates and calculates CF results to other 20% of masses (Appendix 10, Table 2) that are not included in this compared Case experts CF calculations. This was deducted to be resulting from the YM2021 methods structural parts content list (Table 3) that includes only the main parts of the building in the calculation content.

To explore data better Case H data was categorized according to House 80 main groups as this is the categorization principle in Esti Model. The included, excluded building material

and estimation of input data similarity by shares are presented in Appendix 10. Also, the main mass amounts of concrete and steel in both calculations were compared with. This comparison resulted that the initial mass amounts of concrete and steel products differed 1400 tonnes or 14% between recognized concrete and steel amounts. Difference is assumed to be resulted partly from the material consumption conversion factors differences between calculation tools or the estimations of how much reinforced steel is included to pre-cast concrete elements. The difference stems from the fact that Esti Model estimates the masses of structural parts based on spaces and in expert calculation utilizes the BIM model-based amounts of the modelled structures (differing source).

In addition, notable observation of results was that HVAC has estimated by default table values in expert calculation, but Esti Model calculates this based on space-based scenario creation of detailed quantities of HVAC. The HVAC detail CF results were lower with Esti Model than with YM default table values.

To form comparable result from Esti Model calculation data of CF, the data needed to be filtered with following steps:

1) Esti Model's CF calculation's initial content input data was selected according of the content comparison (Appendix 10) and the CF results was filtered according to expert calculation content.

2) The CF results were categorized by building and building site and only building (separating site elements and foundations CF share) was selected for comparison.

3) The HVAC systems CF result was calculated with YM2021 table values method to avoid calculation manner variation on results.

The comparable filtered and categorized Esti Model's CF result in this case was 6.1 $kgCO_2/m^2/a$ (initial data by space-based scenario). This filtered and categorized comparable building's product stage (A1-A3) CF result was still 11% higher than the expert calculation product stage result 5.54 $kgCO_2/m^2/a$ of the case (initial data based on BIM model). This difference is assumed to be based mainly on differing mass input data amounts of these two CF calculations. There is also possibility that expert calculation gives partly higher results as 53% of the data utilises conservative CO2data and partly lower as rest 47% data utilises specific EPD or other default emission factors (Figure 21). The significance of the emission

factor source was not further analysed at this point when input mass data was clearly differing significantly.

### 6.1.2 Esti Model CF calculation testing with Case H

In Case H content analysis, the CF result (A1-A3) between Esti Model scenario and expert calculation with OCL were found to differ. The results showed a difference even though the same building part content was selected for comparison from the CF calculations and the data was organised according to the YM2021 method reporting. This was assumed to be originated from the initial mass data input difference and not from calculation logic difference, since the dominating structural materials concrete and reinforced steel was compared resulting 14% divergence in the mass. Still verification was needed to proof the assumption and to see if the different calculation tool logic were consistent.

As Esti Model creates its own initial mass data (according to space-based listing) it was decided to create product stage (A1-A3) CF calculation with OCL tool utilizing Esti Model's mass data. Previously created space-listing scenario (Appendix 9, Table 1) of Case H with Esti Model created mass listing data that were used directly as imported input data in One Click LCA calculation tool to evaluate calculation principles similarity and compare results. This Case H test scenario in One Click LCA calculation tool resulted product stage CF result of 7.07 $kgCO_2/m^2/a$ as original Esti model CF results was 7.01 $kgCO_2/m^2/a$, resulting less than 1% difference between results. Figure 20 presents this testing process steps and the results.

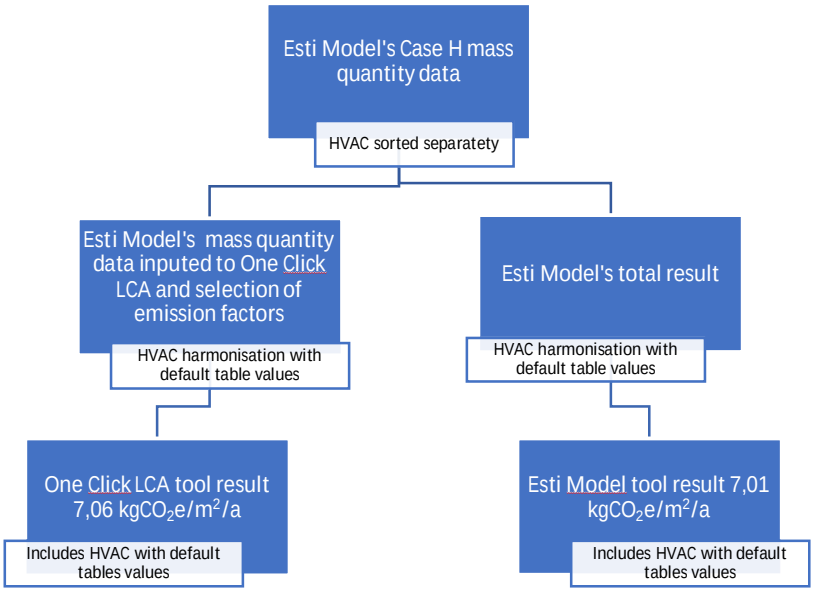



Figure 20. The Case H's Esti Model CF calculation logic testing process.

By this test scenario Esti Model's calculation principle was proven to be highly equal to OCL calculation logic when the initial structural parts mass data input of calculation is consistent with one another. The result difference of 1% was considered to be insignificant. Therefore, it could be assumed that the results' differing is not caused by the calculation tools or software's calculation logic but is caused by the primary input data.

Also, emission factors data source use was evaluated in this point because Esti Model uses CO2 data's typical emission factors and OCL utilizes conservative CO2 data, EPD and OLC generic data. The same data selection principle was followed as in experts' calculations; firstly conservative CO2data was utilized, secondly EPD data used and thirdly OCL general data utilised. Expert OCL calculation and this thesis own Esti Model test simulation in OCL had quite same emissions factor source distribution (Figure 21).

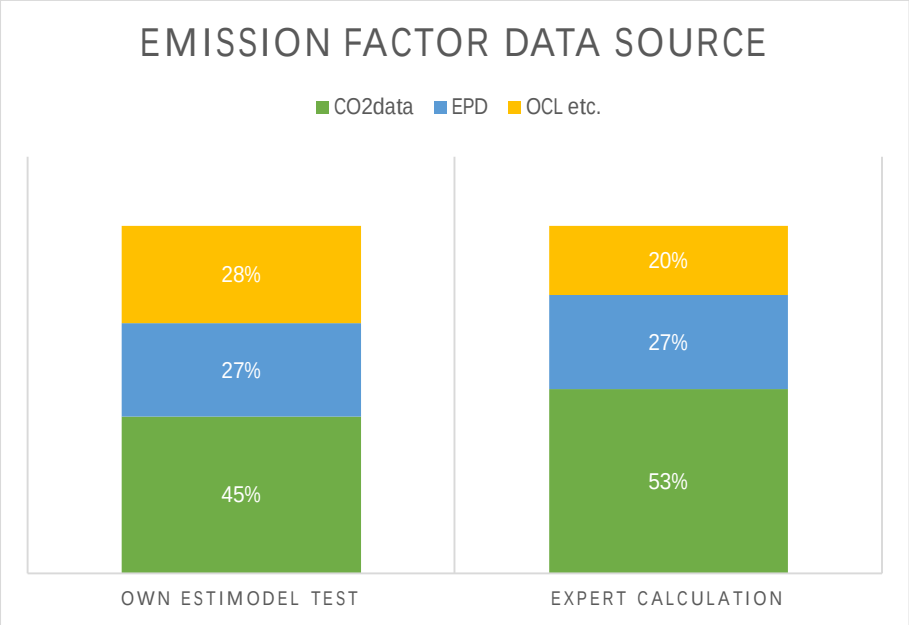



Figure 21. Data source distribution of own Esti Model test scenario in OCL and expert's original OCL calculation's data source distribution.

In the previous part of the analysis (6.1.1.), it was not considered possible to assess evaluation for the emission factors of data sources in reliable manner. Now according to these consistent CF calculation results and as primary data was harmonised in Case H the evaluation was possible. The distribution of data is quite similar in own Esti Model test scenario as it was in expert's original calculation (Figure 21). This shows that the data source selection method was in line and close enough to save similar CF results. The own test simulation data source selection consists 45% of conservative CO2data that has higher emission factors and the rest 27% product specific data, and 28% typical emission data that has lower emission factors than in Esti Model tool. With this emission data distribution, the emission factor source was considered to have unimportant impact on CF results between Esti Model and OCL tools when only 1% difference resulted in testing. In case H, only one test simulation was performed as this was considered sufficient when the results were unambiguous and supported the previous hypothesis, and the findings about differences in mass input data were significant.

## 6.2 Circular economy's impacts on carbon reduction

The possible CE economy potential in general was described earlier and to concretize some benefit of it from the carbon footprint reduction perspective this is further examined by case basis. The cases' expert data about CE materials is presented and one own thesis simulation about CE products with Esti Model is presented to reveal CE material utilization impacts on CF results. Also, the real case of refurbishment construction project is presented and the CE integration to construction business is discovered with development building case project.

### 6.2.1 Low carbon and CE materials impact on CF

The low carbon and the circular economy solutions impact potential to CF was earlier described in chapter 4. In part of researched CF cases (Appendix 1) expert authorities had included materials CF comparisons to the CF reporting. In residential early-stage project Case E, the low-carbon product selection had estimated to have 7% lowering impact on building's CF result in total (Table 7).

Table 7. Low-carbon products' CF reduction potential estimation in residential Case E by experts.

| **Low carbon products** | **Case E Expert estimation with OCL** |
|---|---|
| Low carbon hollow core slabs | 3 % |
| Low carbon concrete | 1 % |
| Low carbon reinforcements | 0 % |
| Low carbon exterior wall insulation (Parma natura) | 1 % |
| Windows insulation value 1,0 -> 0.8W/m$^2$K | 1 % |
| **Total CF reduction potential** | **7 %** |

Also, in office development Case M estimation was made for the product stage CF and it resulted that when choosing the low-carbon products instead of the basic concrete scenario products a carbon footprint reduction was up to 28%. The same comparison was done for the wooden base case scenario where improved low-carbon product selection resulted 12% reduced carbon footprint level for the case project (Sweco, 2021a).

To explore the CE based low carbon products potential a simulation comparison was made in this study with Esti Model. In this simulation the identification of most potential structural

parts was utilized based on Figure 15 and improved scenario of Case H was created with Parma Green products of the precast hollow core slabs and the interior concrete wall elements. In Esti Model the Case H base scenario's environmental profile's emission factors for global warming category (three rows in Esti model calculation) was revised according to Parma Oy's Green product category's EDPs' emission factors GWP of A1-A3 stage, as 95.2 $gCO_2$/kg in solid walls and 91.6 $gCO_2$/kg in hollow core slabs (EPD 2023a; EPD, 2023b). If Parma Oy's Green products could be utilized in all Case H building's precast interior concrete solid wall and interior hollow core slab element structures (not in roofing floor) it could provide 82.6 $tCO_2$ lower product phase CF results. This emission reduction equals 27.5 kg $CO_2$/n-$m^2$ in this building providing 10% lower CF result for the product phase (A1-A3). This comparison was made against to typical CO2data.fi emission factors and if compared to conservative emission factors the results could be even higher.

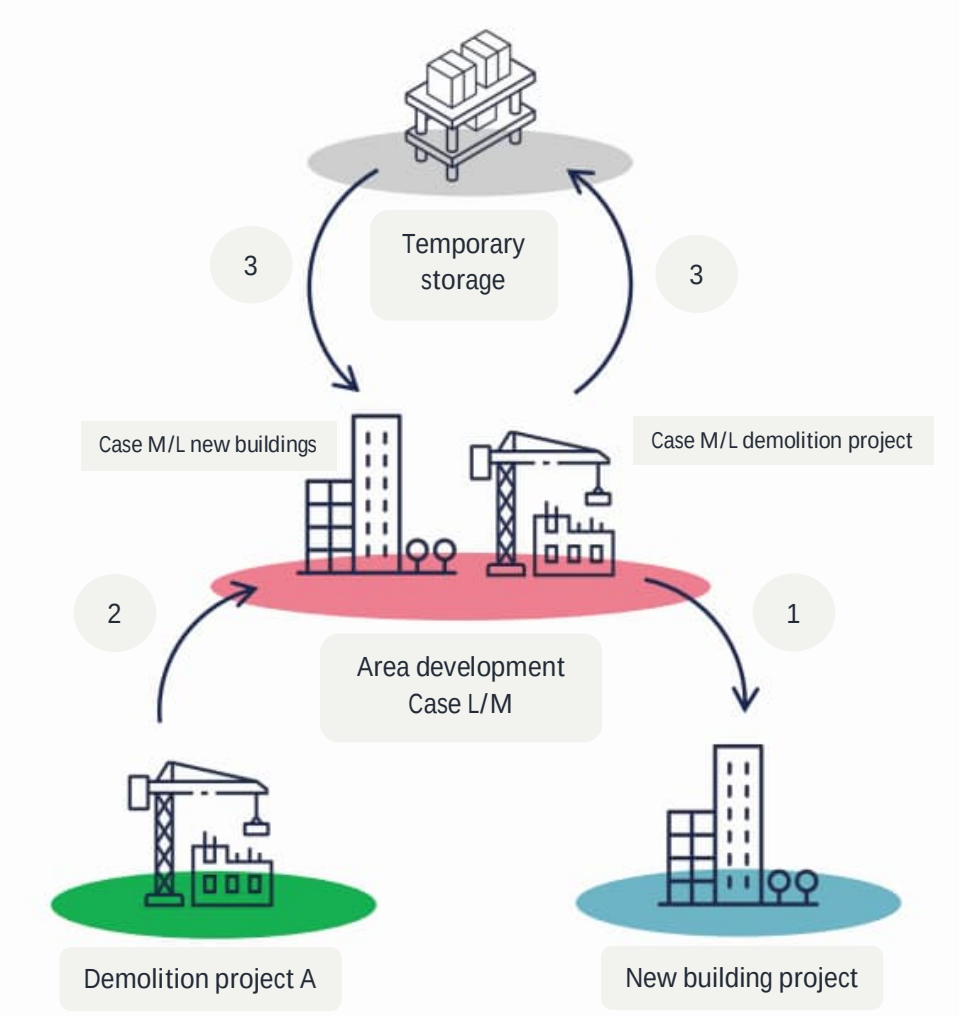
### 6.2.2 Refurbishment Case X material utilization

In company's office refurbishment ongoing project Case X client had set 95% recycling rate target along with CE and CF goals. The CF target was set 15% lower than to normal reference level and material utilization up to 80%. (NCC Suomi Oy, 2022d).

