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Master's Programme in Spatial Planning and Transportation Engineering

Guidance for Neighbourhood Level Life Cycle Assessment

Possibilities to affect greenhouse gas emission levels in neighbourhood early-phase planning

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Abstract

Scientific community has been warning of insufficiency of the climate target limiting the global warming to 2◦C. Finland has set own target to be carbon neutral by 2035. Whatever the target, to reach it, there must be an indicator and tool to measure it. To reach carbon neutral society target, GWP must be calculated in wider level, and more often, than it currently is. In case of built environment next step from building calculations must be taken. This study is done for studying the possibilities to guide and affect the areal GWP in early-phase neighbourhood level planning.

Study is completed, first with literature review, to get to know the scientific research completed of the topic and familiarizing with international best practices, as well as national (Finnish) examples. Research stage is completed as a case study, by comparing Finnish and Norwegian examples. Comparison includes legislation as well as areal calculation example. Finnish calculation tool is HAVA (Helsingin asemakaavojen vähähiilisyyden arviointimenetelmä). Norwegian examples are areal calculation results from NTNU (Norwegian University of Science and Technology) neighbourhood level carbon footprint calculation, and OneClick LCA tool according to the standard NS3720 for buildings, including land use change and use phase transport features. Additional calculation for building guidance is done with OneClick LCA 3D Carbon Designer with the Finnish Ministry of Environment reference values.

From the results is formed a new five stage early-phase LCA process including areal baseline, areal case, building approach, building A1 to A3 calculation and possible additional assessments e.g., for transport or sustainable energy potential, to be used in early-phase neighbourhood level planning.

Keywords Carbon footprint, carbon neutral, embodied carbon, embodied energy, life cycle assessment, low-carbon, neighbourhood level, planning policy, transport energy, zoning

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Tiivistelmä

Tieteellinen yhteisö on varoittanut 2◦C ilmastonlämpenemisrajatavoitteen riittämättömyydestä. Suomi on asettanut oman tavoitteensa olla hiilineutraali 2035. Hiilineutraalin yhteiskunnan saavuttamiseksi GWP pitää laskea laajemmin ja useammin, kuin mitä nykyään tehdään. Rakennetun ympäristön osalta se tarkoittaa laskemisen laajentamista rakennuksista suurempiin kokonaisuuksiin. Tutkimus selvittää hiilijalanjälkilaskennan ohjaus- ja vaikutusmahdollisuuksia naapurustotason alkuvaiheen suunnittelussa.

Tutkimus tehtiin perehtymällä aluksi aiheesta tehtyyn tieteelliseen tutkimukseen, ja tutustumalla kansainvälisiin suosituksiin sekä kansallisiin (suomalaisiin) esimerkkeihin. Tutkimusosuus tehtiin tapaustutkimuksena vertaamalla suomalaisia ja norjalaisia esimerkkejä. Vertailu sisältää lainsäädännön ja esimerkkilaskennan vertailut. Suomalainen laskenta tehdään HAVA:lla (Helsingin asemakaavojen vähähiilisyyden arviointimenetelmä). Norjalainen esimerkki sisältää alueellisen laskennan tulokset NTNU:n (Norjan teknis-luonnontieteellinen yliopisto) laskennasta, sekä rakennusten laskennan OneClick LCA:n NS3720 standardin mukaisella työkalulla sisältäen maankäytön muutoksen ja käyttövaiheen liikenteen. Rakennusten ohjaukseen tehtiin lisäksi laskenta OneClick LCA 3D Carbon Designerilla Ympäristö Ministeriön ohjearvoilla.

Tutkimuksen tuloksista on muodostettu uusi viisivaiheinen alkuvaiheen suunnittelun LCA prosessi; alueellinen perustaso, alueellinen tapaus, rakennuskohtainen, rakennuksen A1-A3 laskenta, sekä mahdolliset lisäselvitykset, esimerkiksi liikenteelle tai uusiutuvan energian potentiaaliselvitys alueella.

Avainsanat Hiilijalanjälki, hiilineutraali, sidottu hiili, sidottu energia, elinkaariarviointi, vähähiilisyys, naapurustotaso, suunnittelupolitiikka, liikenteen energia, kaavoitus

Contents

Preface

Raksystems Insinööritoimisto Oy Green Building Services offered me a great opportunity to suggest and complete a master thesis based on my own interests. Thank you for my advisor MSc. T. Rintala for directing the study, but also giving liberties to develop and make decisions based on my own understanding. As well, for the additional help offered by LCA expert MSc. J. Huuhtanen in improving the output of the study.

From Aalto University, a huge thanks to Professor D. Stead who have been guiding my work as a supervisor. The amount of time used for improving my work and number of discussions during the process exceeded my expectations and certainly improved the scientific performance of the study.

Also, I would like to thank S. de Vocht from the city of Helsinki for sharing the development version of the HAVA with me, N. Nurminen from Ilmarinen for providing the case area, as well as all the experts who took part in the validation process. Your input made the work more valuable.

In memory of MSc A. Yli-Paunu.

Otaniemi, 22 February 2023
Kaisa Yli-Paunu

Abbreviations

ADP	Abiotic depletion potential
CA	Criticality assessment
CBA	Consumption-based approach
CEEQUAL	Building Research Establishment Environmental Assessment Method: Infrastructure
CRMs	Critical raw materials
DALYs	Disability adjusted life years
DH	District heating
EE-IOA	Environmentally extended input-output analysis
FiGBC	Finnish Green Building Council
GHG	Greenhouse gas
GWP	Global warming potential
HAVA	Helsingin asemakaavojen vähähiilisyyden arviointimenetelmä, *Helsinki:* D*etail plan low carbon assessment method*
HERA	Human and environmental risk assessment
IPCC	Intergovernmental Panel on Climate Change
IOTs	Input-output tables
LCA	Life cycle assessment
LCC	Life cycle costing
LEED	Leadership in Energy and Environmental Design
LULUCF	Land use, land-use change and forestry
LRT	Light rail transit
MBA	Metabolism-based approach
MEFA	Material and energy flow analysis
MSLCEA	Multi-scale life cycle energy analysis
NECPs	National energy and climate plans
NTNU	Norwegian University of Science and Technology
ODP	Ozone depletion potential
OTV	Odour threshold value
PA	Potential of acidification
PE	Potential of eutrophication
PEF	Product environmental footprint
SFA	Substance flow analysis
TEM	Työ- ja elinkeinoministeriö, *Ministry of Employment and Economy*
TOD	Transit oriented development
USGBC	U.S. Green Building Council
WtW	Well to wheel
ZEB	Zero energy building
ZEN	Zero energy neighbourhood

1 Introduction

"*The Paris climate agreement set a limit of a 2◦C global warming increase above preindustrial temperature, with an aspirational but more ambitious target of 1.5◦C. However, the 0.5◦C temperature difference has been shown to lead to dramatic consequences, and global warming should be limited to the 1.5◦C target to stabilize the temperature increase at a safe level. Global emissions outcomes of current nationally stated mitigation ambitions as submitted under the Paris Agreement would not limit the global warming to 1.5◦C, and net-zero emissions followed by net-negative emission levels have to be targeted. Reaching these targets requires deep emissions reductions in all sectors, and rapid, far-reaching, and unprecedented changes in all aspects of society (IPCC, 2018).*" from (Lausselet, Ellingsen, Strømman, & Brattebø, 2020)

Finnish government has set a target to be a carbon neutral welfare society by 2035 (Ministry of Environment, 2022), which exceeds the requirements set by the European Union. Finland's ambitious target cannot be achieved without emission reductions on built environment sector. Ministry of Environment has approximated that one third of greenhouse gas emissions comes from built environment (Ministry of Environment, 2021). To fulfil carbon neutral targets, built environment requires guidance towards low-carbon and carbon neutral implementation. However, proper guidance requires proper methods and tools to analyse different alternatives. There is a demand for a study assessing the fulfilment of national carbon neutral requirements and recommendations in neighbourhood level planning guidance and tools. Also, to be able to assess Finland's development in international level, it is important to compare national examples to research findings and best practices learned abroad.

This study will compare the compatibility of method for the whole life carbon assessment of building by Ministry of Environment, based on standards EN 15643, EN 1597 and EN 15804 8 and draft of zoning and building law to preliminary neighbourhood level LCA tool, HAVA, developed by Sitowise Oy for City of Helsinki. Also, comparison is done to Norwegian early-stage planning LCA tool developed by Norwegian University of Science and Technology and based on standard NS 3720. To be able to improve the every-day practices, the used tools need to provide, not only the GWP level, but also a guiding effect towards lower GWP. Possibility to use existing tools to guide a project towards low-carbon solution is studied with case study. A residential block located in Vuosaari Helsinki has been chosen, presenting an infill building project by Keskinäinen Eläkevakuutusyhtiö Ilmarinen. Early-phase areal GWP will be calculated with areal emission calculator HAVA. Comparison will be done with OneClick LCA tool based on standard NS3720, in this

calculation buildings are calculated separately and building specific results will be added together to obtain areal results. Calculation results will be compared to the magnitude of NTNU areal results from Zero Village Bergen. Further guidance for buildings will be tested via OneClick LCA 3D Carbon Designer tool.

The report starts with background. Going through the context; EU and national requirements and role of built environment in GHG mitigation. Next is a brief look to LCA and other environmental assessment methods, and a literature review of scientific research and international best practices. The part closes with a section of national (Finnish) community level ecological tools. Chapter 3 explains the research questions and justifies the use of a case-study method. Next is presented the comparison done between the Finnish and Norwegian cases. Comparison starts with the legislative part, then compares HAVA and NTNU areal calculation tools, and ends with example calculation with HAVA, OneClick NS3720 tool and OneClick 3D Carbon Designer.

Results are gathered in the chapter 5, and more detailed calculation examples are attached. Results chapter ends to validation discussion part, where LCA guiding is discussed with national (Finnish) environmental experts. Validation discussion is completed since there is hardly any peer reviewed research available in the national context, and such it is useful to expand the understanding and verify national best practices with expert discussions. Study ends to a discussion and conclusion part. Part briefly summaries the work and discusses of the importance of the results. Part presents study's shortcomings and strengths, as well as suggest further research based on uncertainties remaining after the study.

2 Built environment in climate change mitigation

2.1 Requirements from the European Union

European Union has set a target to reduce emission 55 % (compared to 1990) to year 2030 and to be carbon neutral in 2050. European Climate Law which came into force in summer 2021 made these targets legally binding. Different EU member countries contribute with different shares to these targets. For Finland has been allocated 39 % reduction of emissions on non-carbon pricing sectors, and 43 % reduction on carbon pricing sectors. (Ministry of Environment, 2022)

Part of the climate process are the national energy and climate plans (NECPs) which were agreed as part of the Clean Energy for All Europeans package and adopted in 2019. NECPs are designed to require climate actions and planning throughout the government levels strengthening coordination between sectors. Key aspects addressed in the plans are, energy efficiency, renewables, greenhouse gas emissions reductions, interconnections, research, and innovation. (European Commission, 2022) For built environment building climate declarations are part of the low-carbon development in Europe. Countries have implemented own methods for declarations, but they are based on European Standards and European Commission's Level(s) method. (Ministry of Environment, 2019)

2.2 Requirements from the Finnish government

Finland's government program from 2019 has set a target, that Finland will be carbon neutral by 2035, and to become the first fossil free welfare society. Ambitious target will require fast emission reductions, as well as reductions on all sectors. Also, to gain the target, strengthening the carbon sinks is essential. (Ministry of Environment, 2022)

Climate change, biodiversity loss and overconsumption are connected, and related, and such the causes will be addressed comprehensively. Main steps to reach environmental targets are close to zero emission heating and electricity generation by the end of 2030, for buildings decreasing the emissions in building phase, promotion of circular economy, and environmentally friendly food production. From governmental approach targets can be addressed via tax guidance and legislation. Taxing will move towards taxing of environmental hindrances. Biodiversity loss will be addressed via renewing nature conservation legislation, providing sufficient funding, and promoting sustainable use of natural resources. (Ministry of Environment, 2022)

Emission reductions in built environment will be addressed also via the renewal of land use and building law (maankäyttö ja rakennuslaki). After renewal the law was planned to be inducted as zoning and building law (kaavoitus ja rakennuslaki). (Ministry of Environment, 2021) The renewed law was planned to come into effect 1.1.2024. Renewed law would have included environmental management requirements for area planning. These requirements would have included guidance towards carbon neutral and biodiversity inclusive zoning. (Ministry of Environment, 2021) However, only part of the proposed law was we presented to the parliament at the autumn 2023. "Rakentamislaki" the building law, and digitalisation of land use part were be presented, while other land use part was not presented. (Ministry of Environment, 2022)

2.3 Role of the built environment in GHG emission reductions

There has been, and still is, an ongoing urban sprawl in Europe. For example, built space increased by 20 % between 1980 and 2000, but more rabid urban sprawl has been seen in growing cities in developing countries (Nematchoua & Reiter, 2019). Due to the current life-styles people spend most of their time inside buildings. Such, built environment, and especially housing sector, has a great influence on the use of natural and abiotic resources. (Nematchoua, Orosa, & Reiter, 2019) Built environment uses 62 % of final energy consumption and use of energy is estimated to increase globally during next decades. 55 % of greenhouse gas emissions origins from built environment. In 2002 as much as 6 to 7 % of global greenhouse gas emissions originated from cement and steel production. (Anderson, Wulhorst, & Lang, 2015)

In Finland Ministry of Environment approximates that one third of greenhouse gas emissions comes from built environment (Ministry of Environment, 2021). Graph below is based on calculation by Rakennusteollisuus RT and Gaia Consulting Oy for year 2018, where built environment GHG emissions were 30 % of the overall GHG emissions in Finland. Land use and land use change is reported separately in LULUCF emissions.

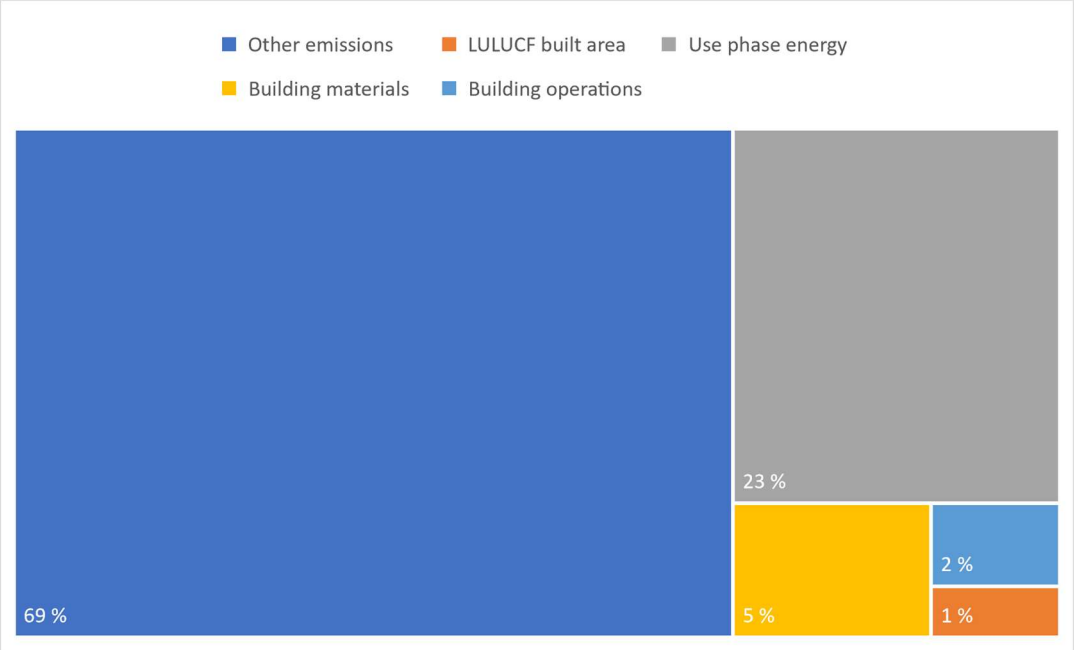


Figure 1 Finnish GHG emission shares in 2018 (Gaia Consulting Oy, 2020)

RT has calculated that carbon footprint of built environment, including used energy, electricity, and building materials have been 17,1 Mt CO2-eq per year (Rakennusteollisuus RT ry, 2020). While Traficom has evaluated that transportation produced 10,4 Mt CO2-eq in year 2020 (Traficom, 2021). Overall CO2 emission 2020 in Finland were approximately 48 Mt CO2-eq, estimated by Tilastokeskus (Suomen virallinen tilasto SVT, 2022).