Case interview revealed that during projects planning the co-operation with project production team had key role contributing to materials utilization target. The production team's collaboration with developer and designers lead to innovating reuse material options and identified potential material parts to be upgraded of building refurbishment. Steel structures of window frames and railings have been able to be upgraded, large portion of old windows have been able to be reused in same value form for private customer markets. Also, old plinth elements have been able to be partly refurbished and saved. Furthermore, some of the old light gravel from roofing demolition has been reused at the site planting reservoirs. Customer has also chosen low carbon concrete to be used and the emission savings compared to conventional products were for in situ concrete 55 kg/$m^3$ and 88 kg/$m^3$ leading to av. 71.7 kg $CO^2$ e/$m^3$ reductions the total potential is dependent of the low carbon mass and in this case as only 68$m^3$ was to be refurbished the total carbon emission reduction resulted was 4862 kg$CO^2$ e total. As project was still ongoing at time of the thesis work, the total emission reductions could not yet be assessed when data was not completed (NCC, 2023c).

### 6.2.3 CE integration to construction business Case M/L

Office development project (Case M/L) is city block area in design phase and at this case old school building demolition's CE potential has been mapped as a part of development design process (NCC Suomi Oy, 2023a). The material utilization potential has been assessed by mapping the old building's material masses, initial plans of structural design and potential reuse of different parts explored in condition examination and with hazardous materials testing. Also, the validity inspection of reused products is needed to be able to recirculate the old product according to material approval regulations. In this case the most significant potential was recognized with workshop co-operation resulted between developer and central designers and consultants of project. The networking is essential in large scale demolition projects to obtain the materials in their best reuse value form. Figure 22 illustrates this Case M/L's scenario of circular process that networks one demolition and one new building case projects to utilize demolition projects structures frame material flows to area development case L/M's and directly to some other new building case. Furthermore, to circulate some non-bearing materials through temporary storage unit back to new building project use at the area building case use is planned. This integration needs co-operation between projects, scheduling and planning to utilize deconstructed structural materials. (Ethica, 2023).




1. Structural frame parts circulation to reuse in other new building project
2. Demolition projects building's structural frame parts deconstruction to Case L/M new building use
3. Case L/M demolished building's non-bearing materials reuse to Case L/M new building via temporary storage

Figure 22. Circular ecomomy consept integration to construction business in Case M/L by Ethica Oy, adabted to English (Ethica, 2023)

This kind of CE integration to build environment still need business partners for un-assembling the materials and circulate the validated materials and products to remarkets use. Furthermore, the rethinking throughout building sectors whole value chain is needed that this kind of co-operation and new working can be planned and executed also from economical perspective. Viability and the emission savings are both connected to transportation distances and effective temporary storage solutions.

# 7 Discussion

The changing calculation methodology has set a challenge for the building industry to keep up and prepare the best practices to reduce GHG emissions. The comparison of CF results is challenging as Finnish national buildings' CF calculation method has evolved between years 2019 and 2021 and still the finalized method is yet to be published. This makes the interpretation of the results difficult as the results reporting, and the content of system boundaries varies between CF calculation methods. This complicates reliable analysis of the plain CF results, and no clear comparison can directly be made between the results. If the CF results are directly compared it is to be noted that the CF calculation method (and tool in line with it) should be harmonised and understanding of the CF results reporting is needed to make correct interpretation. Moreover, when procuring CF calculations, the initial data used in calculations (masses and amounts), and content (included /excluded building parts) should be part of the CF results report to enable evaluation of the results.

The Finnish government's recently accepted climate law that includes aims to build environment's carbon reductions can direct the building sector to reach global responsibility if the act is to set a uniform method to calculate the carbon emissions of building's whole life cycle and by setting an objective emission limit for the new buildings. Clear and transparent method to evaluate the buildings' carbon footprint would also enhance the understanding of the different design and material solutions impacts both on environmental and economical basis as the carbon footprint results would be truly comparable when the methodology is stabilized. Even as the CF calculation can be done with different software's and tools the results reporting should be detailed enough to be used to enable the comparison of the results. The transparency of the included content behind the carbon footprint is essential if carbon efficiency between buildings is compared as the content and the used mass quantities are the basis and most affecting factor of carbon footprint calculation based on case analysis.

In the future it is also recommendable for construction companies to establish unified process and instructions on how additional information of the CF results is to be reported for company's own use. For example, the Helsinki city has their own LCA's carbon footprint calculation instructions for reporting (Helsinki City, 2022). The instructions include content

according to YM2021 categories, division of the data and the results. Furthermore, the calculations' initial data and emission factors used is to be reported for them in detailed manner. In addition, the calculations' initial data is also required to be shared with them in the detailed form (in OCL tool and in excel form) for further usage. (Helsinki City, 2022; Helsinki City, 2023; Tyni, 2023).

In the NCC Building Finland has not yet unified process guidelines concerning the carbon footprint calculations of the building projects. From NCC Nordics company's other regions, the Sweden has already launched process guidelines for environmental description for property development and BREEAM certification (NCC Suomi Oy, 2023a). Similar process guidelines according to Finnish national method would be highly recommendable for all company's unit's usage. The guide could be expanded to be compliance with the different CF calculation methods taking into consideration of the environmental classification like RTS, LEED, BREEM requires for CF results reporting if needed. This kind of multipurpose CF results reporting is already in use at Raksystem's GBP tool base reports to provide several compliances at the same time. The GBP's CF results reporting informs the CF results in detailed manner to serve both REM method and YM method and additional reporting for certain form to the client's use can be additionally provided. (Raksystem, 2020; Raksystems, 2023; GBP, 2023).

One aim of this study was to evaluate how accurately CF of building could be foretold at early stage of project. However, it was possible only to provide case dependent knowledge about the company's carbon footprint calculation tool, due to low initial data availability of the expert reference calculations and scarcity of YM2021 calculation method cases available in the company. The office cases the post construction CF results with Level(s) were 8-15% (figure 18) lower in post construction than design stage and in one residential case results were about 6-9% lower commissioning phase than in construction permit phase (Figure 13). As established in this thesis, the current product stage CF results of Esti Model if filtered could serve the company also in other projects as the calculation logic of Esti Model was proven to be in line with the Finnish national CF calculation method. Company could use the filtered product phase CF results to compare different economic viability scenarios and carbon intensity of the selected project development design. As the whole life cycle CF results creation is not possible with Esti Model (only product phase) also at least the energy certification evaluation is needed to do separately to see bigger picture between solutions. In

development stage projects the early-stage cost and CF evaluation is advantage for company operations as carbon footprint calculation is becoming mandatory and environmental criteria for buildings are emphasized also by clients and investors. Thus, more CF data is needed about company's own projects' CF results by building type at more detailed form to conduct statistical analysis about the differences and variation of results against the reference CF calculations. This is essential if CF is wished to be foretold by finding conversion ratio between early design stage and commissioning stage CF result. One starting point would be to establish practice for collecting the CF results and calculation data of projects in one data bank.

Regardless of the low data availability, this study's results could give case content dependent indication of how much Esti Model's pilot CF results differs at this point when summary is not yet categorized or revised (early-stage results av. 10% and construction permit and commissioning phase av. 24%, both higher, Figure 16). In the study's CF result analysis Esti Model's piloting phase, the CF results of product phase was discovered to include more content than was included to Finnish national methods content or in expert's reference CF calculations. The forthcoming law reform will also add the information about the content and specify method. After this the content and system boundaries of Esti Model's reporting should be revised according to Reform of the Land Use and Building Act reform's when the regulation has been set. This will most likely clarify the future CF calculation results reporting and the content.

To foretell the actualized carbon footprint at early on in development stage, more data is needed to have a comprehensive statistical base of the same CF calculation methods results. This is also needed to establish a correlation ratio between total Esti Model results of the product phase (A1-A3) and the expert calculations' results. Furthermore, if Esti Model tool will be developed further, the detail report could also provide summary of building parts' CF results by categories of House 80 (Talo 80), which would ease the selected building parts detail reporting evaluation. This would clarify the carbon footprint results distribution between building parts and then possible content deviation to the reference CF calculation could be identified directly from the results by comparing different building part groups' subcategory results.

If software development procedure is challenging and adjustment cannot be provided by the software of the company, then a excel tool for detailed results grouping could provide a

solution. The company's tools detailed CF results could be added to excel as input data that would filter and group the results according to different categories. In addition, this kind of coded excel could form reporting according to different methodologies' results requirement thus providing more added value for the company as different projects could utilize it. To gain more added value the company could develop additional part to this proposed excel tool that would evaluate a buildings' whole life cycle's carbon footprint instead of limiting it to just the product stage (A1-A3). Then results could really be used for a full LCA scenario building and an analysis could be conducted to establish the best viable building project's scenario by environmental and economical basis.

The circular economy's impacts on the carbon footprint were researched from literature and with some case examples. Other studies have evaluated the CE solution potential to be great if reused materials could be utilized. At this point the reuse of materials is hindered since reused products' quality needs to be validated (tested) or building site-specific product approval is required. The Finnish building industry's value chain is still lacking the partner companies that would circulate the reused products to new use purposes (Ethica, 2023; NCC Suomi Oy, 2023c). Saving demolition and refurbishment planning that utilizes and upgrades old materials for longer use can provide significant carbon footprint reduction impacts. This kind of CE integration to whole-built environments value chain possess major benefits from environmental perspective. Refurbishment projects already are implementing the CE economy principles (Case X) and providing longer life span for buildings and at same time circulating the product in and outside markets of the projects. The planned co-operation between the demolition project cases and the new building projects can provide major savings of virgin materials, reduce carbon intensity of the built environment, and create new business opportunities for builders and other contractors in the sector.

As this study only concentrated to CF perspective more research is needed about the CE process integration to construction business companies' strategy and about the incentives that drives the change. Moreover, this study's consternation to carbon footprint calculation perspective only glanced the carbon reduction potential with circular economy solutions and the integration method for example to construction industry in Case M/L demolition material utilization plans. More detailed case studies and examples are available, such as the Kristian August gate 13 case (Entra ASA, 2023) in Norway where the reuse potential of old products

is assessed, and materials are reused as the same in refurbishment project and in new building construction (chapter 4.2.1).

Before the reused materials markets arise and the CE is fully involved in the building sectors regime the CF reduction in new building projects can be gained with the low carbon material content products. These low carbon products impact in new buildings was evaluated in the building cases of this thesis to obtain CF reduction between 7% to 22%. The different design solutions' CF reduction potential was not identified in this study by case basis but could be discovered also with company's cost estimation tool easily by varying the selected structural design choices input data in Esti Model. To gain more detailed understanding about the low-carbon solutions' impacts, a trace analysing about the CF calculations and the solutions used to get there could be a part of the company's CF calculation data collection process guidelines. This could provide data for development use about the most potential CF reduction solutions and design choices.

Due to the limitations of this study, there is still much to be discovered. This study concentrates to Finnish national method, and it does not deepen to the other buildings whole life cycle methods like Level(s) and other national methods of Nordic countries are left out. Study's literature review provides a glance about the current building sectors solutions to CF reduction, but as industry develops fast in current demanding regime there will be new solutions coming soon. Furthermore, this study does not take into account the economic viability of different CF reduction solutions, which should be further investigated, and the impact over the whole life cycle of the building should also be examined.

The Finnish national LCA method for buildings allows the default table values usage. The exact CF calculation of these could enhance the HVAC and the construction phase CF reduction and boost the sustainable actions in future. For example, the HVAC technology's share in buildings is increasing that was seen at least when CF evaluation was conducted with Level(s) method for offices (Figure 17). Also, the construction phase could be calculated more exact according to the real energy use implementation which could lead to environmental benefits and show the reality of construction site practices. This study excludes the site practices, but in construction sector, there are many efforts to lower construction phase emissions, such as electrification of the concrete pump trucks and different temporary heating and drying solutions like geothermal heating with the heat pumps by Geolo and the pellets boilers provided by ElBjörn (Swerock, 2022; STT 2022;

ElBjörn 2021). These different aspects and topics need to be examined and assessed further in future to establish a holistic view about the true GHG emission reduction potential of the built environment.

From one perspective the targeted CF limit value level is reverse journey from aimed level to the typical buildings design scenario. The different solutions on this path will enable the carbon footprint reduction of building's whole life cycle (Figure 23).

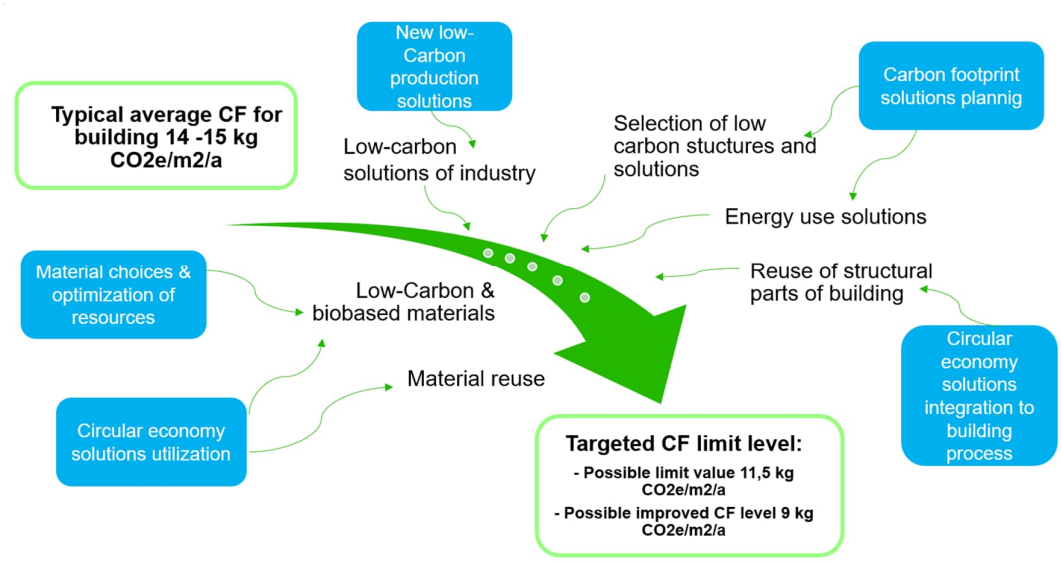



Figure 23. Summary of the opportunities to influence the carbon footprint of a building.

To summarise, the aimed CF result is sum of the selected actions and solutions which are chosen to be implemented during the buildings design and construction process. Therefore, targets for carbon footprint limits in the forthcoming climate revised building law will impact on the hole value chain of the built environment.

# 8 Conclusion

The construction industry has enormous potential for climate change mitigation through circular products and materials and with CE business strategy utilization. When dealing with GHG emission reduction potential and CF calculations is to be noted that there are several different ways to calculate the CF of a building. This study discovered CF calculation results depending on the calculation method used that sets the system boundaries and content of calculation. Also, the results are highly affected by the initial data that has been used. In addition, the emission factors used can vary in calculation tools and this needs to be recognized when comparing the CF results. The empirical case study indicated that the calculation tool will not highly affect to the results if initial mass quantities are harmonised. However, the case study results of this study indicate that currently with filtered and categorised CF results data of product stage the Esti Model's early-stage case cost estimation tool and the commissioning phase CF results of building by expert authority with OCL tool differ about 10%. According to Case H's results analysis the difference is resulting from the initial mass quantity data difference between the calculations. This is caused by exact plans data of commissioning phase calculation by experts and the estimation quantities of space-based scenario formed by company tool, which are not harmonized between tools. If the input data could be harmonised the results would only differ by 1% according to thesis testing with Case H. Even if company's cost estimation software's CF calculation part does not group the CF result yet according to current Finnish national method, the calculation principle for CF calculation was valid. As the real CF estimation result of product phase can be filtered from the current detailed report, company has already possibility to utilize the CF results of product phase. With the filtered CF results the company can estimate the indicative carbon footprint of product phase and cost scenarios of building project already early on at the design stage to determine most viable combination.The best available potential of carbon reduction was identified in the reused materials, if harnessing this CE business opportunity with co-operation as already planned in one development case of company the carbon reduction potential could be almost up to 40%. The potential of circular material solutions was elaborated with the low carbon concrete products simulation (Company tool) that could reduce materials carbon footprint share in residential building 10% if utilizing Parma Oy's low carbon precast concrete element in bearing interior flooring and solid walls. For

comparison, the reused hollow core slab elements have almost 90% lower carbon emissions and the low carbon hollow core slabs have only 50% lower emissions, which demonstrates the unutilized potential that the reused materials can provide.

If the circular economy principles could be applied to the build environment's whole value chain by harnessing demolition and refurbishment project material utilization in larger scale, it would bring the best added value also from the point of view of carbon footprint reduction. This seems interesting business market for value chain stakeholders if products could be harnessed to utilization purpose in new building projects with cost-effective solutions.

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Ympäristö. 2022. www.ymparisto.fi. Ymparistö - Rakentamisen päästöjä voidaan nyt vertailla – uusi päästötietokanta luo perustan vähähiilisen rakentamisen säädösohjaukselle. Ympäristöministeriön ja Suomen ympäristökeskuksen tiedote 1.3.2021. [online] Accessed 30 Nov. 2022. Available at: https://www.ymparisto.fi/fi-FI/Rakentaminen/Rakentamisen_paastoja_voidaan_nyt_vertai(60051)

# Appendix 1. Construction company NCC Suomi Oy's building projects' CF calculation cases research summary

Table 1. Researched carbon footprint calculation cases of NCC Suomi Oy's residential building projects from NCC Suomi Oy internal databases

| **Case name** | **Environ-mental label** | **Calculation phase of building and year of calculation** | **Calculation methodolygy, software, timeline** | **LCA phases included** | **Calculating author** | **CF result's (total /materials)** | **Initial data** | **Esti Model's CF result available** |
|---|---|---|---|---|---|---|---|---|
| Case A | No classification | Commissioning - | GBC calculation instruction & EN 15978 | N/A | Optiplan | 1325 kg $CO_2e/brm^2$ | N/A | N/A |
| Case B | RTS | Construction permit | GBC calculation instruction & EN 15978, 50y | A1-A5, B1-B6, C1-C4 | Green Building Partners | Total: A1-C 25.7 $kgCO_2e/n\text{-}m^2/a$ Material A1-A3 7.02 $kgCO_2e/n\text{-}m^2/a$ | N/A | N/A |
| Case C | RTS | Construction permit | GBC calculation instruction & EN 15978, 50y | A1-A5, B1-B6, C1-C4 | Green Building Partners | Total: A1-C 24,5 $kgCO_2e/n\text{-}m^2/a$ Material A1-A3 6.88 $kgCO_2e/n\text{-}m^2/a$ | N/A | N/A |
| Case D | N/A | Commissioning – LCA 2020 | YM2019, One Click LCA, 50y | A1-A5, B1-B6, C1-C4 | Granlund | Total: A1-C 14.63 kg CO2e/m2/a as 1874 $tCO_2e$ Material A1-A3 45% of total | N/A | N/A |
| Case E | N/A | Draft of planning LCA 2021 | YM2019 & YM2021 partly One Click LCA | A1-C | Sweco | Total YM19 A1-C4 13.86 $kgCO_2/m^2/a$ Material 5.95 $kgCO_2/m^2/a$ | N/A | Available |
| Case F | Swan label | Draft of planning LCA 2019 | GBC calculation instruction & EN 15978, One Click LCA, 60y – Level (s) | A1-A5, B1-B7, C1-C4 | Optiplan | Total A1-C4 av. 882 kg $CO_2e/brm^2$ Material A1-A3 av. 21 kg $CO_2e/brm^2$ | By Optiplan (BIM, plans) | N/A |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Case G | Swan label | Construction permit LCA 2020 | YM2019, One Click LCA, 50y | A1-A5, B1-B6, C1-C4 | Optiplan | Total of three separate houses<br>A1-C4 av. 9.72 $kgCO_2/m^2/a$<br>Material A1-A3 5.27 $kgCO_2/m^2/a$ | By Optiplan (BIM, plans) | N/A |
| Case H | Swan label | Commissioning LCA 2022 | YM2021, One Click LCA, 50y | A1-A5, B1-B6, C1-C4, D | Sweco | Total for 3 houses' A1-C4 av. 12.53 kgCO2e/m2/a Material 5.68 $kgCO_2/m^2/a$ | By Sweco (BIM, plans) | N/A |
| Case I | LEED | Commissioning LCA 2022 | YM2021, GBP tool, 50y | A1-A5, B1-B6, C1-C4, D | Green Building Partners | Total<br>A1-C4 17.6 $kgCO_2/m^2/a$<br>Material A1-A3 9.06 $kgCO_2/m^2/a$ | By Green Building Partners, BIM | N/A |
| Case J | LEED | Construction permit LCA 2022 | YM2021, GBP tool, 50y | A1-A5, B1-B6, C1-C4, D | Green Building Partners | Total<br>A1-C4 15.1 $kgCO_2/m^2/a$<br>Material A1-A3, 8.8 $kgCO_2/m^2/a$ | By Green Building Partners & NCC Suomi Oy mass listing | N/A |
| Case K | LEED | Construction permit LCA 2022 | YM2021, GBP tool, 50y | A1-A5, B1-B6, C1-C4, D | Green Building Partners | Total A1-C4 16.02 $kgCO_2/m^2/a$, Material A1-A3, 9.84 $kgCO_2/m^2/a$ | By Green Building Partners & NCC Suomi Oy mass listing | Available |

*Source references by Case: A) Ahola and Liljeström (2018); B) GBP (2019a); C) GBP (2019b); D) Granlund (2020); E) Sweco (2021b); F) Optiplan (2019); G) Optiplan (2020); H) Sweco (2022); I) GBP (2022a); J) GBP (2022b); K) GBP (2023).*

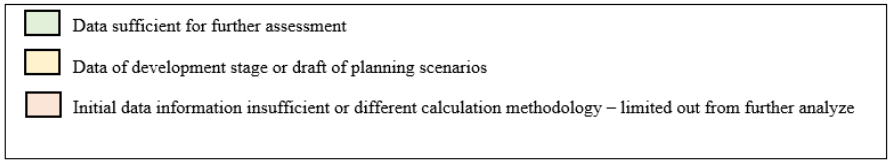


Table 2. Researched carbon footprint calculation cases of NCC Suomi Oy's Oy's Apartment building projects from NCC Suomi Oy internal databases

| Case name | Environ-mental label | Calculation phase of building and year of calculation | Calculation methodolygy, software, timeline | LCA phases included | Calculating author | CF results (total/materials) | Initial data | Esti Model's CF result available |
|---|---|---|---|---|---|---|---|---|
| Case L | BREEAM | Development stage LCA 2021 | YM2019, One Click LCA, 50y | A1-A5, B1-B6, C1-C4, D | Sweco | Total: base 15.83 $kgCO_2/m^2/a$ and improved 11.68 $kgCO_2/m^2/a$<br>Material: A1-A3 base 7.68 $kgCO_2/m^2/a$ and improved 5.74 $kgCO_2/m^2/a$ | By Sweco (BIM, plans) | Available |
| | BREEAM | Development stage LCA 2021 | YM2019, One Click LCA, 50y | A1-A5, B1-B6, C1-C4, D | Sweco | Total: base 11.68 $kgCO_2/m^2/a$ and improved 11.46 $kgCO_2/m^2/a$<br>Material: A1-A3 base 6.62 $kgCO_2/m^2/a$ and improved 5.52 $kgCO_2/m^2/a$ | By Sweco (BIM, plans) | Available |
| Case M | BREEAM | Development stage LCA 2023 - Concrete scenario | YM2021 One Click LCA, 50y | A1-A5, B1-B6, C1-C4, D | Sweco | Total: base 19.43 $kgCO_2/m^2/a$ and improved 14.49 $kgCO_2/m^2/a$<br>Material: A1-A3 base 11.22$kgCO_2/m^2/a$ and improved 7.95 $kgCO_2/m^2/a$ | By Sweco (BIM, plans) | N/A |
| | BREEAM | Development stage LCA 2024 Wood scenario | YM2021, One Click LCA, 50y | A1-A5, B1-B6, C1-C4, D | Sweco | Total: base 16.71 $kgCO_2/m^2$ and improved 13.85 $kgCO_2/m^2/a$<br>Material: A1-A3 base 8.61$kgCO_2$/m2/a and improved 7.59 $kgCO_2/m^2/a$ | By Sweco (BIM, plans) | N/A |
| Case N | BREEAM | Construction permit LCA | GBC calculation instruction & EN 15978, One Click LCA, 60y – Level (s) | A1-A3 | N/A | Material: A1-A3 4.55 $kgCO_2/m^2/a$ | N/A | N/A |
| Case O | BREEAM | Construction permit LCA | GBC calculation instruction & EN 15978, One Click LCA, 60y – Level (s) | A1-A3 | N/A | Material: A1-A3 6.68 $kgCO_2/m^2/a$ | N/A | N/A |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Case P | BREEAM | Construction permit LCA | GBC calculation instruction & EN 15978, One Click LCA, 60y – Level (s) | A1-A3 | N/A | Material: A1-A3 6.94 $kgCO_2/m^2/a$ | N/A | N/A |
| Case Q | BREEAM | Construction permit LCA | GBC calculation instruction & EN 15978, One Click LCA, 60y – Level (s) | A1-A3 | N/A | Material: A1-A3 8.51 $kgCO_2/m^2/a$ | N/A | N/A |
| Case R | BREEAM | Construction permit LCA | GBC calculation instruction & EN 15978, One Click LCA, 60y – Level (s) | A1-A3 | N/A | Material: A1-A3 8.6 $kgCO_2/m^2/a$ | N/A | N/A |
| Case S | BREEAM | Construction permit LCA | GBC calculation instruction & EN 15978, One Click LCA, 60y – Level (s) | A1-A3 | N/A | Material: A1-A3 7.57 $kgCO_2/m^2/a$ | N/A | N/A |