Built environment is a broad entity and its' definition varies slightly. Anderson et al. described built environment as a sum of human-made structures, like buildings, infrastructure, and transportation system (Anderson, Wulhorst, & Lang, 2015). Lotteua et al. included into the built environment buildings, open spaces (including roads and green spaces), networks (including water, telecommunication, sewage, heating distribution, electricity distribution), and mobility (Lotteau, Loubet, Pousse, Dufrasnes, & Sonnemann, 2015). Despite of the exact definition of which emission categories should be included within built environment, it can be stated, that significant share of greenhouse gas emissions in Finland, and globally, are generated via built environment. Significant share of emissions also means a significant possibility to reduce emissions. To meet the 2035 carbon neutral Finland target, built environment has an important role.

Ministry of Environment has been preparing a low-carbon road map for buildings since 2017. The road map includes for example building low-carbon assessment tool and emission data base for building materials. The assessment tool is based on European Commission Level(s) method and EN

standards. (Ministry of Environment, 2022) Finnish transport infrastructure agency (Väylä) is collecting database for infrastructure carbon footprint. Väylä has also published a guideline for calculation of infra carbon footprint. (Väylävirasto, 2020) Currently in EU it is recommended to use EMEP/EEA air pollutant emission inventory guidebook 2019 and EMEP/EEA database for unit emissions. (EEA, 2019). VTT collects road emission data to LIISA calculation base and produces road traffic scenarios with ELIISA model (VTT, 2022). For energy and electricity sector Tilastokeskus provides CO2 emissions for electricity and heating energy, currently most recent available year is 2019. Emissions are calculated with *energiamenetelmä* (energy method) and *hyödynjakomenetelmä* (benefit-sharing method). (Suomen virallinen tilasto SVT, 2022)

In built environment reporting and planning there is a growing need to be able to justify the chosen solutions. Justification is needed due growing pressure from the population, partly by the sense of global responsibility. But also, due measurable effects like the lack of natural resources, detected environmental impacts, the current changes we see, and the changes predicted to the coming decades. (Baynes & Wiedmann, 2012) However, properly combining different emission origins, and calculating their share on specific geographical area is more demanding. In Finland there is currently no official guideline for calculating LCA on neighbourhood level. Preliminary methods have been created. Examples of preliminary methods are presented in chapter “Community level ecological tools in Finland”. Abroad there have been attempts to develop neighbourhood level LCA method for example in Australia, Belgium, Canada, China, France, Sweden, Switzerland, and USA (Lotteau, Loubet, Pousse, Dufrasnes, & Sonnemann, 2015). Next chapter presents the research structure and research questions which are used to gain understanding of neighbourhood level LCA; by studying what has been done on the field and how existing tools and methods could better be utilized for answering the questions of how to do guide low-carbon developments.

3 Research questions and a case study method

3.1 Hypothesis and research questions

Previous research has suggested that areal LCA is a useful tool for early-phase planning to cut the overall GHG emissions of a built environment development project. This study tests the hypothesis that completing LCA calculation in early-phase can guide the decision-making in early-phase towards low-carbon development.

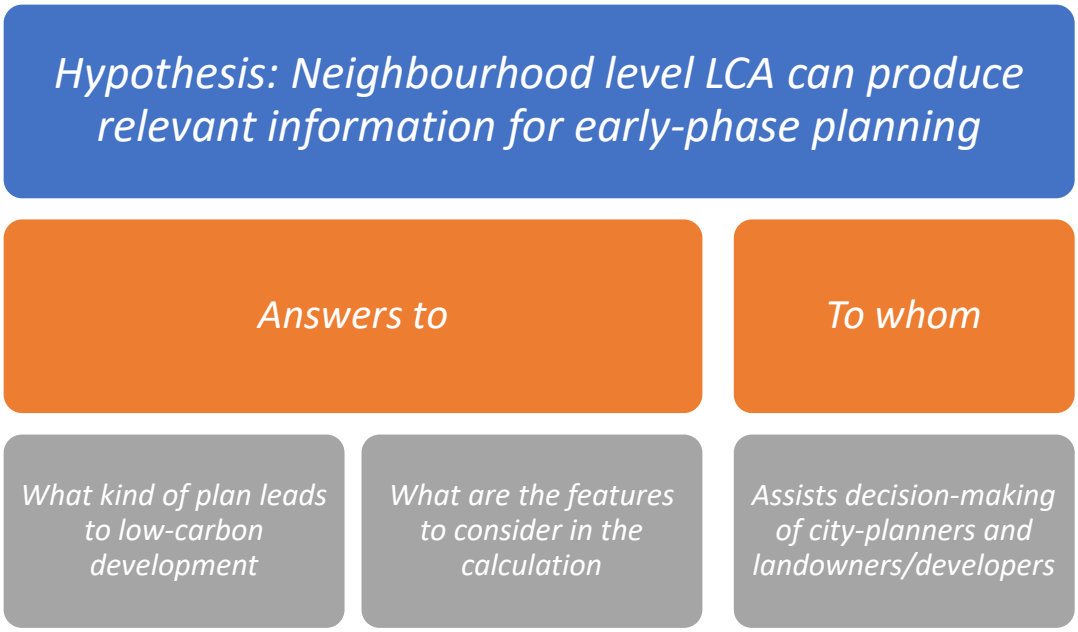


Figure 2 Research hypothesis and relation to decision-making process

Hypothesis is studied via research question and sub-questions presented in the figure below. Main research question "*Can neighbourhood level LCA produce relevant information for low-carbon neighbourhood level planning by verifying the planning solutions which reduce the overall GHG emissions of the plan?*" is testing the hypothesis on general level. Is neighbourhood level LCA useful in general, and can it be used to guide planning process?

Sub-questions are divided to four categories. Firstly, via context questions, to understand environmental assessment field in general by studying different environmental assessment methods, and by studying LCA closer via previously done LCA calculation and best practices learned from them in global and national level. Secondly, LCA questions study why LCA has become popular; is it for example due simplicity or accuracy. Thirdly, regulation questions study if neighbourhood level LCA is compatible with other environmental guidance. Fourthly, comparison questions study Finnish and Norwegian

neighbourhood LCAs to gain more perspective on LCA tools which are used, but also what kind of LCA tools are useful, since they are not homogenous. Lastly, calculation design questions study what should be considered when one does a LCA calculation for neighbourhood development in early-phase and wishes to use calculation results to assist decision making towards low-carbon development.

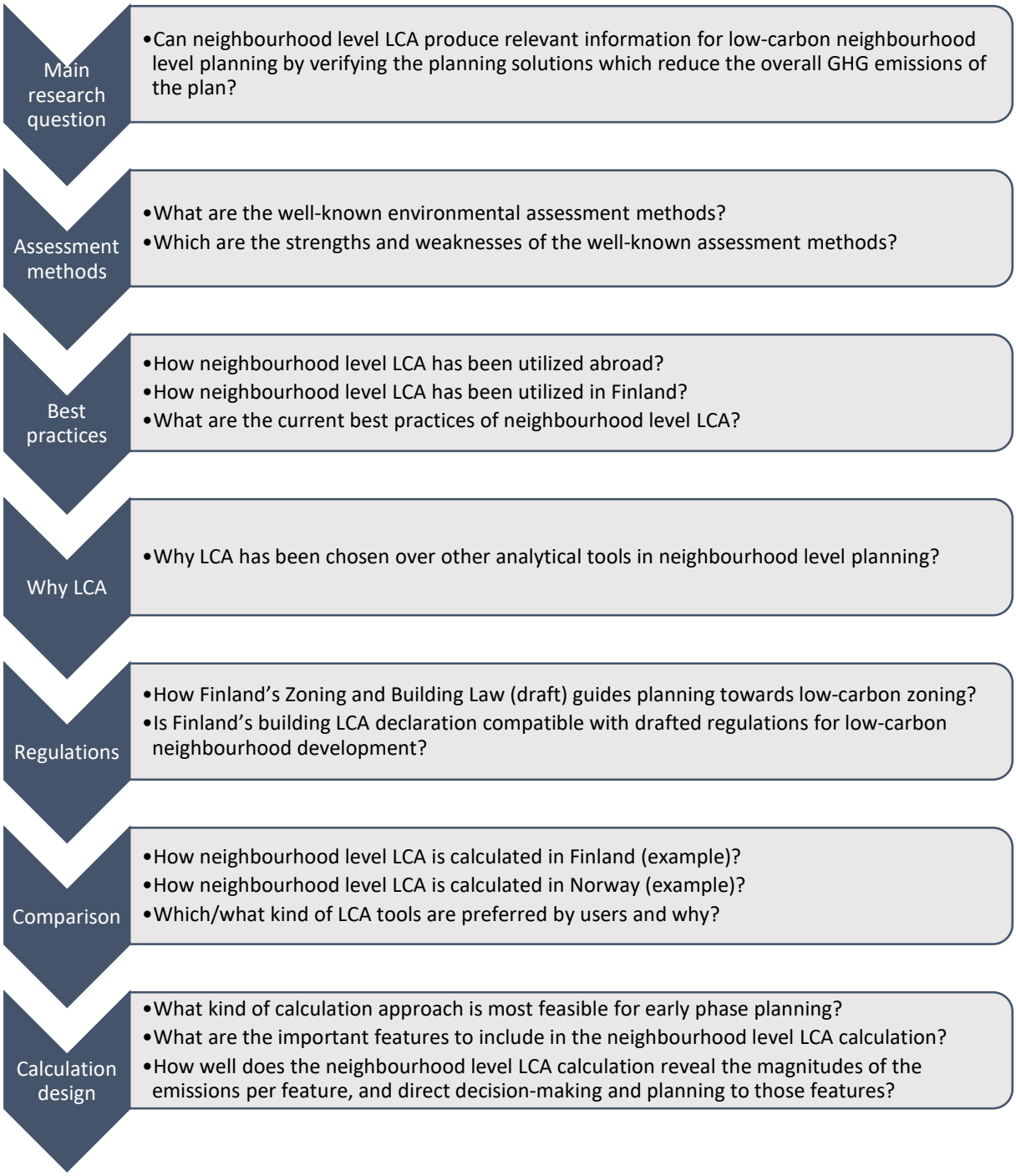


Figure 3 Research question and sub-questions

3.2 Case study method

3.2.1 Why a case study

For this study well-known research methods like experiments, surveys, histories, and archival analyses like economic or statistical modelling, were considered and discarded for various reasons. Experiment research did not suite for the purpose, since the researcher cannot manipulate the events of international, or national LCA calculation decision making. Also, there is no single experiment, which would provide overall understanding of the neighbourhood level LCA and its best practices. Survey research was estimated to have too high probability to produce biased answers of LCA calculations and their results. While at the same time there would have been a problem of getting comprehensive and well justified answers to the complex questions via a survey. History research was abandoned since while LCA methods and calculations have existed for a few decades they are currently under development, as is also the related legislation. Archival analyse was also rejected due to the current development, but as well due to the complexity of the topic, and concern that reports and calculation results would not produce in depth analysis of the situation. However, strength of the study could have been improved by combining different methods, for example survey and case study method, but level of work required the limitation of the used methods.

Case study method is a more resent research method that traditional survey, experimental or history methods. Research method documentation for case study method was done in 2006, and research method have become more popular during past decades in social sciences. Case study method is used for example in psychology, sociology, political science, and community planning. Method is used to study complex social phenomena and/or decision-making process, while wanting to preserve the real-world perspective. (Yin, 2014) Case study method aroused interest in this study, since while a neighbourhood level LCA is a calculation exercise, before and after the actual calculation, it is about planning and policy making. To understand what and why we are calculating, we need to understand how we develop the LCA calculation, and why we have chosen the calculation models we use. In a larger scale neighbourhood LCA connects to decisions of how to measure environmental effects, a complex combination of natural sciences and policymaking.

Table below was completed to ensure the right methodical choice for the study. Left side of the table follows the advice of concepts to consider when deciding whether to do a case study by R. Yin and right-side tests the suitability in this study.

Table 1 Decision over the research method concepts, left column theory (Yin, 2014) and study specific correlation on right column

1. Identify relevant situation to do a case study	
research questions are how and why	• why LCA • how LCA • how LCA can help decision-making
researcher has little or no control over behavioural events	no control over legislation or development of the tools
the focus of the study is contemporary	legislation and tools are new or under development
2. Understand two-fold definition	
scope: a contemporary phenomenon, boundaries between phenomenon and context may not be clear/context is important	• climate targets, EU and national legislation, calculation methods and tools evolve together • local tool for neighbourhood level planning
features: case study design and data collection, more variables of interest than data points, single or multiple cases, quantitative and/or qualitative	• legislation, two approaches to neighbourhood level calculation, two test calculations = 2 examples of LCA calculation utilization • creating one result of usability of LCA in neighbourhood planning
3. Address the traditional concerns over case study	
conducting the research rigorously: literature review, research questions, formal procedures during research, validity, chain of evidence, investigating rival explanations	• literature review • research questions • formal procedures, laws, standardised tools, similar reporting • validity through laws and standards to follow, resent tools, well known tools • evidence chain through different approaches (legislation, current tools, test calculation) • rival explanations through different calculation methods and tools
avoiding confusion with teaching cases, (rigorous and fair presentation of data)	research = explain what data is used, how studied, what does it mean and what not
knowing how to arrive at generalized conclusion if desired, connect to theoretical proposition	what are the important features and indicators, back to literature review, connecting to what we know from the theory

managing the level of effort	two examples, limiting data sources
understanding the comparative advantage of case study research, how and why	NOR-FIN useful comparison, comparison needed for harmonization, complex issues, and context considered
4. Decide whether to do a case study	**yes – concepts necessary for case study can be covered within the study and case study method provides good view to the topic**

3.2.2 Case study design

Empirical research is not just a data collection exercise, but it must include a logical inquiry. Research must have theory, logic, and connection to previous research. (Yin, 2014) Aim of the following section is to ensure the strength of the research design.

There are three different types of case studies as shown in the figure below. Research can combine different types, as is done in this study, where components of exploratory and explanatory case studies are combined. Study starts with exploratory components to study what kind of environmental assessment methods, related legislation and LCA tools we have. Explanatory part studies the tools more thoroughly, to create understanding why the tools are designed the way they are, and how they can be utilized to reach environmental targets on coming decades.

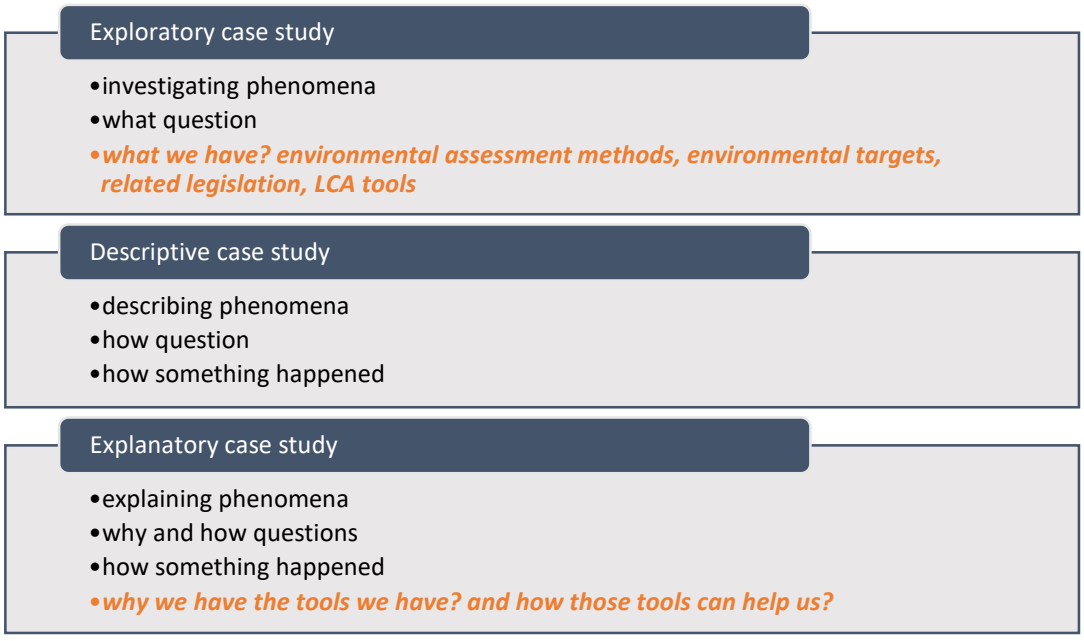


Figure 4 Case study types (Yin, 2014) and connection to this study

Evaluation in a case study is to be done according to four categories presented in a figure below. To ensure a comprehensive understanding of the

topic all evaluation categories are involved in this study. There are explaining, describing, illustrating, and enlightening elements in the study. Fulfilment is illustrated with key elements on the figure below.