*Source references by Case: L) Sweco (2021a); M) Sweco (2021a); N-S) NCC Suomi Oy (2023d)*

Data sufficient for further assessment

Data of development stage or draft of planning scenarios

Initial data information insufficient or different calculation methodology – limited out from further analyze

Appendix 2. Circular principles of buildings structural design variants and their functional lifespan over 200 years

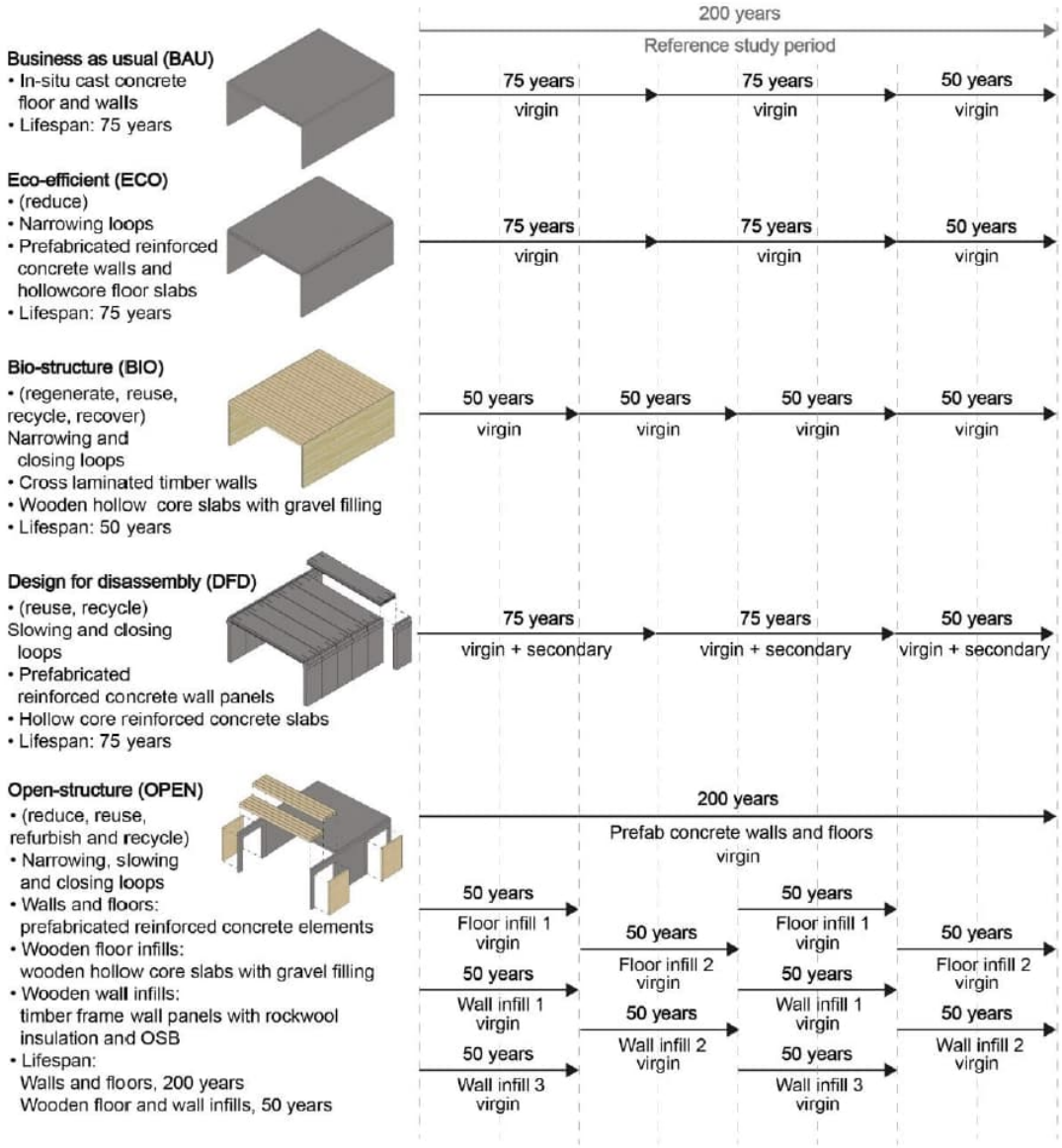


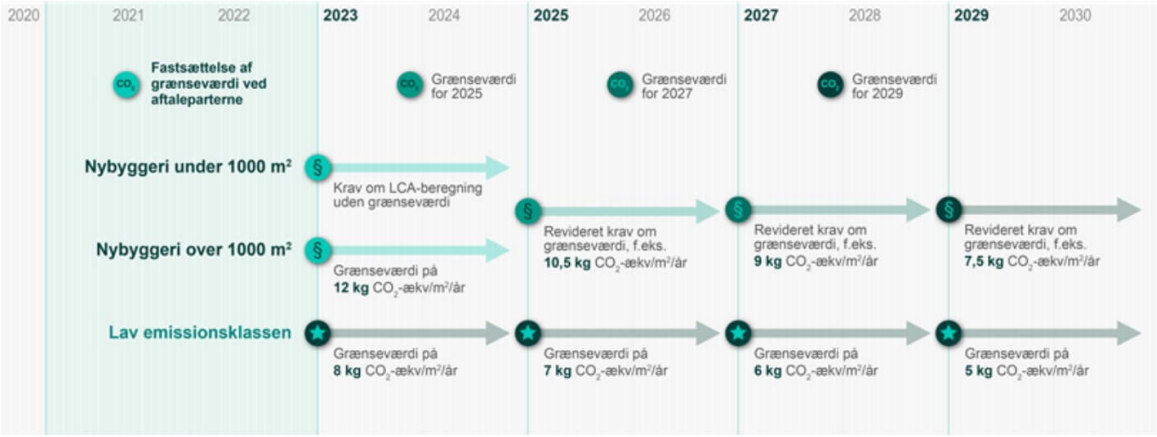

Figure 1. Eberhardt, et al. (2021) study's circular principles of the structural design variants and their functional lifespan compared to the reference study period of 200 years.

Appendix 3. List of interviews of the study

Table 1. List of NCC Suomi Oy's experts' interviews.

| **Expert** | **Title** | **Content** | **Interview date** |
|---|---|---|---|
| Ina Suutari | Project Manager, Residential Construction | Residential buildings CF cases and procurement of CF calculations | 4.11.2022 |
| Eelis Rytkönen | Development Manager, sustainable development | Property Development Office projects carbon footprint levels and calculation results | 10.2.2023 |
| Esko Kerkkänen | Project development Manager | CF calculation tool Esti Model and development of the tool | 14.2.2023 |
| Elias Aaltonen and Tuomas Nousiainen | Construction site area manager and site manager, Refurbishment | Renovation Case X's CE site practices | 17.2.2022 |

Appendix 4. Danish regulations of buildings $CO_2$ limits and aimed development




Tidsplanen viser, hvordan klimakravene (LCA) for bygningers klimapåvirkninger (CO2) gradvist skærpes frem mod 2030. Desuden kan bygningsejer vælge på frivillig basis at opfylde grænseværdierne for lav emissionsklassen. Figuren er fra National Strategi for Bæredygtigt Byggeri, april 2021.

Figure 1. Danish $CO_2$ limit values of new buildings larger than 1000 m2 (Bolig- og planstyrelsen, 2022).

Appendix 5. Case M/L development project's regional energy production for office building and energy use scenarios

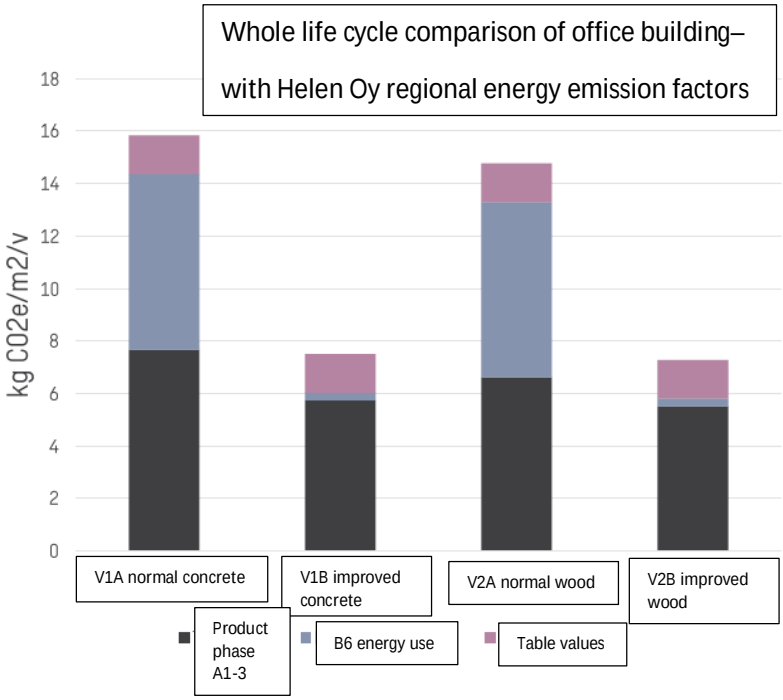



Figure 1. Scenarios of regional energy production and energy use by Sweco (2021a) at Case M/L development project for office building, converted to English.

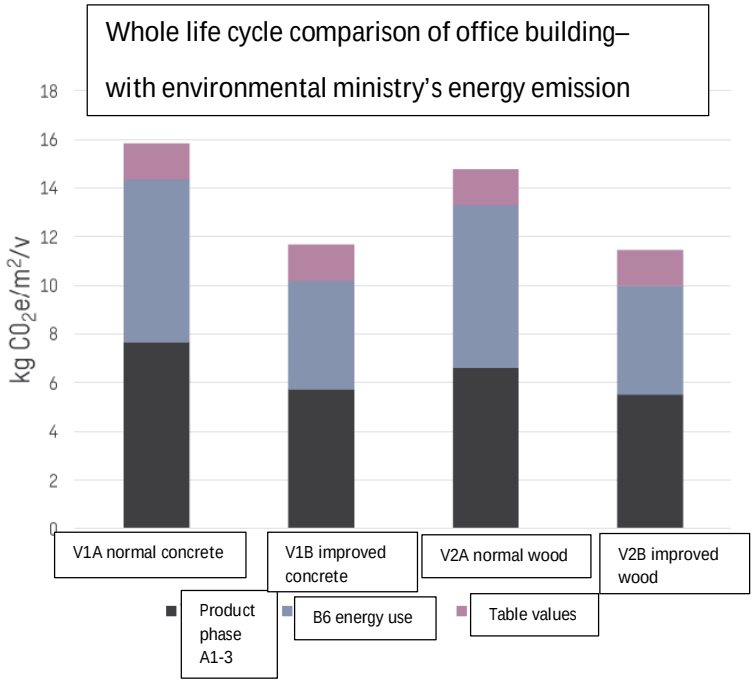



Figure 2. Scenarios of environmental ministry's energy emission factors and energy use by Sweco (2021a) at Case M/L development project for office building, converted to English.

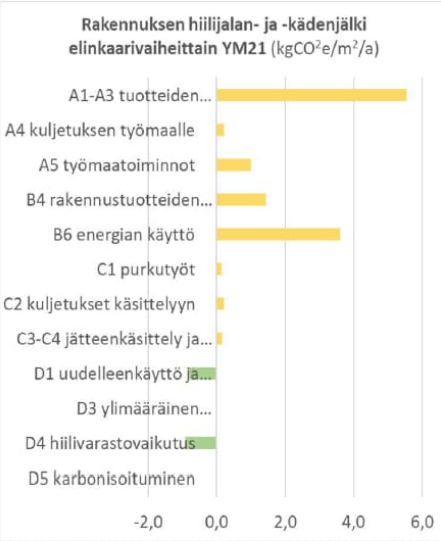
# Appendix 6. Esti Model tool detailed data report example

Table 1. Esti Model calculation tool's detailed CF results by building part quantities, Case H scenario created in this thesis study (House K of the case).

**ESTIModel 08/22**

| | | | | | | 1 054 318 |
|---|---|---|---|---|---|---|
| TALO-80 | Hankinta | Nimike | määrä yks | menekki | CO2 (g/kg) | CO2 [kg] |
| 15 | 1500 | Salaojaputki tupla 100 asennus + sorastus | 95 jm | 1,2 | 2 600 | 296 |
| 15 | 1500 | Salaojakaivo 400 asennettuna h=1500 | 10 kpl | 30 | 2 600 | 741 |
| 15 | 1500 | Perusvesikaivo PVK1000 betonia | 2 kpl | 1000 | 140 | 317 |
| 15 | 1500 | Muovikaivo 400 tk, h = 2000 | 0 kpl | 40 | 2 600 | 40 |
| 15 | 1500 | Ritiläkaivo | 1 kpl | 800 | 140 | 142 |
| 15 | 1500 | Pihaviemäröintityö + putki HT160 mm | 28 jm | 5 | 2 600 | 363 |
| 15 | 1500 | Murskearina 300 mm putkien alle | 28 jm | 450 | 6 | 75 |
| 15 | 1500 | Radon-putkitus | 143 jm | 1,2 | 2 600 | 445 |
| 15 | 1500 | Rännikaivo | 3 kpl | 30 | 2 600 | 216 |
| 15 | 1500 | Kattovesiviemäröinti | 30 jm | 3 | 2 600 | 238 |
| 15 | 1500 | Routaeristys | 14 m2 | 2 | 2 900 | 79 |
| 16 | 1600 | Talon sisäpuolinen täyttö soralla | 438 m3 | 1500 | 4 | 2 630 |
| 16 | 1600 | Murskearina 300 mm anturan alle | 172 m2 | 450 | 6 | 464 |
| 16 | 1600 | Sokkelin vierustäyttö | 161 m3 | 1500 | 4 | 969 |
| 16 | 1600 | Alapohjan alussorastus | 293 m2 | 400 | 4 | 469 |
| 16 | 1600 | Rakennusalueen täyttö soralla | 126 m3 | 1500 | 4 | 756 |
| 16 | 1600 | Kanaalien täyttö soralla | 140 m3 | 1500 | 4 | 837 |
| 17 | 1650 | Kant.krs 100mm murske #0...32mm | 172 m2 | 150 | 4 | 103 |
| 17 | 1650 | 300 mm:n jakavan kerroksen levitys ja kiviaines | 172 m2 | 450 | 4 | 309 |
| 17 | 1730 | Asfaltti 50 AB 22/120 + 50 murske | 100 m2 | 125 | 40 | 501 |
| 17 | 1720 | Laatoitus | 72 m2 | 190 | 130 | 1 769 |
| 17 | 1750 | Kivituhka | 72 m2 | 80 | 6 | 34 |
| 17 | 1720 | Betonireunakivi 100x160, liimattu | 30 jm | 38 | 130 | 148 |
| 18 | 1810 | Reunalauta | 72 jm | 1 | 140 | 10 |
| 18 | 1810 | Istutusten suoja-aita 0,6 m | 19 jm | 3 | 140 | 8 |
| 18 | 1810 | Puurakenteinen piha-aita 1,5 m | 63 jm | 50 | 140 | 444 |
| 18 | 1810 | Teräsrunkoinen puuaita 1,5 m | 0 jm | 100 | 140 | 3 |
| 18 | 1810 | Portti | 1 kpl | 100 | 2 300 | 230 |
| 18 | 1820 | Muut pihavarusteet | 3 285 brm2 | 0,1 | 2 300 | 756 |
| 18 | 1820 | Pylväsjalusta | 3 kpl | 50 | 190 | 29 |
| 21 | 2012 | Muottityö, antura, tavanomainen | 166 m2 | 12 | 80 | 159 |
| 21 | 2021 | Raudoitus | 2 827 kg | 1 | 560 | 1 583 |
| 21 | 2022 | Betonointi, pumppaus sis. yksikköhintaan | 55 bm3 | 2363 | 110 | 14 369 |
| 21 | 2090 | Betonipintojen jälkityöt | 166 m2 | | 350 | |
| 21 | 2030 | Teräsosat | 68 kg | 1 | 2 300 | 156 |
| 22 | 2021 | Raudoitus | 2 504 kg | 1 | 560 | 1 402 |
| 22 | 2022 | Betonointi, pumppaus sis. yksikköhintaan | 30 m3 | 2363 | 110 | 7 811 |
| 22 | 2080 | Kosteuseristys | 120 m2 | 4 | 530 | 255 |
| 22 | 2021 | Raudoitus | 100 kg | 1 | 560 | 56 |
| 22 | 2022 | Betonointi, pumppaus sis. yksikköhintaan | 0 m3 | 2363 | 110 | 100 |
| 22 | 2030 | Peruspulttiryhmä | 2 kpl | 15 | 2 300 | 69 |
| 22 | 2070 | Pilareiden lämmöneristys | 4 jm | 2 | 2 900 | 23 |
| 22 | 2080 | Kosteuseristys | 2 m2 | 4 | 530 | 4 |
| 22 | 3052 | Sokkelipalkkielementti | 108 m2 | 405 | 190 | 8 334 |
| 22 | 3052 | Sokkelikuorielementti | 6 m2 | 300 | 190 | 325 |
| 22 | 5020 | Saumaus | 57 jm | 3 | 1 975 | 338 |
| 22 | 2070 | Routaeristys | 228 m2 | 2 | 2 900 | 1 322 |
| 25 | 2021 | Raudoitus A500H | 16 740 kg | 1 | 560 | 9 374 |
| 25 | 2021 | VSS-verkkoraudoitus | 113 m2 | 20 | 560 | 1 270 |
| 25 | 2022 | Betonointi, pumppaus sis. yksikköhintaan | 130 m3 | 2363 | 110 | 33 687 |
| 25 | 5620 | Täytekerroksen pintalaatta | 108 m2 | 250 | 110 | 2 970 |
| 25 | 3072 | Kevytsoraeristys | 32 m3 | 500 | 330 | 5 346 |
| 25 | 2080 | Kosteuseristys | 216 m2 | 4 | 530 | 458 |
| 26 | 2070 | EPS 120 mm lattia | 108 m2 | 1,92 | 2 900 | 601 |
| 26 | 2021 | Raudoitus B500 K | 879 kg | 1 | 560 | 9 374 |
| 26 | 2022 | Betonointi, pumppaus sis. yksikköhintaan | 23 m3 | 2363 | 110 | 6 093 |
| 26 | 2080 | Muovikalvoeristys | 293 m2 | 0,1 | 2 600 | 76 |
| 26 | 2070 | EPS 180 mm | 293 m2 | 3 | 2 900 | 2 549 |
| 27 | 2021 | Raudoitus | 200 kg | 1 | 560 | 112 |
| 27 | 2022 | Betonointi, pumppaus sis. yksikköhintaan | 4 m3 | 2363 | 110 | 910 |
| 27 | 2030 | Teräsosat | 30 kg | 1 | 556 | 17 |
| 27 | 2030 | Teräskaukalo | 14 m2 | 500 | 556 | 3 753 |
| 27 | 2070 | EPS 100 mm | 12 m2 | 1,6 | 2 900 | 56 |
| 28 | 3030 | Katoksen runko, teräsrakenne KS | 168 kg | 1 | 2 300 | 386 |
| 28 | 3034 | Itsekantava profiilipeti | 4 m2 | 1,5 | 2 600 | 16 |
| 28 | 5014 | Pellitykset | 4 jm | 0,5 | 2 600 | 5 |
| 28 | 3760 | Vesikatteen alusrakenne, puu | 4 m2 | 15 | 68 | 4 |
| 28 | 3560 | Katoksen alapuolinen verhous vaativa | 4 m2 | 15 | 68 | 4 |

Appendix 7. Example of OCL tool-based reporting of results




| Bruttoala: 3 252,5 brm2<br>Lämmitetty nettoala: 3 008 m2<br>Laskentajakso: 50 vuotta, BAU 60 vuotta | YM21: Rakennuksen vähähiilisyyden arviointimenetelmä 2021 | |
|---|---|---|
| **Elinkaaren vaihe** | **Rakennus** | **Rakennuspaikka**** |
| | kgCO₂e/m²,a | kgCO₂e/rp-m²*,a |
| A1-A3 tuotteiden valmistus | 5,54 | 2,33 |
| A4 kuljetuksen työmaalle | 0,22 | 0,34 |
| A5 Työmaahävikki | 0,08 | 0,09 |
| A5 työmaatoiminnot | 0,92 | 0,00 |
| B4 rakennustuotteiden vaihdot | 1,45 | 0,15 |
| B6 energian käyttö | 3,59 | |
| B7 Veden käyttö | | |
| C1 purkutyöt | 0,14 | |
| C2 kuljetukset käsittelyyn | 0,22 | 0,15 |
| C3-C4 jätteenkäsittely ja loppusijoitus | 0,16 | 0,09 |
| C1-C4 Purkaminen | | |
| D1 uudelleenkäyttö ja materiaalikierrätys | -0,82 | -0,09 |
| D2 hyödyntäminen energiana | | |
| D3 ylimääräinen uusiutuva energia | | |
| D4 hiilivarastovaikutus | -0,87 | |
| D5 karbonatisoituminen | | |
| **YHTEENSÄ hiilijalanjälki A-C** | **12,32** | **3,15** |
| **YHTEENSÄ hiilikädenjälki D** | **-1,69** | **-0,09** |

Figure 1. OCL product phase CF results reporting by categories and structural parts (Sweco, 2022a).

| YM2021 laskentasisältö | | Poikkeukset | Määrätiedon lähde |
|---|---|---|---|
| **Alueosat** | 1.1.1 Maaosat | | ARK-suunnitelmat |
| | 1.1.2 Tuennat | | ARK ja RAK tietomallit |
| | 1.1.3 Päällysteet | | ARK-suunnitelmat |
| | 1.1.5 Alueen rakenteet | | ARK ja RAK tietomallit |
| **Rakennusosat** | 1.2.1 Perustukset | | ARK ja RAK tietomallit |
| | 1.2.2 Alapohja | | ARK ja RAK tietomallit |
| | 1.2.3 Runko | | RAK-tietomalli |
| | 1.2.4 Julkisivut, ovet ja ikkunat | | ARK-tietomalli |
| | 1.2.5 Ulkotasot ja parvekkeet | | ARK ja RAK tietomallit |
| | 1.2.6 Kattorakenteet | | ARK ja RAK tietomallit |
| **Tilaosat** | 1.3.1 Jako-osat (väliseinät, ovet, portaat) | | ARK-tietomalli |
| | 1.3.2 Tilapinnat (lattiat, sisäkatot, seinät) pintakäsittelyineen | | Ref. Kohde, ARK-tietomalli |
| | 1.3.3 Tilavarusteet (kiintokalusteet, keittiölaitteet) | | Ref. Kohde, ARK-tietomalli |
| | 1.3.4.2 Hormit ja tulisijat | | Ref. Kohde, ARK-tietomalli |
| | 1.3.5 Tilaelementit (mm. kylpyhuonemoduulit) | Ei huomioitu elementtinä * | |
| **Talotekniikka** | LVIJS-järjestelmät | | Alaperusteinen (CO2data.fi) |
| | Sprinklerijärjestelmän pääosat | Ei rakennuksessa | Alaperusteinen (CO2data.fi) |
| | Hissit ja liukuportaat | | ARK-suunnitelmat |

* = KPH-elementille ei omaa erillistä päästötietoa → huomioitu laskennassa "paikallarakennettuna"

Figure 2. CF results content reporting view (Sweco, 2022a).