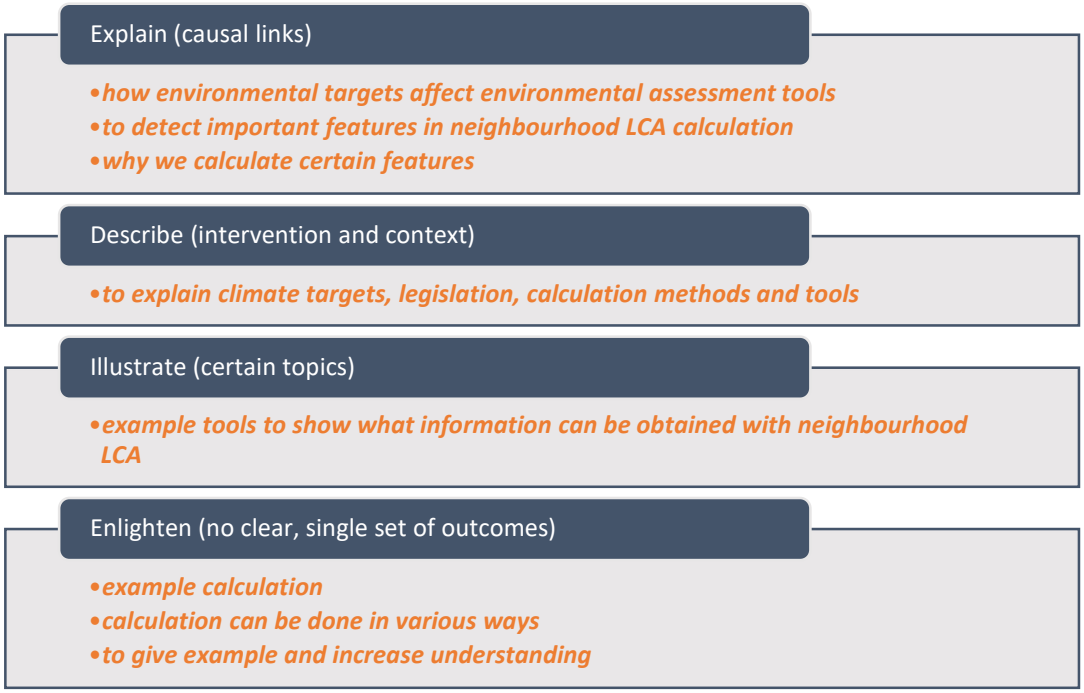


Figure 5 Evaluation categories in case study (Yin, 2014) and connection to this study

Table below goes through the five steps of designing a case study. Table illustrates the design process completed for this study. The five components of a case study design checklist were created to enlighten and justify the choices made for the study protocol, research material and chain of evidence used. There were several possible ways to design the study. For example, tools to be tested, number of tools, and the calculation example could have been different. However, national, and other Nordic example were decided to provide most useful context. During the process example from Sweden was changed to example from Norway since Norwegian example was assessed to provide a better areal LCA tool. Comparison of only two nations, and three tools was chosen, to limit the work and such provide higher quality results from the completed parts.

During the design process a need to complete new calculation examples was questioned. However, it was decided that completing calculations hands-on will most likely provide deeper understanding of how the selected tools function, and such also bring more input on how the tools can be utilized in a decision-making process. Neighbourhood level LCA is a relatively new concept and applying different tools for same calculation example is even more

rare. Such it was decided to be useful to test the calculation within a study and not to rely on third party information of the calculation tools.

Table 2 Five components of a case study design (Yin, 2014) and components for the study in question

Five Components of a Case Study Design	
1. A case study questions	
choosing the research method, how, why, and what questions	covered in the case study method selection table
substance of the questions	• legislation – what required • previous calculations – why and how they have been done • how useful previous calculations were – what was revealed • example calculation – how calculation is done • how different tool compare • how calculation results assist decision-making in early-phase
2. Propositions	
what to study – what we try to prove	LCA can guide early-phase neighbourhood level planning
use of theory to generalize from case study by • analytic generalization, conceptual level higher than the specific case	• compared to findings from literature review, previous research previous cases and their generalizations • results can be according to them or against them
3. Units of analysis	
defining the case(s) holistic (overall nature) / embedded (certain units within the case)	• two cases replication • useful information and reasonable comparison FIN-NOR • differing calculation methods • embedded approach, certain calculation features
bounding the case(s) spatial, temporal etc. boundaries	Finland and Norway specific calculation methods and tools
relevant information • sufficient access to the data • choose cases which illuminate research questions • ensure data from all needed perspectives	• legislation through internet • HAVA tool can be obtained from city of Helsinki • NTNU tool research available • OneClick tools can be bought • traditional infill building development example for calculation

possibility to modify case(s) and relevant information during the process	• Sweden switched to Norway • OneClick calculation tool utilization proposed during the process to add understanding • calculation can be expanded or reduced based on need
4. The logic linking the data to the propositions	
pattern matching, explanation building, time-series analysis, logic models, cross-case synthesis	pattern matching, how well cases resemble each other, how well international best practices
5. The criteria for interpreting the findings	
rival explanations, statistical significance	Rival explanations (literature review and validation discussions) • is it too complicated (or simple) • is it reliable enough • should the calculated features be something else? • should the method (LCA) be replaced? (Added with other)

3.2.3 Quality of a case study design

Quality of a case study design can be assessed through four criteria of validity and reliability according to the table below. Quality of a case study checklist was created to ensure that all four quality features; construct, internal and external validity, and reliability, were addressed during the case study design with at least one feature. However, increased number of cases, adding more evidence sources, or strengthening the chain of evidence would increase the quality of the research. However, to be able to perform the study with reasonable effort the chosen decisions were made to provide good quality while keeping the workload on acceptable level.

Figure 6 Quality of a case study design (Yin, 2014) and fulfillment in this study

4 Methods for assessing environmental effects

4.1.1 Basics of environmental assessment methods

Different methods can be used for monitoring and measuring the past, the current and to simulate alternative futures (Baynes & Wiedmann, 2012). We need to understand magnitudes and impacts of different solutions we use in built environment. In larger scale environmental assessment methods help us to be able to achieve environmental targets, and to do effective climate mitigation acts, when we can compere our options reliably. (Anderson, Wulhorst, & Lang, 2015) Environmental assessment concept has been developed already in 1970s, and assessment is required for example by the European Union with European Directive (2001/42/EC) Strategic Environmental Assessment for large-scale projects. Areal level assessment are often consumption- or production-activity based calculations. (Loiseau, Junqua, Roux, & Bellon-Maurel, 2012)

When comparing different methods Loiseau et al. present five key features to compare to ensure reasonable comparison, comparison process is illustrated in the figure below. There is a wide range of methods, and comparing can be a complex task, such clear process helps to understand the strength and weaknesses of different methods.

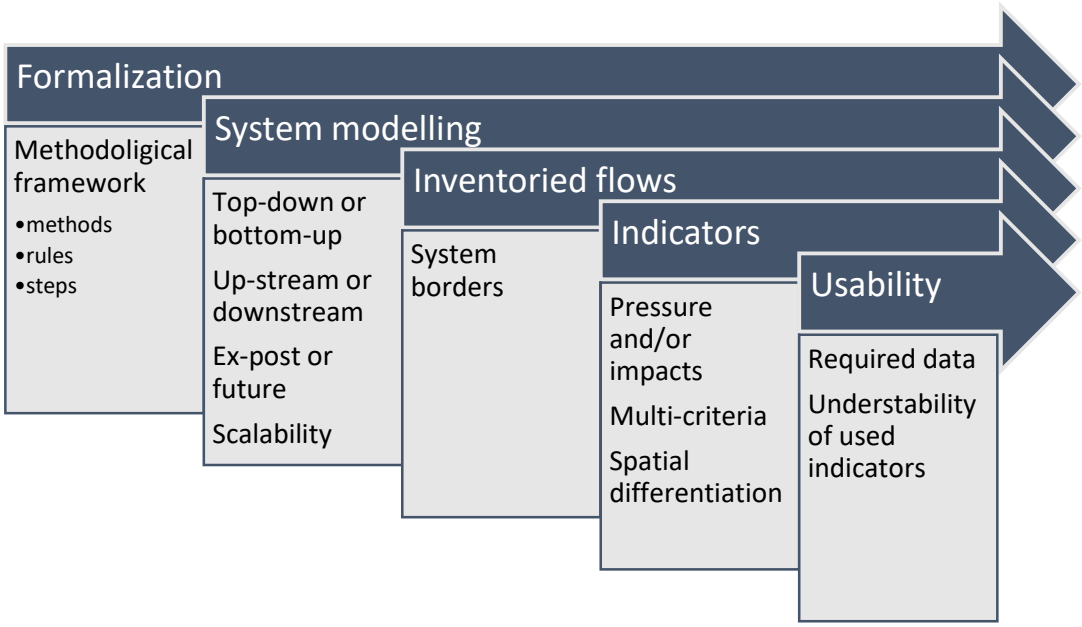


Figure 7 Method comparison process (Loiseau, Junqua, Roux, & Bellon-Maurel, 2012)

There are mainly two kinds of methodological frameworks. The point methods like LEED and BREEAM, giving a relative performance with the scorecard, and the calculation methods which provide the actual values, like

carbon footprint. (Säynäjoki, Heinonen, Säynäjoki, Ala-Mantila, & Pääkkönen, 2014) With methods generality is important, meaning that method is applicable across scales and locations. Examples of widely applicable methods are consumption-based and metabolism-based approaches. (Baynes & Wiedmann, 2012) The following subchapters present well-known environmental assessment methods with scorecard and actual value approach.

4.1.2 Life cycle assessment LCA

Life cycle assessment (LCA) method is defined in the ISO 14040 standard. By the standard LCA consist of four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation. (European Commission, 2022) Also, different organizations have developed specific LCA guidelines to help creating unified LCA utilization in the field. For example, NordFoU which is a co-operation organization between the national Nordic Road administrations to initialize, finance and run R&D projects, provide LCA guide for civil engineering projects. (NordFoU, 2020)

LCA calculates environmental efficiency, by the overall burden, as well as by the impact per functional unit. Calculations include resource flows and emissions resulting from the flows. Calculated indicators are climate change, ozone layer depletion, eutrophication, acidification, human toxicity, ecotoxicity, fossil fuels, minerals, and water. With LCA method emission burden-shifting between indicators can be reduced. All life cycle stages are assessed from cradle-to-grave, and emissions shifting between territories can be avoided when the whole supply-chain is included. However, LCA does not include for example, change in land use, biodiversity, and fresh water. (Loiseau, Junqua, Roux, & Bellon-Maurel, 2012)

First studies of LCA at the building level were published in 1996 in international journals. Number of international publications between 1996 and 2017 was 50 793 of LCA on building and neighbourhood level. However, only 5 153 of those publications were from the neighbourhood level assessments. (Nematchoua, Orosa, & Reiter, 2019) In building and construction product level LCA method is well-defined and commonly used during the past two decades (Lausselet, Borgnes, & Brattebø, 2019) (Lotteau, Loubet, Pousse, Dufrasnes, & Sonnemann, 2015).

Building LCA is calculated for the whole life span based on the upstream emissions. Since buildings are complex systems, comparison between different buildings and their LCA results must be done with care. There may be differences created by building type, location and climate, comfort requirements, local requirements, and regulations. However, similarity of use-phase dominance in created emissions has been noted, when bigger stocks have

been assessed. Use-phase dominance results from energy usage for heating, cooling, and hot water. Use-phase dominance has highlighted the importance of low-energy buildings. However, critic has been presented, that energy issues have gained too significant role in LCA, and that other issues should be studied more. (Lotteau, Loubet, Pousse, Dufrasnes, & Sonnemann, 2015) In recent years when energy production has electrified and use of renewable energy sources has increased there has been seen grown in the importance of construction materials in LCAs. Also, the tightening environmental targets require more strict targets for all life cycle phases in building LCA.

LCA has also been used in urban and other areal level scales, like neighbourhood level. Areal studies can include also features like density, different building use-types, transportation, infrastructure, and consumption. In wider areal scale socio-economic differences create differences in the results and complicate the comparison of the results. (Anderson, Wulhorst, & Lang, 2015) However, for more complex entities like neighbourhoods and city areas there has been done fewer studies and research than for buildings, and such the LCA methods are not as well developed, unified, and commonly used. (Lausselet, Borgnes, & Brattebø, 2019) (Loiseau, Junqua, Roux, & Bellon-Maurel, 2012) However, building, and areal LCA methods have many similarities and one strength of LCA method is the scalability. When deciding the scale of the studied entity one must consider the separation between the scales. For example, when only one building is studied, its role as a part of the city structure and part of the building pattern in the city is ignored. Such, more research between different LCA scales has been recommended. (Anderson, Wulhorst, & Lang, 2015).

Different environmental assessment methods can be combined to cover wider topics and generate information in broader level. For example, LCSA life cycle sustainability assessment combines LCA + social LCA + LCC, including environmental, social, and monetary aspect. Another example, PEF product environmental footprint combines LCA + CA, such also including criticality assessment. PEF includes CRMs (critical raw materials) in CA. Traditional product LCA does not include socio-economic and geopolitical aspects, which can be added with the CA. Change in global relations and upcoming technologies increase the need for CA. (Hackenhaar, et al., 2022) Another option, Hybrid LCA, combines LCA with consumption and metabolism based approaches (Baynes & Wiedmann, 2012).

4.1.3 Examples of well-known international scorecard methods

LEED and BREEAM are point based methods to assess the relative performance of a solution with the scorecard. Methods are also examples of commercial scoring methods, granting certificate to a solution when the assessment is done, and solution fulfils the requirements.

LEED, developed by USGBC origins from the 1990s and most recent version LEED v4.1 is from the year 2019. LEED method provides possibility to assess building design and construction, interior design, and construction as well as building operation and maintenance. Possible scales are buildings, neighbourhood developments, cities, and communities. Entities can be recertificated, and opportunity to aim for LEED Zero is provided. LEED Zero is for projects with net zero goals in carbon and/or resources. LEED for Neighbourhood Development is for projects from planning phase to already existing areas which have been completed within three years. Neighbourhood method aims to improve sustainability and connectivity of the neighbourhood. (USGBC, 2022)

BRE organization origins from 1921 United Kingdom and community has developed methods to assess master planning projects (BREEAM Communities), infrastructure and civil engineering (CEEQUAL), and buildings (New Construction, In-Use and Refurbishment). BREEAM communities include assessing economic, social, and environmental sustainability in master planning level. (BRE, 2022)

4.1.4 Examples of input-output tables and variation methods

Input-output tables IOTs method has been developed by Leontief in 1930s (Heijungs & Suh, 2002). Method was first used to present direct and indirect monetary flows between different sectors. IOTs is scalable for different levels like economy sectors, nations, and economies. **Physical IOTs** present material flows between the entities. Method has been extended with environmental aspect, estimating the pollutants and natural resources per produced unit. However, IOTs have been criticized of lack of subcategories, and such the results have lacked good usability, since they have not been able to assist decision-making sufficiently. Also, lack of adequate data in the tables have created problems when using the method. (Loiseau, Junqua, Roux, & Bellon-Maurel, 2012)

Ecological network analysis ENA is an example of physical input-output table, which aims to rationalize material use in a studied area. ENA includes material flows and ecosystems. Model consists of network of nodes and links. Link features are lengths and directions of transactions. Both, direct and indirect flows are included in the model. ENA is often done in a city level. Method is also scalable for smaller spatial areas. Using ENA in regional or larger scale is uncommon. (Loiseau, Junqua, Roux, & Bellon-Maurel, 2012)

Lotteau et al. define **consumption-based approach CBA** as an environmentally extended input-output analysis (EE-IOA) including direct and indirect water and energy use, ecological footprint, and GHG accounting

(Lotteau, Loubet, Pousse, Dufrasnes, & Sonnemann, 2015). CBA is calculated with emission flows connected to the end-consumers. Aim is to study economy-wide impacts, urban consumption, and urban-lifestyles. Results provide information of urban residents and environmental impacts. CBA is scalable method, possible calculation scales are for example individual, city, or national level. CBA is not limited to certain territory, but includes all consumption of the selected users, despite of the region, where the consumption takes place. CBA is an ex-post method, meaning that it assesses the emissions flows from the past, and can such be used to study for example the effect of the past policies. Results may show if the policies have been significant for the change of lifestyles and consumption patterns in economy-wide level, and such the past policy decisions can guide the future policies based on their effectiveness. However, CBA does not provide direct representation of a territorial economy, since it includes only consumption, not production, and the consumption also includes goods and services outside of the residential area. Such, CBA does not provide enough information for urban land use planning as such. Also, when assessing the results, the effect of the data, and its' possible errors must be considered. (Baynes & Wiedmann, 2012)