Table 1. OCL's product phase CF results data, partial example of exported data shared by Sweco (2022b).

| Entity users | Project name | Design name | Indicator name | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Osio | Resurssi | Käyttäjän syöte | Yksikkö | Ilmaston lämpeneminen kg $CO_2$e/m²/a | Paksuus mm | Rakennusosa | Rakenne | Resurssin tyyppi | Lähde | |
| **A1-A3** | | | | **0,0016** | | **1110 Maatyöt** | | | | |
| A1-A3 | Asfalttibetoni (AB), 2500 kg/m3 | 44 | m2 | 0,0035 | 100 | 1130 Tontin päällysteet | | Asfaltti | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| A1-A3 | Betoniset päällystekivet, betonilaatta | 11594 | kg | 0,012 | | 1130 Tontin päällysteet | | Betonihark | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| **A1-A3** | | | | **0,016** | | **1130 Tontin päällysteet** | | | | |
| A5 | Asfalttibetoni (AB), 2500 kg/m3 | 44 | m2 | 0 | 100 | 1130 Tontin päällysteet | | Asfaltti | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| A5 | Betoniset päällystekivet, betonilaatta | 11594 | kg | 0,00062 | | 1130 Tontin päällysteet | | Betonihark | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| **A5** | | | | **0,00062** | | **1130 Tontin päällysteet** | | | | |
| B4 | Asfalttibetoni (AB), 2500 kg/m3 | 44 | m2 | 0,0035 | 100 | 1130 Tontin päällysteet | | Asfaltti | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| D | Asfalttibetoni (AB), 2500 kg/m3 | 44 | m2 | -0,0012 | 100 | 1130 Tontin päällysteet | | Asfaltti | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| D | Betoniset päällystekivet, betonilaatta | 11594 | kg | -0,0034 | | 1130 Tontin päällysteet | | Betonihark | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| **D** | | | | | | **1130 Tontin päällysteet** | | | | |
| bio-CO2 | Asfalttibetoni (AB), 2500 kg/m3 | 44 | m2 | 0 | 100 | 1130 Tontin päällysteet | | Asfaltti | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| bio-CO2 | Betoniset päällystekivet, betonilaatta | 11594 | kg | 0 | | 1130 Tontin päällysteet | | Betonihark | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| **bio-CO2** | | | | | | **1130 Tontin päällysteet** | | | | |
| | | | | **0,016** | | **1130 Tontin päällysteet** | | | | |
| A1-A3 | Valmisbetoni, C30/37, 2363 kg/m3 | 63 | m3 | 0,13 | 200 | 1211 Perustukset: Anturat | | Valmisbeto | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| A1-A3 | Teräsraudoite betonirakenteisiin, 7850 kg/m3 | 3137 | kg | 0,014 | 4 | 1211 Perustukset: Anturat | | Betoniraud | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| **A1-A3** | | | | **0,15** | | **1211 Perustukset: Anturat** | | | | |
| A5 | Valmisbetoni, C30/37, 2363 kg/m3 | 63 | m3 | 0,0054 | 200 | 1211 Perustukset: Anturat | | Valmisbeto | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| A5 | Teräsraudoite betonirakenteisiin, 7850 kg/m3 | 3137 | kg | 0,00068 | 4 | 1211 Perustukset: Anturat | | Betoniraud | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| **A5** | | | | **0,006** | | **1211 Perustukset: Anturat** | | | | |
| D | Valmisbetoni, C30/37, 2363 kg/m3 | 63 | m3 | -0,051 | 200 | 1211 Perustukset: Anturat | | Valmisbeto | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| D | Teräsraudoite betonirakenteisiin, 7850 kg/m3 | 3137 | kg | 0 | 4 | 1211 Perustukset: Anturat | | Betoniraud | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| **D** | | | | | | **1211 Perustukset: Anturat** | | | | |
| bio-CO2 | Valmisbetoni, C30/37, 2363 kg/m3 | 63 | m3 | 0 | 200 | 1211 Perustukset: Anturat | | Valmisbeto | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| bio-CO2 | Teräsraudoite betonirakenteisiin, 7850 kg/m3 | 3137 | kg | 0 | 4 | 1211 Perustukset: Anturat | | Betoniraud | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| **bio-CO2** | | | | | | **1211 Perustukset: Anturat** | | | | |
| | | | | **0,15** | | **1211 Perustukset: Anturat** | | | | |
| A1-A3 | Valmisbetoni, C30/37, 2363 kg/m3 | 10 | m3 | 0,021 | 200 | 1212 Perustukset: Muurit/pilarit/palkit | | Valmisbeto | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| A1-A3 | Sepeli (8...16 mm), kuiva tilavuus, 1680 kg/m3 | 383 | m3 | 0,019 | 100 | 1212 Perustukset: Muurit/pilarit/palkit | | Hiekka, m | LCA inventory for gravel production, Ecoinvent 2014 | |
| A1-A3 | Sepeli (8...16 mm), kuiva tilavuus, 1680 kg/m3 | 531,1 | m3 | 0,026 | 100 | 1212 Perustukset: Muurit/pilarit/palkit | | Hiekka, m | LCA inventory for gravel production, Ecoinvent 2014 | |
| A1-A3 | Teräsraudoite betonirakenteisiin, 7850 kg/m3 | 800 | kg | 0,0036 | 4 | 1212 Perustukset: Muurit/pilarit/palkit | | Betoniraud | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| **A1-A3** | | | | **0,07** | | **1212 Perustukset: Muurit/pilarit/palk** | | | | |
| A5 | Valmisbetoni, C30/37, 2363 kg/m3 | 10 | m3 | 0,00085 | 200 | 1212 Perustukset: Muurit/pilarit/palkit | | Valmisbeto | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| A5 | Sepeli (8...16 mm), kuiva tilavuus, 1680 kg/m3 | 383 | m3 | 0 | 100 | 1212 Perustukset: Muurit/pilarit/palkit | | Hiekka, m | LCA inventory for gravel production, Ecoinvent 2014 | |
| A5 | Sepeli (8...16 mm), kuiva tilavuus, 1680 kg/m3 | 531,1 | m3 | 0 | 100 | 1212 Perustukset: Muurit/pilarit/palkit | | Hiekka, m | LCA inventory for gravel production, Ecoinvent 2014 | |
| A5 | Teräsraudoite betonirakenteisiin, 7850 kg/m3 | 800 | kg | 0,00017 | 4 | 1212 Perustukset: Muurit/pilarit/palkit | | Betoniraud | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| **A5** | | | | **0,001** | | **1212 Perustukset: Muurit/pilarit/palk** | | | | |
| D | Valmisbetoni, C30/37, 2363 kg/m3 | 10 | m3 | -0,008 | 200 | 1212 Perustukset: Muurit/pilarit/palkit | | Valmisbeto | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| D | Teräsraudoite betonirakenteisiin, 7850 kg/m3 | 800 | kg | 0 | 4 | 1212 Perustukset: Muurit/pilarit/palkit | | Betoniraud | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| **D** | | | | | | **1212 Perustukset: Muurit/pilarit/palk** | | | | |
| bio-CO2 | Valmisbetoni, C30/37, 2363 kg/m3 | 10 | m3 | 0 | 200 | 1212 Perustukset: Muurit/pilarit/palkit | | Valmisbeto | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| bio-CO2 | Sepeli (8...16 mm), kuiva tilavuus, 1680 kg/m3 | 383 | m3 | 0 | 100 | 1212 Perustukset: Muurit/pilarit/palkit | | Hiekka, m | LCA inventory for gravel production, Ecoinvent 2014 | |
| bio-CO2 | Sepeli (8...16 mm), kuiva tilavuus, 1680 kg/m3 | 531,1 | m3 | 0 | 100 | 1212 Perustukset: Muurit/pilarit/palkit | | Hiekka, m | LCA inventory for gravel production, Ecoinvent 2014 | |
| bio-CO2 | Teräsraudoite betonirakenteisiin, 7850 kg/m3 | 800 | kg | 0 | 4 | 1212 Perustukset: Muurit/pilarit/palkit | | Betoniraud | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| **bio-CO2** | | | | | | **1212 Perustukset: Muurit/pilarit/palk** | | | | |
| | | | | **0,071** | | **1212 Perustukset: Muurit/pilarit/palk** | | | | |
| A1-A3 | Valmisbetoni, C30/37, 2363 kg/m3 | 23,78 | m3 | 0,051 | 200 | 1220 Alapohjat | | Valmisbeto | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| A1-A3 | Teräsraudoite betonirakenteisiin, 7850 kg/m3 | 1800 | kg | 0,008 | 4 | 1220 Alapohjat | | Betoniraud | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| **A1-A3** | | | | **0,059** | | **1220 Alapohjat** | | | | |
| A5 | Valmisbetoni, C30/37, 2363 kg/m3 | 23,78 | m3 | 0,002 | 200 | 1220 Alapohjat | | Valmisbeto | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| A5 | Teräsraudoite betonirakenteisiin, 7850 kg/m3 | 1800 | kg | 0,00039 | 4 | 1220 Alapohjat | | Betoniraud | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| **A5** | | | | **0,0024** | | **1220 Alapohjat** | | | | |
| D | Valmisbetoni, C30/37, 2363 kg/m3 | 23,78 | m3 | -0,019 | 200 | 1220 Alapohjat | | Valmisbeto | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| D | Teräsraudoite betonirakenteisiin, 7850 kg/m3 | 1800 | kg | 0 | 4 | 1220 Alapohjat | | Betoniraud | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| **D** | | | | | | **1220 Alapohjat** | | | | |
| bio-CO2 | Valmisbetoni, C30/37, 2363 kg/m3 | 23,78 | m3 | 0 | 200 | 1220 Alapohjat | | Valmisbeto | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| bio-CO2 | Teräsraudoite betonirakenteisiin, 7850 kg/m3 | 1800 | kg | 0 | 4 | 1220 Alapohjat | | Betoniraud | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| **bio-CO2** | | | | | | **1220 Alapohjat** | | | | |
| | | | | **0,061** | | **1220 Alapohjat** | | | | |
| A1-A3 | Valmisbetoni, C30/37, 2363 kg/m3 | 105 | m3 | 0,22 | 200 | 1231 Runko: Väestönsuojat | | Valmisbeto | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| A1-A3 | Teräsraudoite betonirakenteisiin, 7850 kg/m3 | 10500 | kg | 0,047 | 4 | 1231 Runko: Väestönsuojat | | Betoniraud | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| **A1-A3** | | | | **0,27** | | **1231 Runko: Väestönsuojat** | | | | |
| A5 | Valmisbetoni, C30/37, 2363 kg/m3 | 105 | m3 | 0,0089 | 200 | 1231 Runko: Väestönsuojat | | Valmisbeto | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| A5 | Teräsraudoite betonirakenteisiin, 7850 kg/m3 | 10500 | kg | 0,0023 | 4 | 1231 Runko: Väestönsuojat | | Betoniraud | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| **A5** | | | | **0,011** | | **1231 Runko: Väestönsuojat** | | | | |
| D | Valmisbetoni, C30/37, 2363 kg/m3 | 105 | m3 | -0,084 | 200 | 1231 Runko: Väestönsuojat | | Valmisbeto | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| D | Teräsraudoite betonirakenteisiin, 7850 kg/m3 | 10500 | kg | 0 | 4 | 1231 Runko: Väestönsuojat | | Betoniraud | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| **D** | | | | | | **1231 Runko: Väestönsuojat** | | | | |
| bio-CO2 | Valmisbetoni, C30/37, 2363 kg/m3 | 105 | m3 | 0 | 200 | 1231 Runko: Väestönsuojat | | Valmisbeto | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| bio-CO2 | Teräsraudoite betonirakenteisiin, 7850 kg/m3 | 10500 | kg | 0 | 4 | 1231 Runko: Väestönsuojat | | Betoniraud | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| **bio-CO2** | | | | | | **1231 Runko: Väestönsuojat** | | | | |
| | | | | **0,28** | | **1231 Runko: Väestönsuojat** | | | | |
| A1-A3 | Väliseinäelementti, 200 mm, 493 kg/m2 | 16,83 | m3 | 0,048 | 200 | 1232 Runko: Kantavat seinät | | Betoniseini | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| A1-A3 | Precast concrete solid wall element, 200 mm, 500 kg/ | 22,64 | m3 | 0,055 | 200 | 1232 Runko: Kantavat seinät | | Betoniseini | EPD SOLID WALL CONSOLIS PARMA | |
| A1-A3 | Precast concrete solid wall element, 200 mm, 500 kg/ | 244,49 | m3 | 0,59 | 200 | 1232 Runko: Kantavat seinät | | Betoniseini | EPD SOLID WALL CONSOLIS PARMA | |
| **A1-A3** | | | | **0,69** | | **1232 Runko: Kantavat seinät** | | | | |
| A5 | Väliseinäelementti, 200 mm, 493 kg/m2 | 16,83 | m3 | 0 | 200 | 1232 Runko: Kantavat seinät | | Betoniseini | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| A5 | Precast concrete solid wall element, 200 mm, 500 kg/ | 22,64 | m3 | 0 | 200 | 1232 Runko: Kantavat seinät | | Betoniseini | EPD SOLID WALL CONSOLIS PARMA | |
| A5 | Precast concrete solid wall element, 200 mm, 500 kg/ | 244,49 | m3 | 0 | 200 | 1232 Runko: Kantavat seinät | | Betoniseini | EPD SOLID WALL CONSOLIS PARMA | |
| **A5** | | | | | | **1232 Runko: Kantavat seinät** | | | | |
| D | Väliseinäelementti, 200 mm, 493 kg/m2 | 16,83 | m3 | -0,019 | 200 | 1232 Runko: Kantavat seinät | | Betoniseini | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| D | Precast concrete solid wall element, 200 mm, 500 kg/ | 22,64 | m3 | -0,026 | 200 | 1232 Runko: Kantavat seinät | | Betoniseini | EPD SOLID WALL CONSOLIS PARMA | |
| D | Precast concrete solid wall element, 200 mm, 500 kg/ | 244,49 | m3 | -0,28 | 200 | 1232 Runko: Kantavat seinät | | Betoniseini | EPD SOLID WALL CONSOLIS PARMA | |
| **D** | | | | | | **1232 Runko: Kantavat seinät** | | | | |
| bio-CO2 | Väliseinäelementti, 200 mm, 493 kg/m2 | 16,83 | m3 | 0 | 200 | 1232 Runko: Kantavat seinät | | Betoniseini | SYKE, CO2data.fi, conservative values, version 1.00.003, 2021-08-23 | |
| bio-CO2 | Precast concrete solid wall element, 200 mm, 500 kg/ | 22,64 | m3 | 0 | 200 | 1232 Runko: Kantavat seinät | | Betoniseini | EPD SOLID WALL CONSOLIS PARMA | |
| bio-CO2 | Precast concrete solid wall element, 200 mm, 500 kg/ | 244,49 | m3 | 0 | 200 | 1232 Runko: Kantavat seinät | | Betoniseini | EPD SOLID WALL CONSOLIS PARMA | |
| **bio-CO2** | | | | | | **1232 Runko: Kantavat seinät** | | | | |
| | | | | **0,69** | | **1232 Runko: Kantavat seinät** | | | | |
| A1-A3 | Betonipilariselementti, raudoitettu, C32/40, C32/40 (S | 1 | m3 | 0,0034 | | 1233 Runko: Pilarit | | Betonipilar | Columns, Skonto Prefab SIA 2014 | |
| A1-A3 | Betonipilariselementti, raudoitettu, C32/40, C32/40 (S | 2,31 | m3 | 0,0079 | | 1233 Runko: Pilarit | | Betonipilar | Columns, Skonto Prefab SIA 2014 | |
| **A1-A3** | | | | **0,011** | | **1233 Runko: Pilarit** | | | | |
| A5 | Betonipilariselementti, raudoitettu, C32/40, C32/40 (S | 1 | m3 | 0 | | 1233 Runko: Pilarit | | Betonipilar | Columns, Skonto Prefab SIA 2014 | |
| A5 | Betonipilariselementti, raudoitettu, C32/40, C32/40 (S | 2,31 | m3 | 0 | | 1233 Runko: Pilarit | | Betonipilar | Columns, Skonto Prefab SIA 2014 | |
| **A5** | | | | | | **1233 Runko: Pilarit** | | | | |
| D | Betonipilariselementti, raudoitettu, C32/40, C32/40 (S | 1 | m3 | -0,0012 | | 1233 Runko: Pilarit | | Betonipilar | Columns, Skonto Prefab SIA 2014 | |
| D | Betonipilariselementti, raudoitettu, C32/40, C32/40 (S | 2,31 | m3 | -0,0029 | | 1233 Runko: Pilarit | | Betonipilar | Columns, Skonto Prefab SIA 2014 | |
| **D** | | | | | | **1233 Runko: Pilarit** | | | | |
| bio-CO2 | Betonipilariselementti, raudoitettu, C32/40, C32/40 (S | 1 | m3 | 0 | | 1233 Runko: Pilarit | | Betonipilar | Columns, Skonto Prefab SIA 2014 | |
| bio-CO2 | Betonipilariselementti, raudoitettu, C32/40, C32/40 (S | 2,31 | m3 | 0 | | 1233 Runko: Pilarit | | Betonipilar | Columns, Skonto Prefab SIA 2014 | |
| **bio-CO2** | | | | | | **1233 Runko: Pilarit** | | | | |