4.1.5 Material and energy flow analysis and variation methods

Material and energy flow analysis MEFA studies material and energy balance in system, via material and energy inputs and outputs, i.e., flows and stocks. In the model are included flows to and from anthroposphere, i.e., the human made part of the environment, as well as to and from ecosphere. Method measures environmental damage in correlation to material flows. However, assessment of indirect flows has often been limited. Method has been criticized for its' accuracy. Environmental damage has in the past been estimated similarly for different materials, which does not provide truthful results. Also, the amount of input and output data has been insufficient, which has resulted to limited reliability of the results. Accessibility and completeness of proper data is affected by the need of regional data, which is not always available or is out-dated. (Loiseau, Junqua, Roux, & Bellon-Maurel, 2012) Method has also been criticized of not providing usable results to support policy decision making, which has been the target. However, MEFA has highlighted the need to decouple social wellbeing and material usage, i.e., promote dematerialization. (Loiseau, Junqua, Roux, & Bellon-Maurel, 2012)

MEFA has been developed further as **metabolism-based approach MBA.** Method includes material, water, waste, and energy flows for consumption and production. Also, the number of indirect and cross-boundary flows has been increased. (Lotteau, Loubet, Pousse, Dufrasnes, & Sonnemann, 2015) MBA uses direct data for the mentioned flows. Increased number of flows creates increased requirements for amount and quality of the used data. However, like in MEFA, in MBA up-to-date and location

specific data is not always available, which creates error and uncertainties in the results. On advantage, MBA has a good scalability. Method is applied within spatial and geopolitical boundaries, meaning that it is scalable for example to household, neighbourhood, metropolitan, or country level. MBA is an ex-post method, and such it can be used to assess efficiency and effectivity of past policies. While CBA lacks useful information, since production feature is not included, in MBA production is included. Such, it can better be used for economy and spatial planning. For example, when applying MBA to spatial areas there has been found repeating differences on flows of food, waste, construction materials and fuel consumption and production correlating with the density in the area. (Baynes & Wiedmann, 2012)

4.1.6 Other actual value environmental assessment methods

Human and environmental risk assessment HERA studies a likelihood of harmful effects in the area for humans and environment. (Loiseau, Junqua, Roux, & Bellon-Maurel, 2012). HERA was developed by the American Academy of Science in 1980s (INERIS, 2003) in (Loiseau, Junqua, Roux, & Bellon-Maurel, 2012). Nowadays for example EU recommends and guides the use of HERA in The Commission Directive 93/67/EEC (Loiseau, Junqua, Roux, & Bellon-Maurel, 2012). HERA is calculated with identifying any substances in the area, which create harmful effects. Aim is also to find any additional sources of pollution, as well as possible measures to decrease the pollution and risk level. (Copin, Chèvre, Charles, Klein, & Margni, 2008) HERA is multicriteria study, and such provide overview of human toxicity and ecotoxicity in the studied area. While HERA is most often calculated in local level, it is scalable method. (Wegener Sleeswijk, 2010) in (Loiseau, Junqua, Roux, & Bellon-Maurel, 2012) However, method studies only toxicity, and interactions between toxic substances have not been studied. (Wegener Sleeswijk, 2010) in (Loiseau, Junqua, Roux, & Bellon-Maurel, 2012). Also, HERA has been noticed to enable problem shifting from substance or impact to other, depending on the system boundaries. Results have been detected to include lot of uncertainties, though that is common with many environmental assessment methods requiring lot of data. (Loiseau, Junqua, Roux, & Bellon-Maurel, 2012)

Magnitude of pollution in given area is studied also in **Substance flow analysis SFA.** Method does not provide exact amount of pollution, but approximation, and enables magnitude level comparison. Aim is to detect problematic substances, inflows, outflows, and stocks. Calculation is done in given area and in given time, and studied area is presented with the features, i.e., study area is not a black box. However, like HERA, also SFA has been criticized for allowing problem shifting between substances and impacts, if system borders have been set to limit some substances out of the scope of the study. (Loiseau, Junqua, Roux, & Bellon-Maurel, 2012)

In 1990s Wackernagel and Rees developed **Ecological footprint EF** method (Ayres, 2000). Rees defines EF as a capacity of a habitat, where capacity presents population, the habitat can support without permanently harming the ecosystem (Rees, 1992). EF presents consumption patterns and pressure humans create to the environment. Method can be used to compare different spatial areas like regions and territories and their performance. However, used measuring unit, the global hectare and its usability has been criticised. Method has been detected to include also other shortages. EF does not include for example different land categories, pollutants, toxic substances, biodiversity, technologies (heavy machine farming), diffuse pollution or land degradation. (Loiseau, Junqua, Roux, & Bellon-Maurel, 2012)

4.1.7 Energy based methods

Exergy was developed in the end of 1950s (Sciubba & Wall, 2007). Method calculates the part of the system energy which can be converted to other forms of energy, such presenting the maximum quantity of work, which can be obtained from the system. Obtained energy can then be converted to other system. Obtained energy is presented in joules. (Dewulf, et al., 2008). Aim of the method is to study different energy sources in the overall system. Exergy can be used to improve energy performance and resource availability. Method does not include environmental effects; however, method can be extended to include for example GHG emissions. More complex indicators like biodiversity and land use change cannot be included. (Loiseau, Junqua, Roux, & Bellon-Maurel, 2012)

Emergy was develop in 1980s by H.T. Odum (Brown & Ulgiati, 2004). Emergy is a top-down method. Method calculates the previous work, i.e., used energy which is needed to produce a product or a service. Emergy include both, energy used by nature or human production. Method includes created emissions. Results describe resource independency of a study area, as well as the area's interconnections with the environment. Aim is to better understand resource and energy use in the given area when environmental services are included. (Loiseau, Junqua, Roux, & Bellon-Maurel, 2012)

4.1.8 Complex system approach

Lotteau et al. define **complex system approach** as a method to reveal underlying dynamics in a system. Complex system approach includes nodes and links, attributes' effectiveness, and the relationships as well as feedback loops between the attributes. (Lotteau, Loubet, Pousse, Dufrasnes, & Sonnemann, 2015) Method can be used to describe systems like housing, employment, land use, transport, urban growth, and their interactions with climate. Method is also scalable. System can be extended to include for example used

materials, energy, waste, and water. Method can also be used to present the emissions created by the system. (Baynes & Wiedmann, 2012)

Method is used to present cause-effect relations. However, complex system approach modelling does not present exact results. Aim is to create understanding of the system, not provide exact values. Method can assist policy making. Policies are often non-additive, and such better understanding of cause-effect relations may help to increase effectiveness in multi-feature system. However, while complex system approach may be useful for future planning, modelling and used data are likely to cause uncertainties and errors to the results, which must be considered in the utilization of the results. (Baynes & Wiedmann, 2012)

4.1.9 Environmental assessment methods summary

A key principle of methods and models, the system borders, repeats with the environmental assessment methods. Method assesses only a part of a reality. Borders can for example relate to number of features, spatial or timely restrictions. When using a method, one needs to ask, what is a scope and a target of the method, and where the borders can be set, to provide most useful, but accurate enough results. In many methods features like history, geography, biodiversity, or urban ecology, may not be addressed (Baynes & Wiedmann, 2012). Such in addition to an assessment method, a location specific assessment may be needed to be able to evaluate the area specific results (Baynes & Wiedmann, 2012). Effects to human health and ecosystem quality are often excluded from the assessment methods and need to be assessed separately (Loiseau, Junqua, Roux, & Bellon-Maurel, 2012).

Also, understanding what the method and its results do provide, and what not, is crucial for a good assessment. For example, a life cycle approach prevents emissions burden shifting between stages. Also, a multi-criteria approach prevents problem-shifting from impact category to other. Included spatial covering affects the results the calculation provides. A regional aspect is enough for local effects, while covering the whole supply-chain is needed, if global effects of solutions are wanted to be included. (Loiseau, Junqua, Roux, & Bellon-Maurel, 2012) Also, different methods have complementary features, and such it can be beneficial to combine different methods to one assessment. For example, LCA, CBA and MBA are complementary (Anderson, Wulhorst, & Lang, 2015). CBA, MBA, and complex systems are suggested to be combined (Baynes & Wiedmann, 2012). As well as HERA and LCA (Loiseau, Junqua, Roux, & Bellon-Maurel, 2012). However, a tool that is simple and easy to use has a better possibility to be adopted to a wide public use (Weidema, Thrane, Christensen, Schmidt, & Løkke, 2008). When doing an assessment, the goal and scope need to be defined to understand what a proper complexity for the assessment is.

To provide a reliable and realistic results all methods, and tools based on them, require large quantity of high-quality data. Lack of proper data increases the uncertainty and errors in the results and may lead to reducing the scope of the assessment. (Loiseau, Junqua, Roux, & Bellon-Maurel, 2012) The problem of availability or access to proper data; up-to-date, area specific, level-of-detail, is one of the potential weaknesses of all environmental assessment methods. Results of a calculation methods are only as good as the data used in the process.

Below is presented a summary table of some of the most used environmental assessment methods. Summary table follows the structure of method comparison process presented earlier in this chapter. Comparison of different methods is however challenging, and information of different methods is limited in the table. Table presents key elements of formalization, system modelling, inventoried flows, indicators, and usability of eight well-known environmental assessment methods; LCA (life cycle assessment), LEED certification, BREEAM certification, IOTs (input-output tables), CBA (consumption-based approach), MEFA (material and energy flow analysis), MBA (metabolism-based approach), and HERA (human and environmental risk assessment).

Table 3 Summary of well-known environmental assessment methods

	Formalization	System modelling	Inventoried flows	Indicators	Usability
LCA	actual value	up-stream scalable	resource emissions	climate change ozone layer depletion eutrophication acidification human toxicity ecotoxicity fossil fuels minerals water	requires lot of accurate data several clear indicators prevents problem shifting
LEED	scorecard	scalable		points	easy to compare overall performance
BREEAM	scorecard	scalable		points	easy to compare overall performance
IOTS	actual value	top-down	monetary material pollutant natural resources	monetary units material units pollutant units resource units	requires lot of accurate data lack of subcategories
CBA	actual value	ex-post scalable	water energy GHG	emission flow per consumer ecological footprint GHG accounting	direct and indirect flows no territorial representation requires lot of accurate data
MEFA	actual value	ex-post scalable	material energy	environmental damage in correlation to material flows	indirect flows not included requires lot of accurate data incorrect weighting of materials
MBA	actual value	ex-post scalable	material water waste energy	environmental damage in correlation to several flows	some indirect flows requires lot of accurate data
HERA	actual value	scalable	harmful substances	human toxicity ecotoxicity	lacks interconnection between substances enables problem shifting

5 Best practices of international neighbourhood level LCA

5.1.1 Basics of neighbourhood level LCA

Neighbourhood level is often used as an operational scale for urban development projects. Neighbourhood level is also an effective level when planning for urban density, mobility, shared systems like energy and heating systems, as well as for ecological features like eco-design and bioclimatic design. However, in 2015 Lotteua et al. compared the case studies of 14 cases on 21 papers, those being all sufficient case studies available at the time for their research. While neighbourhood level LCA is not that commonly used and relatively new concept, LCA calculation as process is well-know and commonly used. According to the standardized process LCA calculation includes four phases presented on the figure below. Process is designed to produce quantitative information to assist planning and decision-making. (Lotteau, Loubet, Pousse, Dufrasnes, & Sonnemann, 2015)

Figure 8 Life cycle process (Lotteau, Loubet, Pousse, Dufrasnes, & Sonnemann, 2015)

Neighbourhood level LCA can be executed for various reasons, which is why the first phase, goal and scope definition is highly important, for the results to fulfil the information demand for the specific case. Method can be used for existing and planned areas, as well as for model neighbourhoods. Imaginative cases can be used for creating information of current or possible situations and to improve general knowledge of the neighbourhood LCAs or the method in general. (Lotteau, Loubet, Pousse, Dufrasnes, & Sonnemann, 2015) Also, the need to assess areas on different scales has been brought up, to enable the improvement of the whole built environment system (Allende & Stephan, 2022).

Due to the different scopes, neighbourhood level LCA calculation have different system boundaries and functional units. Figure below presents one possible classification of scope.

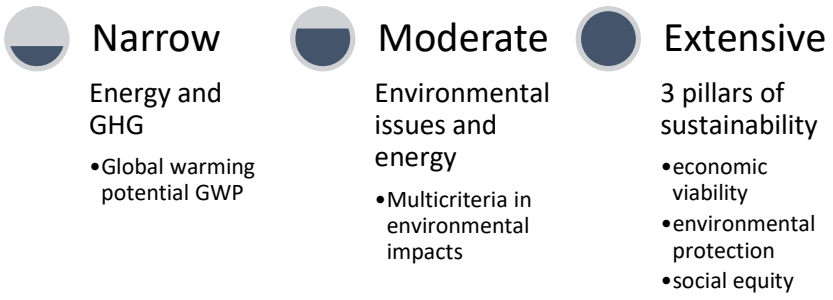


Figure 9 LCA scope classification (Lotteau, Loubet, Pousse, Dufrasnes, & Sonnemann, 2015)

Complex nature of built environment and areal assessment in the LCA has been recognized. Many neighbourhood LCAs have limited the calculated flows based on process-based approach. Process-based analysis have been criticised of underestimating the embodied energy created with the project. Embodied energy includes operational and transport energy and related GHG emissions. Proposed additions to calculation have been also including the whole supply chain and flows like water, and energy needed for hot water. (Allende & Stephan, 2022) In the figure above the inclusivity of different sustainability aspect increases from left to right. Despite of the calculation scope indicator/s should be clearly stated. Possible indicators are for example number of inhabitants or total floor area etc in correlation to environmental burden, like GWP. (Lotteau, Loubet, Pousse, Dufrasnes, & Sonnemann, 2015)

LCA has been developed as multicriteria method to avoid problem shifting. However, it has been noted that many studies are done with energy and climate change attributes, providing only the GWP indicator. Many impact and damage attributes like land use, urban morphology, vegetation, air quality, surface materials, urban heat islands and mineral resources depletion are excluded. However, these all are attributes, which have been brought up as potential extensions of the method and would be important for the urban sustainability. (Lotteau, Loubet, Pousse, Dufrasnes, & Sonnemann, 2015).

However, development projects are often calculated with GWP indicator to keep the calculation manageable. Strategic framework and a tool to clarify the life cycle energy and GHG calculation in green or sustainable development is needed. Unified framework would support existing regulations and unify the flows include in the calculations. (Allende & Stephan, 2022) Anderson et al. propose neighbourhood level LCA framework which is divided into building and transport part and to their embodied and operational impacts. Framework is presented in the figure below.

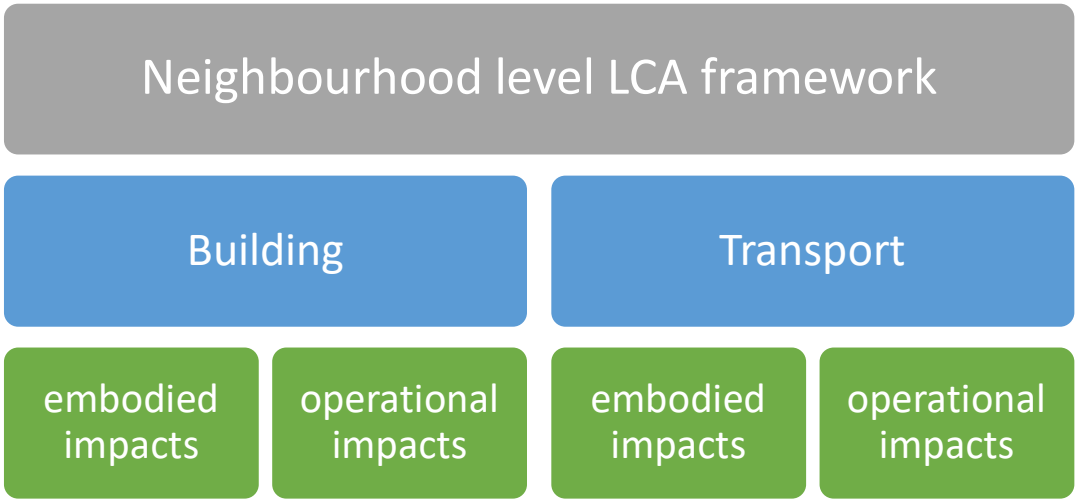


Figure 10 Neighbourhood level LCA framework (Anderson, Wulhorst, & Lang, 2015)

To ensure the claimed environmental benefits, built environment should be modelled via systems-thinking approach. The concept of green or sustainable development project in urban planning is currently not clearly defined. IPCC uses NZEB net-zero energy building definition for building energy efficiency, meaning that a building generates as much energy with renewable energy sources, as it uses within a year. Energy efficiency definitions focus on use phase of a building, while embodied energy in buildings and infra, as well as use phase transport should also be assessed. (Allende & Stephan, 2022) Transportation has been noted to have a significant role in GHG, in use phase, as well as built infrastructure (Anderson, Wulhorst, & Lang, 2015).