# Appendix 8. Example of GBP tool reporting

Table 1. GBP tools product phase CF results reporting by categories and structural parts (GBP, 2022).

| | | Asuinkerrostalo | | Autohalli | | Yhteensä | |
|---|---|---|---|---|---|---|---|
| Nimike ja kuvaus | | kg $CO_2$ e | kg/n-$m^2$ | kg $CO_2$ e | kg/ap | kg $CO_2$ e | kg/n-$m^2$ |
| A1-A3 Yhteensä | | 3 700 449 | 393,1 | 927 426 | ##### | 4 627 875 | 491,6 |
| | | | | | | | |
| Rakennuspaikan hiilijalanjälki | | 305 397 | 32 | 117 497 | 1 487 | 422 894 | 45 |
| | Rakennuspaikkaan huomioidaan 111 Aluerakennus ilman 115 nimikettä | | | | | | |
| Rakennuksen hiilijalanjälki | | 3 395 052 | 361 | 809 929 | 10 252 | 4 204 981 | 447 |
| | Rakennukseen huomioidaan kaikki muut nimikkeet | | | | | | |
| 11 | Aluerakennus | 339 576 | 36,1 | 117 497 | 1 487,3 | 457 073 | 48,6 |
| 111 | Maaosat | 0 | 0,0 | 0 | 0,0 | 0 | 0,0 |
| 112 | Tuennat ja vahvistukset | 221 646 | 23,5 | 117 497 | 1 487,3 | 339 143 | 36,0 |
| 113 | Päällysteet | 83 751 | 8,9 | 0 | 0,0 | 83 751 | 8,9 |
| 115 | Alueen rakenteet | 34 179 | 3,6 | 0 | 0,0 | 34 179 | 3,6 |
| 12 | Talo-osat | 2 578 926 | 274,0 | 774 065 | 9 798,3 | 3 352 990 | 356,2 |
| 121 | Perustukset | 248 053 | 26,4 | 185 114 | 2 343,2 | 433 167 | 46,0 |
| 122 | Alapohja | 56 764 | 6,0 | 205 969 | 2 607,2 | 262 733 | 27,9 |
| 123 | Runko | 1 478 726 | 157,1 | 381 462 | 4 828,6 | 1 860 188 | 197,6 |
| 124 | Julkisivut | 545 618 | 58,0 | 1 231 | 15,6 | 546 849 | 58,1 |
| 125 | Ulkotasot | 170 701 | 18,1 | 288 | 3,7 | 170 990 | 18,2 |
| 126 | Vesikatot | 79 063 | 8,4 | 0 | 0,0 | 79 063 | 8,4 |
| 13 | Tilaosat | 390 435 | 41,5 | 0 | 0,0 | 390 435 | 41,5 |
| 131 | Tilanjako-osat | 62 992 | 6,7 | 0 | 0,0 | 62 992 | 6,7 |
| 132 | Tilapinnat | 237 939 | 25,3 | 0 | 0,0 | 237 939 | 25,3 |
| 134 | Tulisijat ja hormit | 30 320 | 3,2 | 0 | 0,0 | 30 320 | 3,2 |
| 135 | Tilaelementit | 59 183 | 6,3 | 0 | 0,0 | 59 183 | 6,3 |
| 2 | Talotekniikka | 391 513 | 41,6 | 35 864 | 454,0 | 427 377 | 45,4 |
| 210 | Lämmitysjärjestelmät | 53 340 | 5,7 | 0 | 0,0 | 53 340 | 5,7 |
| 220 | Vesi- ja viemärijärjestelmät | 37 652 | 4,0 | 2 006 | 25,4 | 39 658 | 4,2 |
| 230 | Ilmanvaihtojärjestelmät | 150 608 | 16,0 | 9 280 | 117,5 | 159 888 | 17,0 |
| 240 | Jäähdytysjärjestelmät | 0 | 0,0 | 0 | 0,0 | 0 | 0,0 |
| 250 | Palotekniset järjestelmät | 15 688 | 1,7 | 10 032 | 127,0 | 25 720 | 2,7 |
| 260 | Sähköjärjestelmät | 134 224 | 14,3 | 14 546 | 184,1 | 148 770 | 15,8 |

Table 2. GBP tools product phase CF results reporting annex and included structural parts, quantities, and masses (GBP, 2022).

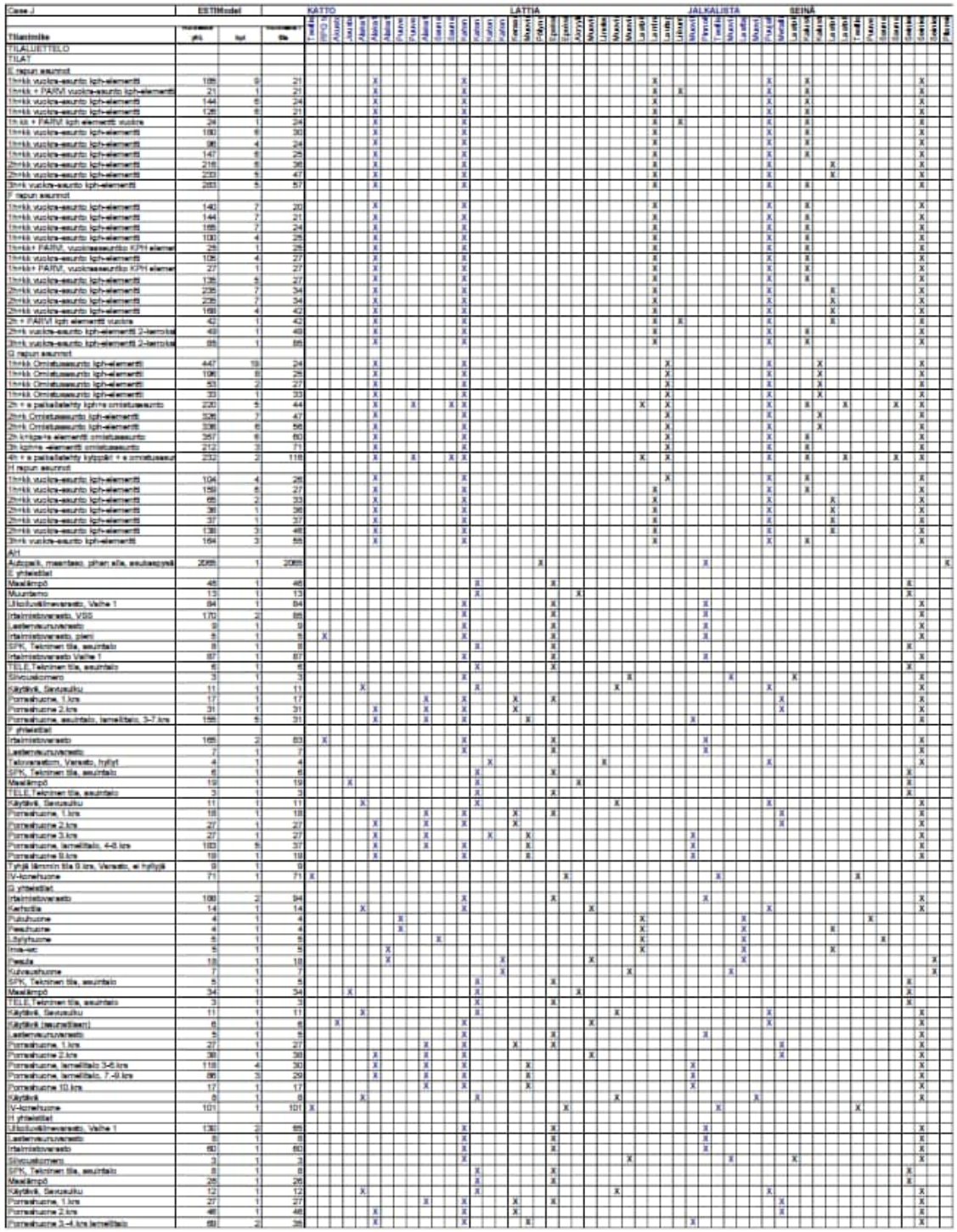
| Nimike | Rakennusosa / Materiaali | Määrä | Kokonais-massa kg | A1-A3 Tuote-vaihe $kgCO_2e$ | $kgCO_2e$/ t | $kgCO_2$ e/ n-m² | B4 Osien vaihto $kgCO_2e$ | D-moduuli kgCO2e |
|---|---|---|---|---|---|---|---|---|
| 112 | Paalutus | 6376 jm | 1 434 600 | 221 646 | 155 | 23,5 | 0 | 0 |
| 113 | Pihakansi | | 195 210 | 48 036 | 246 | 5,1 | 0 | 0 |
| 113 | Päällysteet | 2043 m2 | 556 454 | 35 715 | 64 | 3,8 | 0 | 0 |
| 115 | UVV | | 77 106 | 22 051 | 286 | 2,3 | 620 | -12 577 |
| 115 | Alueen portaat | | 89 806 | 12 129 | 135 | 1,3 | 0 | 0 |
| 125 | Rakennusten välinen katos | 1 kpl | 16 180 | 41 663 | 2575 | 4,4 | 0 | -21 034 |
| 125 | Sisäänkäynnin katos | 1 kpl | 3 076 | 3 973 | 1292 | 0,4 | 0 | -1 028 |
| 121 | Anturat | 730 m2 | 1 348 405 | 194 093 | 144 | 20,6 | 0 | 0 |
| 121 | Sokkelit | | 153 435 | 40 040 | 261 | 4,3 | 0 | 0 |
| 121 | Tukimuurit | 13 m2 | 6 455 | 892 | 138 | 0 | 0 | 0 |
| 121 | Perusmuurit | | 97 540 | 13 028 | 134 | 1 | 0 | 0 |
| 122 | Alapohja | 2595 m2 | 383 189 | 56 764 | 148 | 6 | 0 | 0 |
| 123 | VSS | | 1 186 983 | 182 976 | 154 | 19 | 0 | 0 |
| 123 | Runko: kantavat väliseinät | 6196 m2 | 2 984 221 | 455 827 | 153 | 48 | 0 | 0 |
| 123 | Runko: Hissikuilu | | 20 217 | 3 017 | 149 | 0,3 | 0 | 0 |
| 123 | Runko: pilarit | 87 jm | 34 306 | 6 714 | 196 | 1 | 0 | 0 |
| 123 | Betonipalkit | 23 jm | 52 632 | 8 335 | 158 | 0,9 | 0 | 0 |
| 123 | Runko: Delta-palkit | 47 jm | 19 354 | 23 625 | 1221 | 3 | 0 | -7 456 |
| 123 | Runko: PV kaistat | | 345 187 | 43 754 | 127 | 5 | 0 | 0 |
| 123 | Runko: Ontelolaatasto | 6584 m2 | 3 313 889 | 497 889 | 150 | 53 | 0 | -20 741 |
| 123 | Runko: Kuorilaatasto | 793 m2 | 675 673 | 98 181 | 145 | 10 | 0 | 0 |
| 123 | Runko: Laattaelementit | 834 yks | 519 150 | 85 556 | 165 | 9,1 | 0 | 0 |
| 123 | Välipohjien pintabetonit | | 446 812 | 54 495 | 122 | 5,8 | 0 | 0 |
| 123 | Runko: Tilaportaat | | 80 734 | 18 357 | 227 | 2 | 0 | -1 664 |
| 124 | Julkisivut: Julkisivuelementit | 4486 m2 | 1 576 500 | 312 527 | 198 | 33,2 | 0 | -7 886 |
| 124 | Julkisivut: muuraus ja rappaus | 1703 m2 | 395 540 | 71 229 | 180 | 7,6 | 0 | -1 527 |
| 124 | Julkisivut: puualumiini-ikkunat | 779 m2 | 33 497 | 96 605 | 2884 | 10 | 96605 | -56 945 |
| 124 | Julkisivut: lasiseinät | 254 m2 | 9 271 | 31 512 | 3399 | 3 | 31512 | -13 907 |
| 124 | Julkisivut: ulko-ovet | 226 kpl | 11 449 | 33 745 | 2947 | 4 | 0 | -18 910 |
| 125 | Parvekkeet/terassit | | 377 284 | 116 102 | 308 | 12 | 0 | -2 887 |
| 125 | Parvekkeiden väliseinät | 82 m2 | 5 910 | 8 964 | 1517 | 1,0 | 0 | -2 680 |
| 126 | Vesikatto | 1081 m2 | 140 132 | 79 063 | 564 | 8 | 0 | -40432 |
| 131 | Kevytrakenteinen seinä | 207 m2 | 2 726 | 4 057 | 1488 | 0,4 | 0 | -2616 |
| 131 | Levyväliseinät | 3150 m2 | 71 102 | 35 076 | 493 | 4 | 0 | -9608 |
| 131 | Muuratut väliseinät | 231 m2 | 47 519 | 6 486 | 137 | 1 | 0 | 0 |
| 131 | Sisäovet | 606 kpl | 12 300 | 17 374 | 1412 | 2 | 0 | -16222 |
| 132 | Lattiapinnat | 6292 m2 | 517 110 | 198 542 | 384 | 21 | 100782 | -64080 |
| 132 | Seinäpinnat | 1315 m2 | 27 368 | 19 545 | 714 | 2 | 19545 | 0 |
| 132 | Alakatot | 3451 m2 | 27 848 | 19 852 | 713 | 2 | 5280 | -14730 |
| 133 | Varastokomerot | 190 kpl | 17 805 | 5 861 | 329 | 0,6 | 0 | -28095 |
| 134 | Elementtihormit | 366 kpl | 223 232 | 30 320 | 136 | 3 | 0 | -1931 |
| 135 | Tilaelementit | 133 kpl | 173 489 | 59 183 | 341 | 6 | 0 | -19664 |