It has been argued that user mobility should be included in LCA studies to increase the role of induced impacts. Induced impacts describing the interactions between individuals and buildings. It has also been suggested that this kind of mobility studies could be included to building level scorecard methods of LEED and BREEAM to shift the focus from building's operational performance towards more comprehensive analysis. However, some of the completed mobility assessments have been criticized for lacking understanding of difference between travel distance and accessibility. Mobility should be assessed via distance, mode, and speed, since there has been noted a weak correlation between density and travel behaviour, when factors like accessibility and street network have been excluded. Also, embodied emissions of travel infrastructure and vehicles should be included in the transportation LCAs. (Anderson, Wulhorst, & Lang, 2015) Also, variation between different spatial areas is well-known in spatial planning. Life-style choices and family sizes create differences between areas. For example, high- and low-density areas provide different results and calculation interpretations must be done with care. (Anderson, Wulhorst, & Lang, 2015) Also, the aspect of regional

differences should be considered in the used data and in result interpretation (Lotteau, Loubet, Pousse, Dufrasnes, & Sonnemann, 2015).

LCA includes whole life cycle, the cradle-to-grave approach, however, the proper life cycle duration is not unambiguous. Often used cycles are 50 and 60 years, and cycles up to 100 have been used. Long cycles create the problem of increased uncertainties in the results. Technologies develop during decades, and these will affect for example electricity production and its emissions. Technological developed can be included in the model, however, future predictions are only suggestive. It has been recommended that uncertainty analysis should be completed for critical attributes which are prone to changes during the used life cycle. (Lotteau, Loubet, Pousse, Dufrasnes, & Sonnemann, 2015)

5.1.2 Variations of neighbourhood level LCA

LCA has been suggested to be applied in early-phase planning. Lausselet et al. developed an **early-phase planning LCA** model for neighbourhood level calculating GHG emissions and consisting of five elements: buildings, mobility, open spaces, networks, and on-site energy infrastructure.

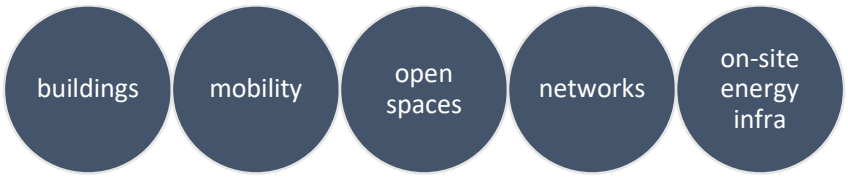


Figure 11 Early-phase LCA model (Lausselet, Borgnes, & Brattebø, 2019)

Proposed system boundaries separate from previous research and examples and differences have created significant impact on the end-results. The model was applied for a case study in Norway, but the methodology and system boundaries are designed to be applicable for any early-phase neighbourhood development. (Lausselet, Borgnes, & Brattebø, 2019) Previously it has also been suggested that statistical data, not project specific, could be used in early phase planning to simplify early-phase calculations. (Lotteau, Loubet, Pousse, Dufrasnes, & Sonnemann, 2015).

Lausselet et al. detected the two parameters, travel distance per inhabitant and the buildings' energy load to have significant impact on results due to the large sensitivity ratio. Most important uncertainties were created by the future electricity emission intensity (g CO2-eq/kWh) as well as future technologies in relations to buildings, infrastructure, and mobility. Also, the temporal distribution of environmental impacts created significant uncertainties. In the study was also discussed the uncertainties created by the climate change. The forecasted climate change is expected to decrease heating energy

consumption and to increase cooling energy consumption. Changes are estimated to end in a net increase of energy consumption. (Lausselet, Borgnes, & Brattebø, 2019) Norway case study and this method will be studied more in the case study section.

5.1.3 Land use and transportation variations

Buildings create primary and secondary **land use impacts**. Primary; building footprint; including land use change for the projects, changes during the project, and changes after the project. And secondary; resource extraction, production, transport, and end-of-life treatment of construction products. Trigaux et al. used the MMG method, developed within Environmental profile of building elements research project, which provides results as individual impact indicators and with combined monetary value. Results, including buildings and road infra, open spaces (for primary stage), energy, and water, detected that primary and secondary impacts created impact of same magnitude. However, study brought up the uncertainties related to MMG method's monetary values. Trigaux et al. suggested that primary impacts of land use should be included in the neighbourhood level LCA. More precisely primary impacts consist of two parts. Firstly, land use occupation; calculated via soil quality and biodiversity, and secondly land transformation at the beginning, during and after the land occupation. (Trigaux, Allacker, & De Troyer, 2017)

Chester et al. combined transport and land use impacts in their LCA study. **ITLU-LCA** (integrated transportation and land use life cycle assessment) combines life cycle and behavioural assessment. Impact features in the study were energy, GHG, human health respiratory and smog formation. Study compared 4 scenarios of different density with TOD (transit-oriented development). Land use availability was analysed via GIS analysis, and LCA was calculated for building design, building construction, and building use phase. Transportation energy and environmental assessment included GREET1 (fuel cycle model) and GREET2 (vehicle cycle model), providing the amount of used energy and produced air emissions. Behaviour analysis for transport changes related to each TOD were estimated according to behaviour on current LRT areas. Household travel mode shift was estimated with bounding analysis, concluding to shorter trips in dense areas. Commercial trip reduction for mixed use buildings was estimated with Nelson-Nygaard 2005 method, providing approximately 20 % fewer vehicle trips compared to suburban choice. TOD design increased the reduction further with 30 to 40 % difference between BAU and TOD. (Chester, Nahlik, Fraser, Kimball, & Garikapati, 2013)

Highest energy and emission impacts features were cars (22-51 %) and buildings (22-44 %). Different TOD scenarios provided different results for life-cycle phases, for example high density resulted to higher construction effects

and smaller effects during use phase. Upstream effects (26-30 %) were noted to be significant, meaning that there are significant number of emissions created also outside the study area. Couple of other important notions were done from the results, car trip emissions were estimated with petrol cars, not electric cars. Also, monetary saving in scenario 2-4(denser building) was calculated and estimated to approximately 9 000 $ per household per year. However, it was noted that to result in the predicted modal shift in denser areas additional incentives might be needed. (Chester, Nahlik, Fraser, Kimball, & Garikapati, 2013)

5.1.4 Comprehensive energy LCA framework

Stephan et al. created a **comprehensive LCA energy analysis framework** for residential buildings. Framework is an input-output-based hybrid analysis, utilizing IOTs and process data. For the framework a new tool was coded with Python, and Buzhug was used for regional variables and energy data and to allow the user to edit and add data. Software included approximately 400 input parameters to allow the user to make case specific modifications to the calculation. Parameters included for example, building geometry, structure, envelope, systems, finishings, as well as areal features like building's urban location and generated car transportation. (Stephan, Crawford, & de Myttenaere, 2012)

Energy analysis for buildings most commonly include operational energy, however, it has been noticed, that embodied energy and transportation energy can cover 50 % of buildings energy consumption during life cycle. Such, comprehensive framework must include embodied, operational and transportation energy consumption. In the framework embodied energy consists of building's energy for raw material extraction, manufacturing, construction, maintenance, and replacements. Analysis was extended to areal features like energy of nearby infrastructure, consisting of roads, power lines, water, gas distribution, and sewage. Operational energy in the framework includes building operations and use stage. Use stage including energy consumption for heating, cooling, ventilation, lighting, domestic hot water, cooking, and appliances. User transportation energy consumption was calculated with direct consumption including fuel etc., as well as indirect, consisting of vehicle and infra production and maintenance. Demolition phase was not included in this study. (Stephan, Crawford, & de Myttenaere, 2012)

Comprehensive LCA energy analysis was developed to a MSLCEA (multiscale life cycle energy analysis) and possibility to utilize via tool called Energy Metric (Beta 0.2). Analysis includes embodied and operational energy consumption and GHG emissions for buildings, operation, and transport. Analysis can be done in various scales from single buildings to neighbourhoods

and includes scenario options for example for energy sources and mobility patterns. (Allende & Stephan, 2022)

Allende & Stephan utilized the tool for a green development in Nightingale Village in Melbourne. In the results energy demand divided to embodied 31 %, operational 35 % and transport 34 %, which confirmed the need to study the whole life cycle and all features to gain proper results. In the study was also made couple of important notices. Green development uses only electricity in the operational phase, and such emission reduction are highly dependent on the electricity production's emission reductions. However, it was found out that with low-energy development building material and additional technologies embodied energy increased by 17 % and GHG by 30 % during the life cycle. In transport significant effect was noted with decrease of use of private vehicles, 25 % reduction in use of private vehicles accounted for 15 % reduction in energy and GHG. Uncertainties during the life cycle in relation to technological development were noted, possible changing parameters were for example energy conversion factor for electricity, energy efficiency of appliances and energy intensity of transport. (Allende & Stephan, 2022)

However, in the results it was highlighted, that none of the studied solutions was a net-zero solution. Features like raw material extraction, manufacturing, construction processes and embodied energy in renewable energy solutions create emissions. Also, it was important to notice, that when consumption of operational energy was reduced, there was offsets in other impact categories. Results visualized why it is important to demand a comprehensive analysis of a project which is claimed to be a net-zero development, and to prevent problem shifting. Furthermore, in the results was touched on the relation between green developments and reaching the IPCC emission threshold which is under a strict timeline during the coming decades. (Allende & Stephan, 2022)

5.1.5 Comparison of Belgian neighbourhoods with Nova-EQUER

In Belgium has been done neighbourhood level LCA studies with Nova-EQUER environmental quality assessment tool. Nematchoua & Reiter studied influence of mobility choices and on-site energy production (2019). Nematchoua, Orosa & Reiter studied a comparison of an old traditional and new eco-neighbourhood (2019). And Nematchoua, Asadi & Reiter studied a comparison of urban and suburban neighbourhood (2020). Studies were completed by using ALCYONE; for geometrical presentation, COMFIE-PLEIADES; for thermal simulation and nova-EQUER; for environmental analysis. Environmental data was according to ECOINVENT 2.2. Used software are well-known and used by many international research laboratories. (Nematchoua, Orosa, & Reiter, 2019) Indicators in the studies were

according to twelve (12) LCA impacts: (1) greenhouse effect, (2) acidification PA, (3) cumulative energy demand, (4) used water, (5) produced waste, (6) depletion of abiotic resources ADP, (7) eutrophication PE, (8) production of photochemical ozone ODP, (9) damage to biodiversity, (10) radioactive waste, (11) damage to health DALYs, and (12) odours OTV. (Nematchoua, Orosa, & Reiter, 2019)

In the study of **influence of mobility choices and on-site energy production** in neighbourhood LCA was used additional data of for example energy mix, mobility of users, constitution of outdoor spaces and networks. Mobility assumptions in the study included two scenarios, BAU scenario, and urban site scenario. In BAU scenario home-to-work trip (20 km) was done by car and by 80 % of the occupants, while in urban site trip (2,5 km) was done by bus and by 100 % of the occupants. Weekly shopping trip (5 km) was also done by car in initial scenario, while on urban site it (300 m) was done by bike or foot. Electricity assumptions in the study included two scenarios, BAU scenario, where all electricity was supplied by the Belgian electricity grid, and production impacts were considered. In photovoltaic scenario there was photovoltaic system on all roofs, covering two thirds of the available roof space. Climatic conditions were assumed to be according to the current situation when there is no need for cooling system in residential buildings. The scenario panels were mono-crystalline photovoltaic solar panels. Orientation was assumed to be optimal in Belgium, south and inclined 35 °. With the assumptions above results revealed that at the neighbourhood area, during the entire life cycle sustainable mobility can lead to reduce of 4 % to 50 % of each of the twelve environmental impacts considered. In case of the photovoltaic panels' reduction was up to 25% of GHG. However, proposed scenario increases 18 % the damage to biodiversity and 21% the waste production. (Nematchoua & Reiter, 2019)

In the study **comparing an old 19th standard neighbourhood and a new eco-neighbourhood**, climate comparison scenarios according to the IPCC future scenarios were used. The study used Meteonorm; for meteorological modelling, showing that climate change has a significant effect on both neighbourhoods. Used features in the study were: building materials, energy, water, waste, mobility, rainfall, open spaces, lighting, green spaces, streets, and climatic data for past, current, 2020, 2050, 2080 and 2100 scenarios. (Nematchoua, Orosa, & Reiter, 2019)

All four life cycle phases were noted to have significant environmental impacts, but in both cases use phase contributed to major share (70–90%) of environmental impacts in the 12 categories. Transportation contributed to significant share of emissions, with 45.9% of gas used during the operation phase. Results showed that the environmental impact rate per occupant is

69.6% higher in standard than in eco-neighbourhood. In the study was estimated that renovation of old residential buildings could reduce the environmental impacts up to 30 %, which demonstrates the importance of renovating existing buildings. However, the twelve impacts categories do not act similarly between the options. For example, CO2 emissions were 36.6% higher in an old neighbourhood than in an eco-neighbourhood. However, in impact category OTV, the impact value was double for the eco-neighbourhood compared to old one. Also, during the construction phase, radioactive waste and wastewater impacts were higher in the eco-neighbourhood. Also, it was noted that a presence of water retention system can reduce the environmental impacts significantly. With the case study reductions were eutrophication (68.1%), waste production (31.3%), acidification (28.7%), damage to health (21.3%), photochemical ozone production (16.6%) and GHG (9.3%). The amount of clean water saved was more than 6 000 l per person per year, concluding to 14 % decrease in water usage during the life cycle. When the runoff water is not directed to drainage system and to treatment plants, waste production decreased additional 7 % during the life cycle, and 15 % during the use phase. (Nematchoua, Orosa, & Reiter, 2019)

In the study **comparing urban and suburban neighbourhoods,** additional mobility data was gained from BELDAM mobility studies in Belgium, and interviews with occupants. Used features were materials, equipment, heating, construction area, roads, public spaces, water management, renewable energy, mobility, urban and suburban life cycle. Aim of the study was to especially assess the impact of storm water management, density, mobility, management of unoccupied space, and the use of renewable energies and their effect on environmental impacts on neighbourhood area. Results revealed that in acidification, waste product, eutrophication, photochemical ozone, biodiversity damage and health damage have greater impact on suburban than urban area. When results were considered by dwelling units, all twelve impact categories have greater effect on suburban than urban neighbourhood. (Nematchoua, Asadi, & Reiter, 2020)

Possible reasons for greater impact were estimated to be large living area and low density in suburban area. The results revealed that the impacts of the use phase were most significant. However, behaviour of individuals is hard to predict, and behaviour has significant effect on energy consumption and such the LCA results. Also, density is related to the transportation options in the area, and such to daily trips made by the occupants. For overall environmental effects the length of daily trips made by the population, or the presence of public transportation and bike path had no great influence. Most significant impact was detected with the production of photochemical ozone. Results were acquired with comparing base scenario to scenarios 1, 2 and 3, for which the paths were longer, and such the ODP increased. However, complete

transport simulation was not done in the study, used simulation tool does not present reality in all features, also journey types and effects of weather conditions were limited in the tool. (Nematchoua, Asadi, & Reiter, 2020)

5.2 Community level ecological tools in Finland

5.2.1 Role of city planning phase in reaching climate targets

A study lead by Aalto University and funded by Sitra and Ministry of Environment, studied the possibilities of detail planning phase (asemakaavataso) to affect the emissions in carbon dioxide equivalents for the built environment. The study was completed by Department of Architecture and final report published in 2013. Report is based on the information and experiences received from the Porvoo Skaftkärr project. Report concluded that national legislation and climate targets can provide target levels to detail planning, but not exact emission levels due to the different calculation methods. If areal calculation is compared to national targets, calculation should be comparable with national greenhouse gas inventory method, but that would exclude some of the possibilities for city planning phase options. Also, Land use and building law should be updated in relation to planning requirements (kaavamääräykset) related to climate targets. CO2 emission counting is part of MLR 9§, impact assessment, but legislation does not require computational assessment, and common methods are not established. (Lylykangas, Lahti, & Tuukka, 2013)

Calculation results should be understood as directive results, not exact; since everything will not be built as planned, and assumptions are made for the calculation. Also, all indirect emissions cannot be estimated, such calculation result does not justify reducing the non-calculable qualitative features. There are planning solutions, like high quality green spaces, which can reduce need to travel for free time, but effects are hard to compute in CO2-eq. In case of detail planning, it is vital to understands the special requirements and the land use targets in the specific area to enable low-carbon solutions and support other climate target methods. Methods and strategies can vary between areas. Detail planning phase and emission reductions should be connected to other planning phases to increase effectiveness. Detail planning CO2 calculation is a guiding tool to assess different options, but national databases should be developed, and calculation methods specified to obtain more useful results. (Lylykangas, Lahti, & Tuukka, 2013)

It was concluded in the report, that it is also important to consider amount of living space, as well as building and infra life span when assessing the results. In the results important features must be reported separately. Also, comparison to LCC to provide feasible solutions should be done. Study utilized a LCA model, including natural and built environment. Most effective

features were found to be person transport, building materials, building energy usage and land use change. (Lylykangas, Lahti, & Tuukka, 2013) Model figure based on the study is presented below.