Appendix 9. Thesis' Esti Model scenarios space listings of Case H and Case J

Table 1. Case H's Esti Model scenario's space listing (House K)

| Cse H | ESTIModel | | KATTO | | | | | | | | | LATTIA | | | | | | | | JALKALISTA | | | | | SEINÄ | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tilanimike | Huoneala yht. | kpl | Huoneala / tila | Teollis | Akusto | Alakat | Alakat | Puuve | Akusto | Alakat | Sauna | Katon | Katon | Katon | Muovi | Epoksi | Polyur | Vinyyli | Muovi | Laatoi | Lamin | Muovi | Pinnoi | Muovi | Laatta | Muovij | Puujal | Laatoi | Kalust | Laatoi | Teollis | Puuve | Sauna | Seinie | Seinie | Seinie |
| TEKNISET TILAT JA PORRASHUONEET | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Porrashuone, asuintalo [-93 m2] | 236 | 7 | 34 | | | | | | X | X | | X | | | X | | | | | | | X | | | | | | | | | | | | X | |
| IV-konehuone [29 m2] | 79 | 1 | 79 | X | | | | | | | | | | | | | X | | | | | | X | | | | | | | | X | | | | |
| TILAT | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| KERROSTALO, vuokra-asunto, KPH-elemer | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1h+kk vuokraasunto kph-elementti | 138 | 4 | 35 | | | | X | | | | | X | | | | | | | | | X | | | | | | X | | X | | | | | X | |
| 1h+kk vuokra-asunto kph-elementti | 315 | 10 | 32 | | | | X | | | | | X | | | | | | | | | X | | | | | | X | | X | | | | | X | |
| 2h+kk vuokra-asunto kph-elementti | 261 | 6 | 44 | | | | X | | | | | X | | | | | | | | | X | | | | | | X | | | X | | | | X | |
| 2h+kk vuokra-asunto kph-elementti | 270 | 6 | 45 | | | | X | | | | | X | | | | | | | | | X | | | | | | X | | | X | | | | X | |
| 2h+kk vuokra-asunto kph-elementti | 48 | 1 | 49 | | | | X | | | | | X | | | | | | | | | X | | | | | | X | | | X | | | | X | |
| 2h+kk vuokra-asunto kph-elementti | 297 | 6 | 50 | | | | X | | | | | X | | | | | | | | | X | | | | | | X | | | X | | | | X | |
| 3h+k vuokra-asunto kph-elementti | 305 | 5 | 61 | | | | X | | | | | X | | | | | | | | | X | | | | | | X | | X | | | | | X | |
| 4h+k vuokra-asunto kph-elementti | 131 | 2 | 66 | | | | X | | | | | X | | | | | | | | | X | | | | | | X | | X | | | | | X | |
| 4h+k vuokra-asunto kph-elementti | 414 | 6 | 69 | | | | X | | | | | X | | | | | | | | | X | | | | | | X | | X | | | | | X | |
| Yhteistilat | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Irtaimistovarasto | 108 | 1 | 108 | | | | | | | | | X | | | | X | | | | | | | X | | | | | | | | | | | X | |
| Irtaimistovarasto | 31 | 1 | 31 | | | | | | | | | X | | | | X | | | | | | | X | | | | | | | | | | | X | |
| Sähkö, Tekninen tila | 7 | 1 | 7 | | | | | | | | | | X | | | X | | | | | | | | | | | | | | | | | X | | |
| LJH, Tekninen tila, asuintalo | 40 | 1 | 40 | | | | | | | | | | X | | | X | | | | | | | | | | | | | | | | | X | | |
| Savusulku | 5 | 1 | 5 | | | X | | | | | | | X | | | | | X | | | | | | | | | X | | | | | | | X | |
| Savusulku | 3 | 1 | 3 | | | X | | | | | | | X | | | | | X | | | | | | | | | X | | | | | | | X | |
| Lastenvaunuvarasto | 11 | 1 | 11 | | | | | | | | | X | | | | X | | | | | | | X | | | | | | | | | | | X | |
| WC | 2 | 1 | 2 | | X | | | | | | | X | | | | | | | | X | | | | X | | | | X | | | | | | X | |
| Pukuhuone | 6 | 1 | 6 | | | | | X | | | | | | | | | | | | X | | | | X | | | | | | | X | | | | |
| Pesuhuone | 6 | 1 | 6 | | | | | X | | | | | | | | | | | | X | | | | X | | | | | X | | | | | | |
| Löylyhuone | 6 | 1 | 6 | | | | | | | | X | | | | | | | | | X | | | | X | | | | | | | | X | | | |
| Tele, Tekninen tila | 4 | 2 | 2 | | | | | | | | | | X | | | X | | | | | | | | | | | | | | | | | | X | |
| Ulkoiluvälinevarasto | 116 | 1 | 116 | | | | | | | | | X | | | | X | | | | | | | X | | | | | | | | | | | X | |
| Asuintalon käytävä | 10 | 1 | 10 | | | | | | | | | X | | | | | | X | | | | | | | | X | | | | | | | | X | |
| Siivouskomero | 2 | 1 | 2 | | | | | | | | | X | | | | | | | X | | | | X | | | | | X | | | | | | X | |
| Kuivaushuone | 8 | 1 | 8 | | | | | | | | | | | X | | | | | X | | | | X | | | | | | | | | | | | X |

Table 2. Case J's Esti Model scenario's space listing



# Appendix 10. Case H input data comparison between study's calculation scenario and expert calculation

Table 1. Esti Model's scenarios building material content that is included and share of materials included CF that is estimated to be included or excluded from expert calculation inputs.

| **Esti Model scenarios building parts content** | | **Estimation of expert calculation input data content to classification group** | |
|---|---|---|---|
| | **Group (Talo 80)** | **Materials CF's included share** | **Materials CF's excluded share** |
| Foundation underlay filling | 16 | 85 % | 15 % |
| Traffic areas | 17 | 100 % | 0 % |
| Foundations | 21 | 99 % | 1 % |
| Foundation wall, -beams, -columns | 22 | 96 % | 4 % |
| Air-raid shelter | 25 | 94 % | 6 % |
| Ground flooring structure | 26 | 100 % | 0 % |
| Lift shaft foundations | 27 | 23 % | 77 % |
| Supporting exteriof floors and columns | 32 | 100 % | 0 % |
| Hollow core slabs | 33 | 100 % | 0 % |
| Precast concrete stairs | 34 | 100 % | 0 % |
| Sandwich elements | 35 | 91 % | 9 % |
| Exterior planes and balconys | 36 | 93 % | 7 % |
| Interior space elements | 38 | 100 % | 0 % |
| Windows and windowdoors | 41 | 74 % | 26 % |
| Special windows | 42 | 75 % | 25 % |
| Doors | 43 | 100 % | 0 % |
| Interior partition wall | 45 | 67 % | 33 % |
| Railings and maintainance planes | 47 | 80 % | 20 % |
| Flue and duct components | 48 | 69 % | 31 % |
| Roofing | 51 | 33 % | 67 % |
| Interior wall tiling and other surfaces | 52 | 99 % | 1 % |
| Interior roof surfaces | 53 | 49 % | 51 % |
| Interior surfaces of stairscase | 54 | 97 % | 3 % |
| Floorings underlayer structures | 56 | 76 % | 24 % |
| Interior surfaces of sauna | 57 | 2 % | 98 % |
| Paintworks | 58 | 98 % | 2 % |
| Standard fittings | 61 | 98 % | 2 % |
| Standard fixtures, e.g., owens, fridges, stoves | 63 | 91 % | 9 % |
| Passenger elevators | 74 | 92 % | 8 % |

Table 2. Esti models scenarios building material content that is excluded from expert calculation inputs.

| **Extra carbon footprint content in Esti model** | |
|---|---|
| Building material group | **Group (House 80)** |
| Underdrain and canals | 15 |
| Exterior equipments | 18 |
| Exterior structures | 28 |
| Attic and roofing structures | 37 |
| Special doors | 44 |
| Special dividing walls | 46 |
| Exterior surfacestructures | 55 |
| Equipments | 62 |
| Space group furnitures | 64 |
| Air-raid shelter equipments | 67 |
| | |
| *HVAC that was reported separately:* | |
| Plumbing elements | 71 |
| Air conditioning and data transfer elements | 72 |
| Electrical elements | 73 |

Table 3. Esti models scenarios building material content that is excluded from expert calculation inputs.

| **HVAC groups in Esti model** | |
|---|---|
| Plumbing elements | 71 |
| Air conditioning and data transfer elements | 72 |
| Electrical elements | 73 |