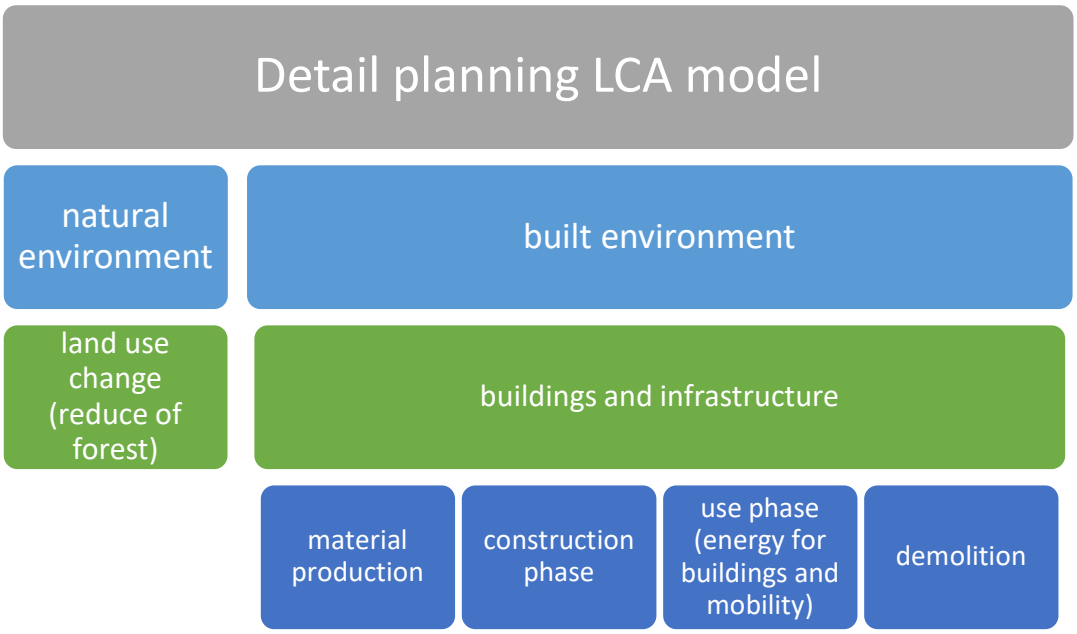


Figure 12 Detail planning LCA model (Lylykangas, Lahti, & Tuukka, 2013)

Overall, detail planning has a significant effect on GHG emissions and energy use. In detail planning it is important to do LCA calculation in early stage when different features can still be affected and to be used to estimate the bigger picture. Also, calculation can be done with 0-model and comparison done with different options in relation to 0-model. It should be kept in mind that calculation studies the effects of planning solutions, not effects off individual behaviour to environmental performance. (Lylykangas, Lahti, & Tuukka, 2013) Key requirements for a good areal LCA tool design are presented in a figure below.

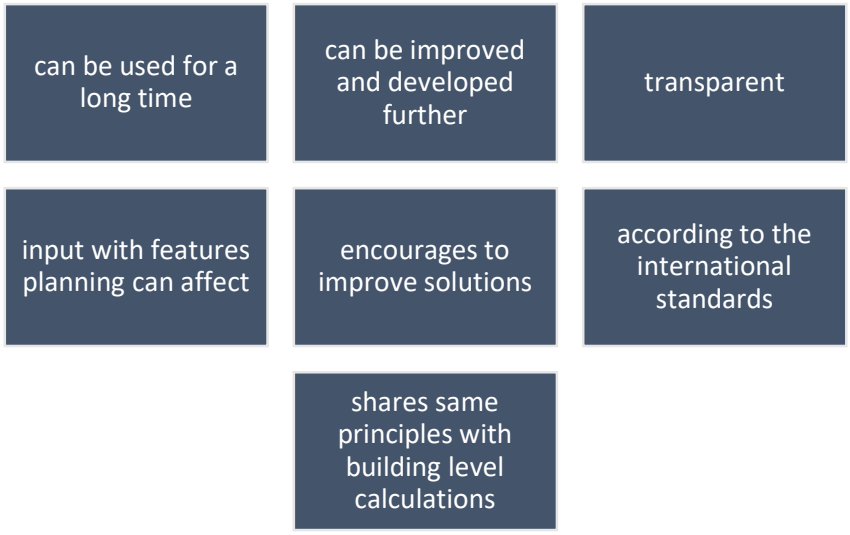


Figure 13 Requirements for good areal LCA tool design (Lylykangas, Lahti, & Tuukka, 2013)

5.2.2 Examples of developed environmental assessment tools

Green Building Council Finland assessed areal level carbon footprint tools and methods used in Finland in 2021. Assessment revealed that there were no unified tools and methods in common use. Tools and methods were chosen case by case, combining common tools and/or tools developed by private companies. (FiGBC, 2021) Below are presented advanced methods related to community level environmental assessments used in Finland.

MALTTI – matalahiilisen aluekehityksen tukityökalu (low carbon neighbourhood development tool) was developed in Aalto University, in School of Engineering, in Department of Real Estate, Planning and Geoinformatics, as part of K-EASY project (2011-2014) and based on previous research done in Aalto University during 2009-2013. Tool is not specifically intended for general (yleis-) nor detail plan (asemakaava) phase, but to provide a tool for strategic planning on all levels. MALTTI is a consumption and input-output life cycle assessment calculator calculating absolute emissions, providing carbon footprint as a result. Tool considers the time of origin of the emissions, and global emission account, such that there is no matter when and where in the supply chain emissions are created. Tool provides 3 energy scenarios and 3 car fuel scenarios for alternative futures. (Säynäjoki, Heinonen, Säynäjoki, Ala-Mantila, & Pääkkönen, 2014)

As part of the project recommendations for low carbon development were created. Figure below presents the five main recommendations to consider when designing a low carbon development. (Säynäjoki, Heinonen, Säynäjoki, Ala-Mantila, & Pääkkönen, 2014)

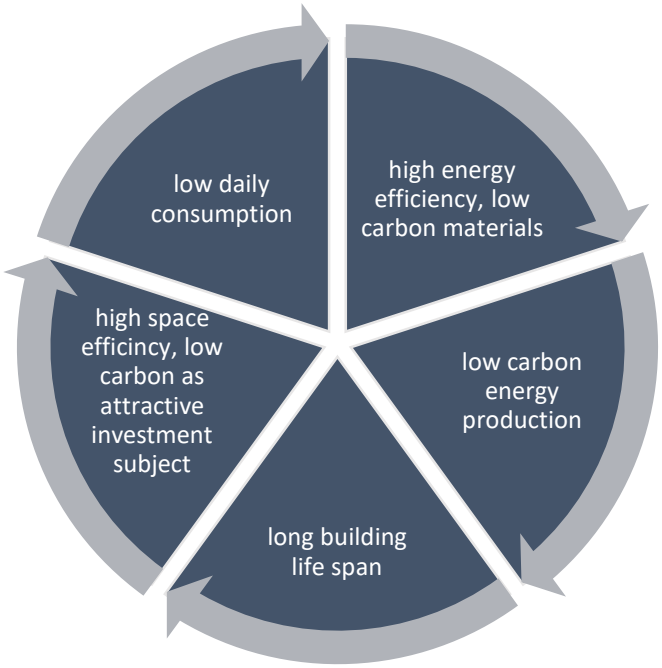


Figure 14 Low carbon development recommendations (Säynäjoki, Heinonen, Säynäjoki, Ala-Mantila, & Pääkkönen, 2014)

Kaupunkien ja kuntien alueelliset ekolaskurit (KEKO), is an ecologic calculator developed for assessing the ecologic sustainability of communities in building and use phases. The calculator assesses GHG, natural resource extraction, and impacts to biodiversity and ecosystem services. Tool is designed for assessing different plan possibilities in early stage, and mostly used on partial master plan level. Tool has been developed by SYKE, Aalto University, VTT and experts outside these organizations when required. Tool is maintained by SYKE, and it is under development. (FiGBC, 2021) KEKO is available for all users on user fee, fee is required to support the maintenance of the tool (SYKE, 2016).

Tool produces an estimation of area's overall efficiency and combines it to the national average (SYKE, 2016). Area's ecological efficiency is formulated by proportioning the environmental effects to the physical size of the community (number of residents or floor area), or it's number of activities (number of jobs). Features include area location and sizing, land use change, valuable nature areas and green structures, location in community structure, existing buildings, new buildings and energy renovations, energy supply, and transportation infrastructure. (SYKE, 2016B)

EcoCity Evaluator was published in 2011, several cities like Espoo, Helsinki, Tampere, Turku, and Vantaa tested calculator between 2011-2012. Possible area sizes varied from city level to single construction site level. Features

in calculator included building, transportation, energy, industry, agriculture, and carbon stocks. Calculator provided results of energy efficiency, GHG, and monetary costs of reducing carbon footprint. However, use and development of the tool has been terminated. (FiGBC, 2021)

AveClimate is designed and used by FCG Finnish Consulting Group Oy. Calculator has been developed since the beginning of 2000. Calculator is geospatial tool, counting socio-economic and climate impacts, and representing result on map. Features include land use greenhouse gas balance, transportation emissions, and energy supply emissions. However, there is sparsely information available of the calculator. (FiGBC, 2021)

Helsingin asemakaavojen vähähiilisyyden arviointimenetelmä (HAVA), calculator is owned by city of Helsinki, and it has been developed by Sitowise Oy. Calculator has been designed to assess detail plan (asemakaava) level life cycle carbon footprints and handprints. Calculator is aimed to produce easy-to-use tool to assess the carbon levels and develop low-carbon and carbon-neutral solutions. (FiGBC, 2021) Calculator is currently under development in co-operation with several municipalities and Sitowise Oy. Early version is excel-based calculator, and currently there is also a development version of a web-based tool. Commercial tool will be released later by Sitowise Oy. These excel- and web-based tools will be assessed in more detail in chapter 6, when presenting the Finnish tool.

6 Finland and Norway LCA comparison

To assess buildings' environmental performance nations have developed LCA frameworks to unify calculations. In the EU level Level(s) framework has been used to unify calculation and reporting of environmental performance. Neighboring nations often co-operate in economics, environmental issues, and other important subjects, which do not limit inside the nations' borders. Nordic harmonization has been discussed also in case of LCA frameworks. Figure below presents building declaration development process in Finland and connections to EU and Nordic co-operation.

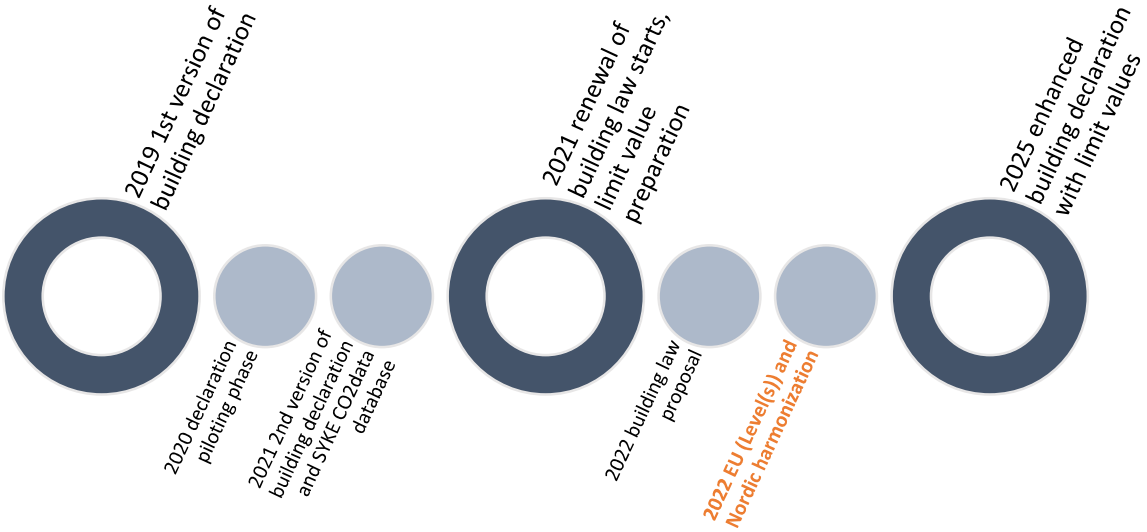


Figure 15 Building declaration process in Finland (One Click LCA Ltd., 2022)

Neighbourhood level LCA calculations are not as established as building calculations and such it was decided that to increase the reliability of the results it would make sense to compare at least two different calculation methods in this study. To avoid national biases comparison tool would be searched from abroad, also to avoid possibility that same people and organizations would have been involved in the development of both tools. In the beginning of the study the idea was to compare Finnish and Swedish examples since Sweden is Finland's closest co-operation partner in many global issues. However, while there is available Swedish building declaration framework and recommendations for areal development projects, there was not available proper calculation tool for areal environmental performance. Idea for Nordic comparison was retained, and alternative was searched from Norway. Norway has a valid building LCA standard NS3720 where areal features like land use change and user transport have been included to building features. Also,

areal LCA tool has been developed in NTNU, and enough data has been published in peer reviewed scientific publications.

Comparison will evolve through three steps. Firstly, comparing of national legislation for building LCA and areal development. Also, other non-regulatory guidelines significantly affecting neighbourhood developments are briefly addressed. On second phase areal LCA calculation tool examples are studied; HAVA from Finland, and NTNU tool from Norway. Third step includes neighbourhood development LCA calculation with HAVA and OneClick NS3720 tool, as well as result comparison to NTNU tool. To better address the early-phase planning approach including OneClick 3D Carbon Designer for buildings, and Infrastructure LCA tool for the test calculation part was considered. It was estimated that more neighbourhood level developments are done within existing city structure, and such it was decided that 3D Carbon Designer will be included since it could be useful in most of the cases. Infrastructure tool was excluded, while it could be useful with developments including more comprehensive infrastructure building, this kind of special development is outside of the scope of this study.

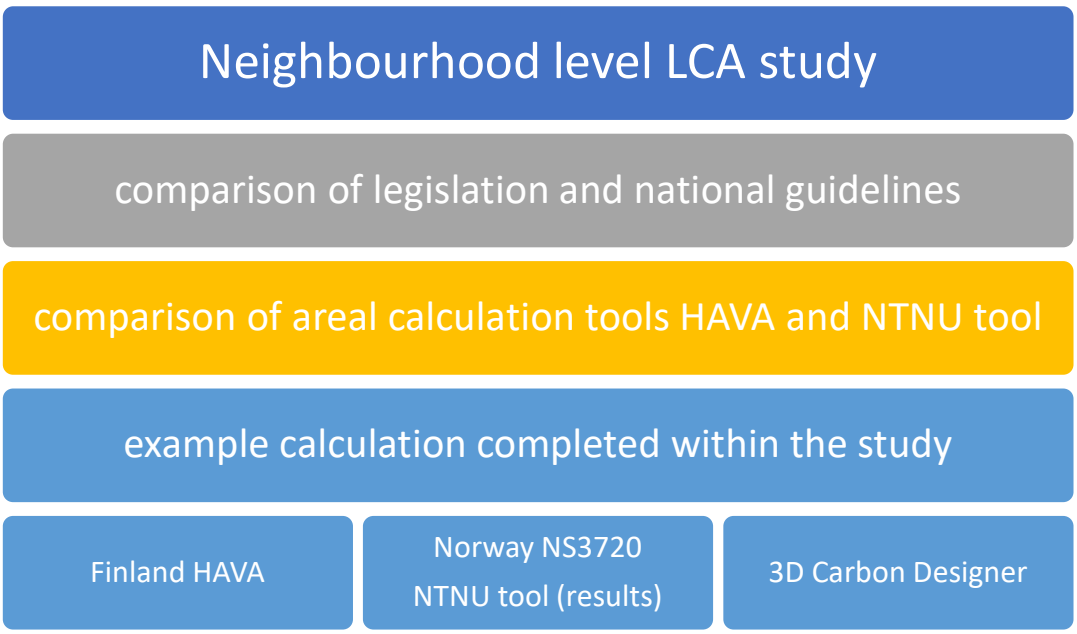


Figure 16 Model presenting steps for neighbourhood level LCA case study

Comparison is intended to bring insight on *how* the neighbourhood level LCA calculation is done, and *why* it is done the way it is done. But also, it is designed to answer the question of *how* neighbourhood level LCA calculation can be utilized in early-phase planning, and *how* it can help us to change the neighbourhood developments towards low-carbon solutions.

6.1 Presence of LCA in legislation

6.1.1 Principles for legislation comparison

Legislative norms give framework for the low-carbon development in planning, assessment, building and reporting phases. They describe the necessary actions planners and developers need to consider. For being able to describe a decision-making tool for GHG calculation, one must consider the up-to-date regulations. In Finland there is on-going renewal of MRL (land use and building law), and aim is to include in the new version also guidelines for low-carbon areal development. In the MRL renewal process there was proposed a new Kaavoitus- ja rakennuslaki (zoning and building law). However, during the proses the zoning part has been removed from the proposal version which was presented to the parliament at the autumn 2022 (Ministry of Environment, 2022). New proposal is called Rakentamislaki ja alueidenkäytön digitaalisuus, including mainly the low-carbon building declaration framework and area planning digitalization framework (Ministry of Environment, 2022).

The proposed actions in the MRL law draft will be assessed in this study. It is assumed that the proposed actions are according to the long-term targets and such useful for the future development, even if actions will realize in different form or be developed in later phase of law renewal. From the proposal is studied general targets, sections including detail plan (asemakaava) phase, climate mitigation and climate adaptation in city planning and building, as well as impact assessment section. Also, FiGBC works for carbon neutral area definition to unify the use of carbon neutral area status. In Norway there is a non-regulative ZEN areal development organisation working for zero emission neighbourhood development projects. Work of these organizations is briefly touched in this study to demonstrate the most important non-regulative guidelines for areal development. While neighbourhood and areal level LCAs are non-regulatory common guidelines are expected to direct development and such valuable for the study.

In Finland the building declaration proposal which guides the building level low-carbon development has been through several development steps and was presented to parliament at autumn 2022, while in Norway NS3720 standard for low-carbon building level development is already in force. Building LCA has been developed further than neighbourhood level LCA calculations and inclusion to legislation is further, or already happened like in Norway. Such it is expected that building level regulation will also affect the development of neighbourhood and other areal level calculations. From the Finnish building declaration model and Norwegian NS3720 were studied factors listed in the figure below.

Figure 17 Studied building level factors from legislation

6.1.2 Areal environmental legislation and guidelines (FIN)

General target in the MRL renewal law draft relating to low-carbon development is to build carbon-neutral society by lowering carbon footprint of building, land use and transport and to support sustainable community structure. Own section on climate mitigation and climate adaptation in city planning and building will be added to the legislation (ilmastonmuutoksen hillintä ja siihen sopeutumisesta kaavoituksessa ja rakentamisessa). (Ministry of Environment, 2021)

In city planning low-carbon development will be promoted by climate mitigation with community structure integration, resource efficient community structure, low-carbon and sustainable transport, and renewable energy production. City plan quality requirements will include center area service development to reduce need of transport, and special note on low-carbon transport prerequisites by transport and service placement. Low-carbon building will be promoted by setting a carbon footprint limit value for buildings and requiring climate declaration according to the national LCA model. Climate mitigation will be included to impact assessment in city planning, containing effects which are most likely significant. Targeting and level of accuracy (kohdentaminen ja tarkkuustaso) can be decided with each city plan impact assessment. (Ministry of Environment, 2021) Law sections related to both city planning and climate change are presented in more detail in figure below on essential parts.

Chapter 1 General decrees 5§ Climate mitigation and adaptation in city planning and building (p598)

- stregthening community structure (city areas, existing infrastructure)
- supporting resource efficient community development
- prerequisities for low-carbon and sustainable transport & renewable energy sources
- taking into account risks due climate change and abidance of ecological connections

Chapter 6 City plan 39§ Qualitative requirements (p607)

- versatile areas, prevent harmful separation
- service accessibility and center area development
- transport functionality and safety (public transport, biking, walking)
- retaining special values (built and natural environment)
- parks and green areas on planned areas

Chapter 6 City plan 40§ City plan regulations (p608)

- preventing and limiting harmful environmental effects
- protection regulations

Chapter 12 Impact assessment 70§ Impact assessment when doing the city plan (p617)

- city plan based on planning guided by impact assessment and possible other studies
- impact assessment includes scope and goal definition, and significant impacts of a plan
- separate government decree on city plan impact assessment and information provision

Chapter 12 Impact assessment 71§ Study on impact targeting and scope (p618)

- must include impacts on community structure, community and energy economy, transportation
- occupants living conditions, living environment, health, amenity
- biodiversity, plants, and animals
- land and bedrock, water, air, natural resources
- climate, climate mitigation, climate adaptation
- landscape, built environment, city view, cultural heritage
- economy conditions and functioning competition

Chapter 26 Essential technical requirements 206§ Low-carbon building (p659)

- in future buildings must be planned and built as low carbon
- buildings' carbon footprint and handprint reported with climate declaration (includes whole life cycle, according to national method, utilizes national database or other suitable information)
- buildings' carbon footprint cannot exceed the limit value
- carbon footprint and limit values must be based on whole life cycle energy and material consumption
- in later phase there will be separate government decree on limit-values, national LCA method and climate declaration

Figure 18 Areal and building level environmental regulations in MRL renewal

FiGBC is developing a guide for carbon neutral area definition, guide is aimed to be published in the beginning of 2023. In Finland there has not been a common definition of carbon neutral area or areal development. Meaning that it has not been clear, what features and parameters should be included in calculation, and such calculated areas have not been comparable. Carbon neutral area does not mean in this definition, that total emissions on the area are zero, but that created emissions are balanced at some point during the life cycle. Definition is developed from emission perspective, not to include environmental quality features like biodiversity. Carbon handprint is included. It has been planned that calculation excludes consumption, air travel and vehicle production. Calculation will include whole life cycle from production to demolition. Calculation period will be 50 years. Features included in the model are presented in the figure below.

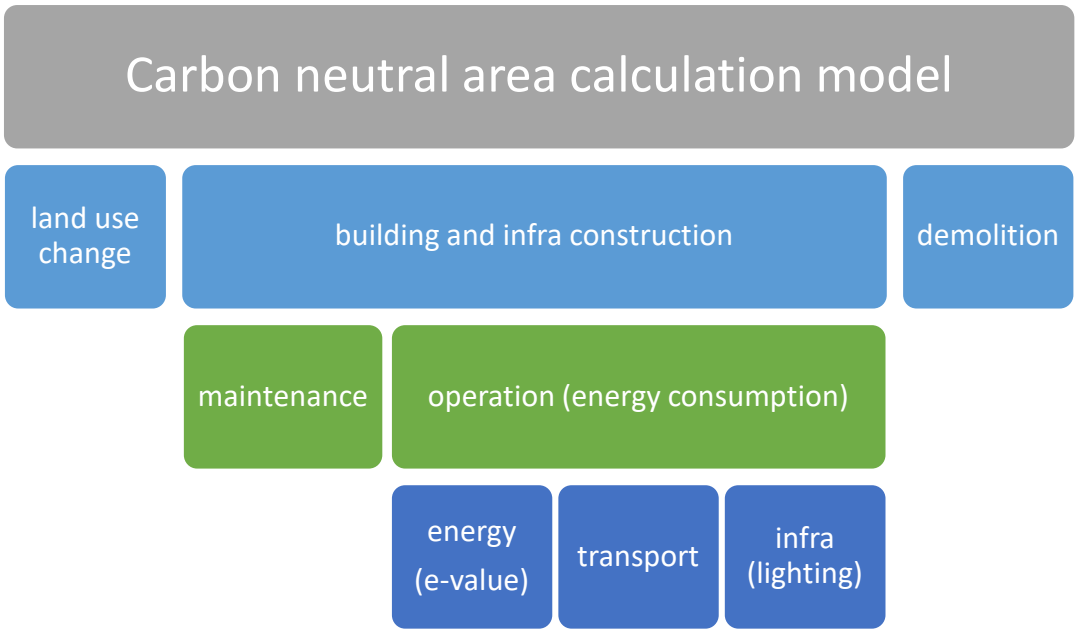


Figure 19 Carbon neutral area calculation based on FiGBC development project (FiGBC, 2022)

There are still some problems and uncertainties with the model development. For example, vehicle production is not included, model developers were reluctant to include public transportation vehicles per area when right share of their emissions is unknown. Also, the definition of proper "current" method to calculate the features is problematic. While for buildings building declaration can be used, for other features the definition of right method is unclear. Also, right databases to be used in the calculation have similar problem as feature methods. Two other aspects still to be clarified are the emission to be included, is GWP enough, or should other indicators be stated. Also, allowed compensations are still unclear. (FiGBC, 2022)

6.1.3 Building climate declaration (FIN)

In Finland climate declaration and LCA calculation has been developed further for buildings. For buildings low-carbon development has been aimed to become part of the building regulations by mid 2020s, and there is currently ongoing law renewal. Method version studied here is 2019 version (Method for the whole life carbon assessment of buildings), which will be updated before declaration requirements will become come to force. (Ministry of Environment, 2019) Studied factors are shown in the figure below.

Level building/neighbourhood

- building

Based on (standards EN etc.)

- European Commission's Level(s) and European Standards on sustainable construction including EN15643, EN15978 and EN15804, other scientific research

Calculation period

- 50 years (or service life when used as basis for the design)

Indicators

- GWP, carbon handprint (positive effect which would not realize without the project: reuse, renewable energy, biogenic carbon, cement carbonization)

Reference units

- per 1m2 of heated net space per year

Building types/elements (applicable to)

- all building types
- construction and refurbishment
- not directly suited for infrastructure

Time of assessment

- design state, when enough info on materials and energy needs

Assessment consists of

- entire building, structures on site but no paving, main building service systems
- no vegetation, water bodies, soil, temporary scaffolding, protective covers etc. worksite facilities or demolition of old buildings
- stages A-C: A1-5, B3-4, B6, C1-C4, D supplementary benefits and loads beyond the system, not included B1, B2, B6: use of products, maintenance, water
- energy method: construction, repairs, demolition. used energy, (no appliances and technical systems). emission coefficients given (national scenario). for district heating can be used the producer specific coefficient
- transportation method: transport to site, transport needed for repairs, transport at the end-of-life. machinery and workers, each mode

Information needed (typical values, required databases)

- Finnish database for material and process emissions (under development) CO2data.fi

Further development

- updated before being included in legislation

Figure 20 Finnish building declaration (Ministry of Environment, 2019)

6.1.4 Areal environmental guidelines (NOR)

2017 in Norway was founded the Research Centre on Zero Emission Neighbourhoods in Smart Cities (ZEN Centre). Centre's work aims for development of low carbon society by sustainable neighbourhoods with zero GHG emissions. Organization does not provide legislation, but research and development ideas to guide the development in the longer term. The Norwegian University of Science and Technology (NTNU) is the host in the organization and leads it together with SINTEF Community and SINTEF Energy. ZEN Centre is part of the Centres for Environment-friendly Energy Research (FME) community, which produces long-term research on renewable energy, energy efficiency, carbon capture and carbon storage. Community centres are selected via a detailed process administered by the Research Council of Norway. (FME ZEN, 2022)

ZEN community has partners throughout the building sector, including representatives from municipal and regional governments, property owners, developers, consultants, architects, ICT companies, contractors, energy companies, manufacturers of materials and products as well as governmental organisations. Centre has nine test areas around Norway and centre also takes part in the EU led syn.ikia Sustainable Plus Energy Neighbourhoods project. Centre's work is divided into six work packages presented in the figure below. (FME ZEN, 2022)

Figure 21 ZEN Centre work packages (FME ZEN, 2022)

6.1.5 Building climate declaration (NOR)

In Norway there is an existing standard (Metode for klimagassberegninger for bygninger) to guide building level LCA calculation. Studied factors of standard are described in the figure below.

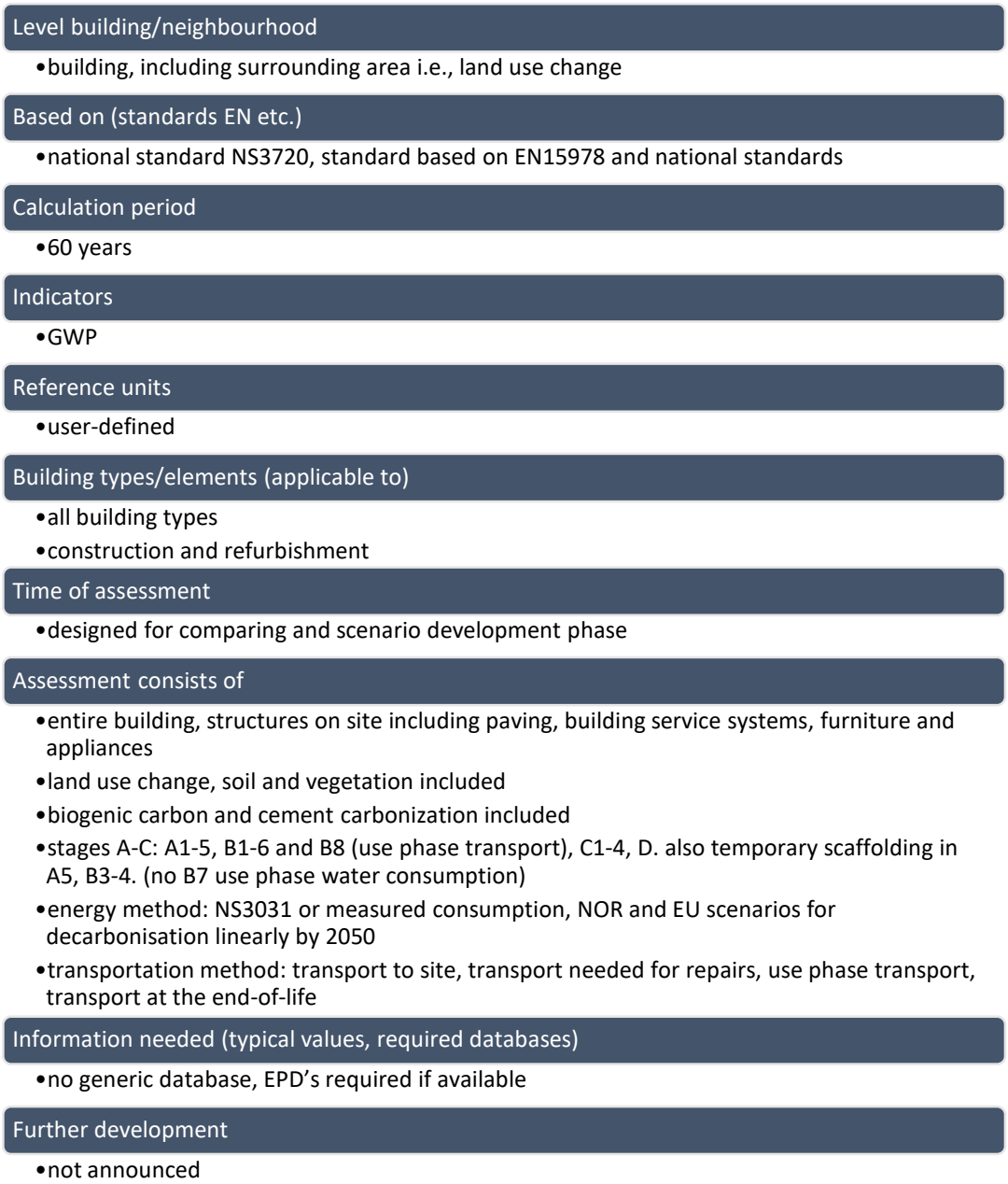


Figure 22 Norwegian building declaration (Kuittinen, 2022) and (Selvig, 2018)

6.2 Neighbourhood level LCA tools

6.2.1 Principles for neighbourhood level tool comparison

Comparing neighbourhood level tools and results reasonably is challenging. Tools may include several different factors, data sources, scope or target of tools can vary, and such results may vary, and sometimes it can be challenging to find out how the differences in the results have been formed. Aim of this comparison is to compare most important factors in the tools to create an overview of the tools and reveal most important similarities and differences. This comparison does not aim for explaining all factors in the tools. Figure below presents the most important factors to be compared from the tools.

Figure 23 Factors to be compared from neighbourhood level LCA tools

6.2.2 HAVA (Helsinki - FIN)

City of Helsinki aims to be carbon neutral 2035, including emissions created on the city area, consisting most significantly of heating, electricity, and transport. However, there is also a need to cut overall emissions. For example, building material production is low in Helsinki area, and such those emission do not show in city emission calculation. Such detailed areal calculations of built environment are needed. HAVA calculates Helsinki detail plan life cycle emission, i.e., carbon footprint and handprint. HAVA is aimed to be clear and easy-to-use tool. Tool is designed to be used to assess low-carbon and carbon positive (negative carbon load) solutions in detail plan planning phase. In browser-based version there is possibility to compare three options. City of Helsinki uses also “viherkerroin” green factor and “Helsingin kierto- ja jakamistaloudentiekartta” rotation and sharing economy roadmap. Such HAVA answers only to GHG part of the environmental effects. (Puurunen, Mattinen-Yuryev, & Soininen, 2021) See summary table of HAVA in the figure below.

Tool owner and developer

- owner: city of Helsinki
- developer Sitowise Oy

What kind of tool is available web/excel/other

- excel and browser-based tools available, but they are sandbox versions
- excel 4.11.2021 HAVA v.1.1
- browser-based later to common use, currently only for internal testing

Calculation and reference periods

- calculation: 50 years (according to Ministry of Environment recommendation)
- reference: in current version 2025-2075 (for scenarios)

Reference unit

- kgCO2e/a, per GFA, per resident (45 GFA per resident) or per workplace (25 GFA per person)

Features

- pre-construction
- infra and common spaces
- buildings and plot
- energy consumption
- transport
- soil and vegetation carbon stocks

Targets

- comprehensive (GHG in city development)
- focus on relevant features (significant, possible to affect during planning)
- easy-to-use (after data received, half-day work)
- good quality (public report of suppositions and references used)
- long life span (connected to other high quality tools and methods)

Scope

- 1 to 5 plots (usability case by case when larger areas)

Preferred use-types

- residential and commercial

Most significant features

- buildings construction and maintenance, energy consumption, transport
- in completed assessments these have concluded to 87-99% of GHG

Figure 24 Factors for HAVA based on HAVA v.1.1 excel and (Puurunen, Mattinen-Yuryev, & Soininen, 2021)

Features are described into more detail in the figures below. Figures include typical shares of emission in percentages and brief description of how features are calculated in the tool.

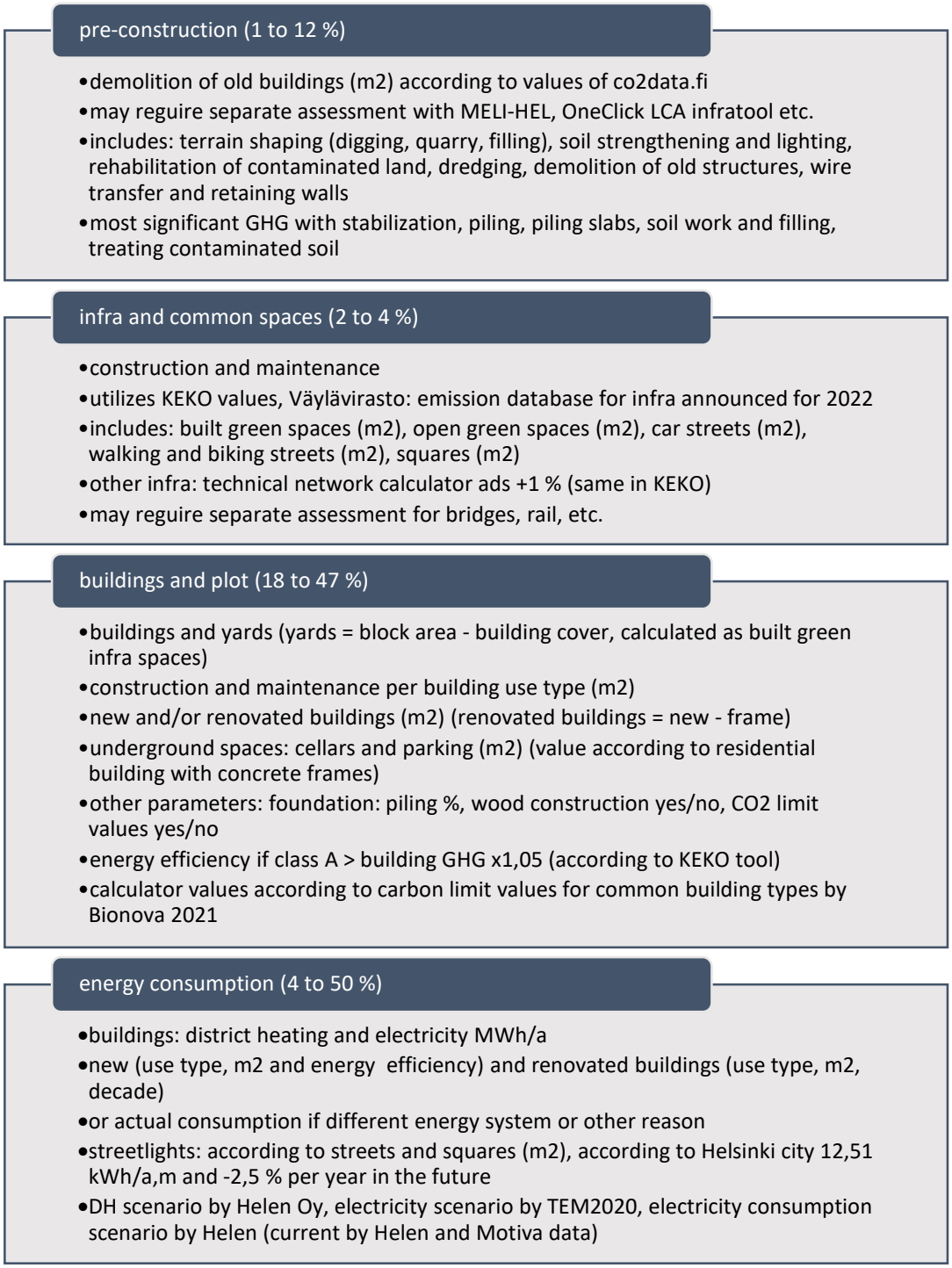


Figure 25 Feature calculation explanation for HAVA part 1 pre-construction, infra, buildings and plot, and energy consumption (Puurunen, Mattinen-Yuryev, & Soininen, 2021)

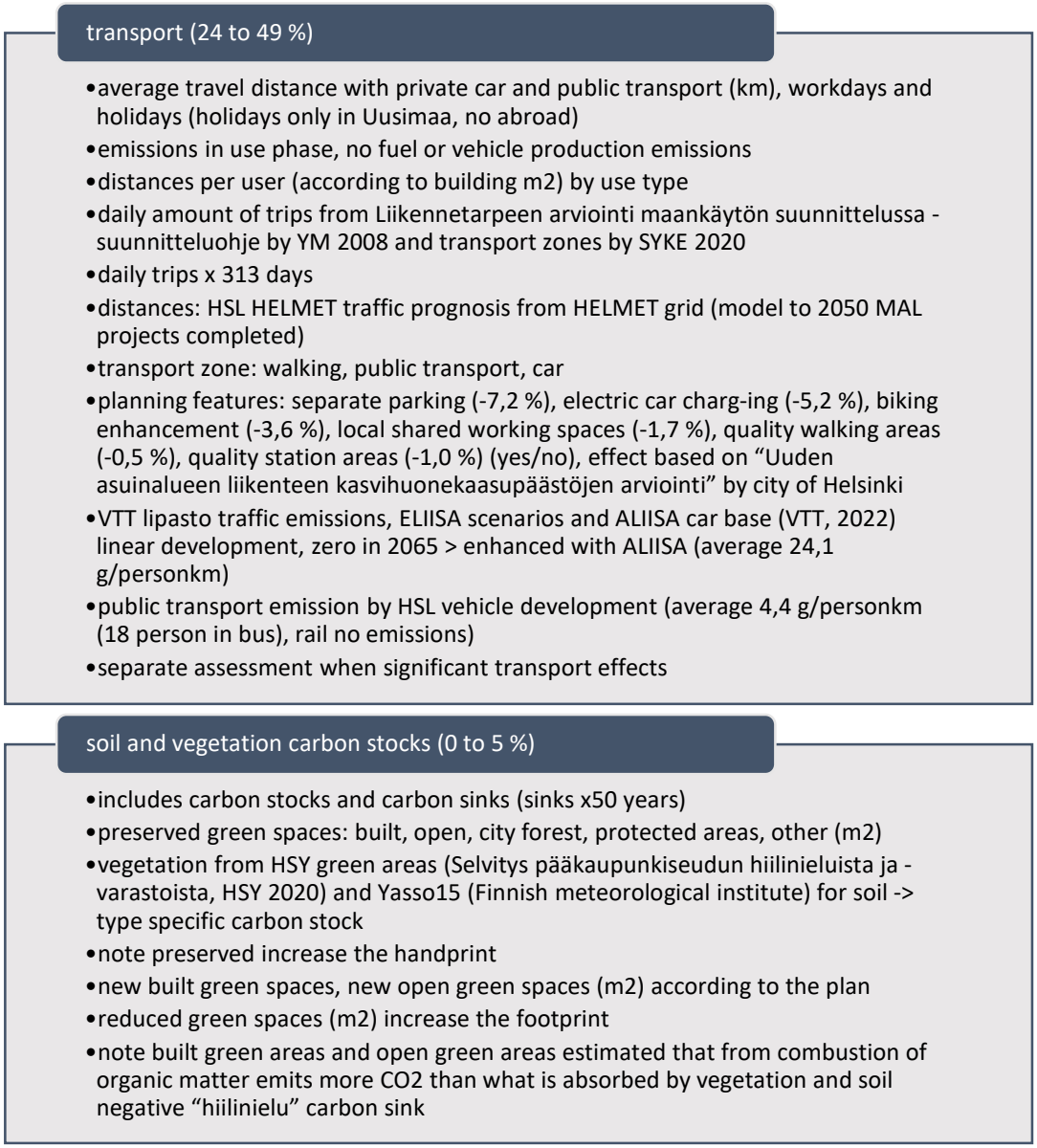


Figure 26 Feature calculation explanation for HAVA part 2 transport and soil and vegetation carbon stocks (Puurunen, Mattinen-Yuryev, & Soininen, 2021)

During the HAVA development project it has been noted that different planning levels have significant impacts on different features. While "yleiskaava" general plan has great impact on pre-construction, infra and common-spaces, energy consumption, transport, and soil and vegetation carbon stocks. "Asemakaava" detail plan level has great impact on buildings, plot, and energy consumption. Also, detail plan phase has also middle impact on pre-construction, infra and common spaces, and transport features. However, detail plan's impact on soil and vegetation carbon stocks is quite low. During the process was also noted several ways to affect detail plan emission

amount. Ways to impact emission in detail plan level planning are presented in the figure below. (Puurunen, Mattinen-Yuryev, & Soininen, 2021)

Figure 27 Detail plan level, means to affect emission levels (Puurunen, Mattinen-Yuryev, & Soininen, 2021)

6.2.3 NTNU neighbourhood level LCA tool (NOR)

Use of LCA in neighbourhood level early-phase planning has been tested in Norway for example with NTNU neighbourhood level LCA tool in Zero Village Bergen project. Results for Zero Village Bergen give total GHG emissions of 117 ktons CO2-eq over 60 years, equivalent to 1.5 tons CO2-eq/ capita/year or 21.2 kg CO2-eq/m2 /year on average over the period. Embodied emissions over the life cycle of the building have been 55 to 87 % of the total GHG emissions for Norwegian ZEB case studies examined by the ZEB Centre, while in Zero Village Bergen they concluded to 41 %. The choice of system boundaries has significant impact on results, and creates differences compared to previous research. (Lausselet, Borgnes, & Brattebø, 2019) See summary table of NTNU neighbourhood level LCA tool on figure below.

Tool owner and developer

- NTNU / Industrial Ecology Program
- has been utilized in ZEN projects / Zero Village Bergen

What kind of tool is available web/excel/other

- University model / Matlab based program and excel based calculations

Calculation and reference periods

- calculation: 60 years
- reference: mobility 2018-2077, electricity 2015-2080

Reference unit

- ktonsCO2-eq per year, tons CO2-eq/ capita/year, kg CO2-eq/m2 /year

Features

- buildings
- mobility
- open spaces
- networks
- on-site energy infrastructure

Targets

- identify dominant physical elements and life cycle stages producing GHG in neighbourhood level
- identify critical factors and sensitivities for GHG contributors
- find strengths and weaknesses of the model and does it provide useful information for early-stage planning

Scope

- applicable to any neighbourhood level study
- ZEN OM (operation and manufacturing for all features > modifiable), networks only M
- electricity: scenarios NOR (used in results) and EU28+NOR (waste incineration in B6 DH), buildings according to ZEB simulation

Preferred use-types

- residential and office buildings

Most significant features

- buildings 52%, mobility 40%, and only 2.3% from networks and open spaces. Emissions embodied in the materials consumed in all the elements of the neighbourhood account for as much as 56% of total emissions, with a large share coming from materials consumed in mobility vehicles. Critical parameters are emission intensities for electricity and heat production by waste incineration. High sensitivity ratio for parameters: daily distance travelled by the inhabitants and buildings' energy load.

Figure 28 Factors for NTNU LCA tool (Lausselet, Borgnes, & Brattebø, 2019)

Features are described into more detail in the figure below. Figure includes percentage shares of GHG emissions for features in Zero Village Bergen results, and a brief description of how features are calculated in the tool.

Figure 29 Feature calculation explanation for NTNU tool (Lausselet, Borgnes, & Brattebø, 2019)

In the use of NTNU neighbourhood level LCA tool has been detected significant uncertainties. Most significant factors are future emission intensity of electricity (g CO2-eq/kWh), future technologies in buildings, infrastructure and mobility, and the temporal distribution of environmental impacts. Also, in Norway due climate change the energy consumed for building heating is expected to decrease, while cooling energy consumption is estimated to increase. Changes in heating and cooling energy consumption has been estimated to conclude to a net increase in energy consumption. Uncertainties have been suggested to be reduced via a flexible energy system, for example waterborne heat systems in the buildings. Also, due rapidly growing share of electric vehicles the local storage capacity of electricity network should be increased. (Lausselet, Borgnes, & Brattebø, 2019)

NTNU neighbourhood level LCA tool has been utilized also later in Norway. Lausselet, Ellingsen, Strømman and Brattebø applied the tool to study zero emission neighbourhoods with scenario comparison of house sizes, household sizes, used and produced energy, and mobility patters. Comparison was completed with single-family house neighbourhood. In the study neighbourhood was defined as "*a group of interconnected buildings with associated infrastructure, located within a confined geographical area*". Such they argued that functional units should be per neighbourhood and per person when providing the results. For example, per m2 floor area, should be used only as a subunit when defining the building. (Lausselet, Ellingsen, Strømman, & Brattebø, 2020)

When calculation on ZEN level, ZEBs contribute to major share of the emissions. Such it is suggested in the research, that ZEB development should be in major part in the ZEN development. From building stock, it was also noted that in Norway 50 % of the current dwelling stock will need significant renovation based on material life cycles before 2050. Such, also existing buildings create a significant potential for energy efficiency renovation also within the customary renovation schedule. However, also the building stock without major life cycle renovation needs on next decades, should be considered from the energy efficiency perspective. However, while buildings are important in neighbourhood level development, they are not the only significant feature. Study noted the need to assess mobility also from the vehicle production perspective. While internal combustion engine vehicles have pipe tail emissions and pure battery electric vehicles not, indirect emissions associated with electricity production and materials can be significant for electric vehicles. Such, the life cycle approach should be done with wider range of features to avoid problem shifting inside the life cycle. (Lausselet, Ellingsen, Strømman, & Brattebø, 2020)

If neighbourhood level sustainable development is wanted to play significant role in reducing the GHG emissions and reaching the set climate targets, all the following factors are stated to be crucial to include in the ZEN development projects.

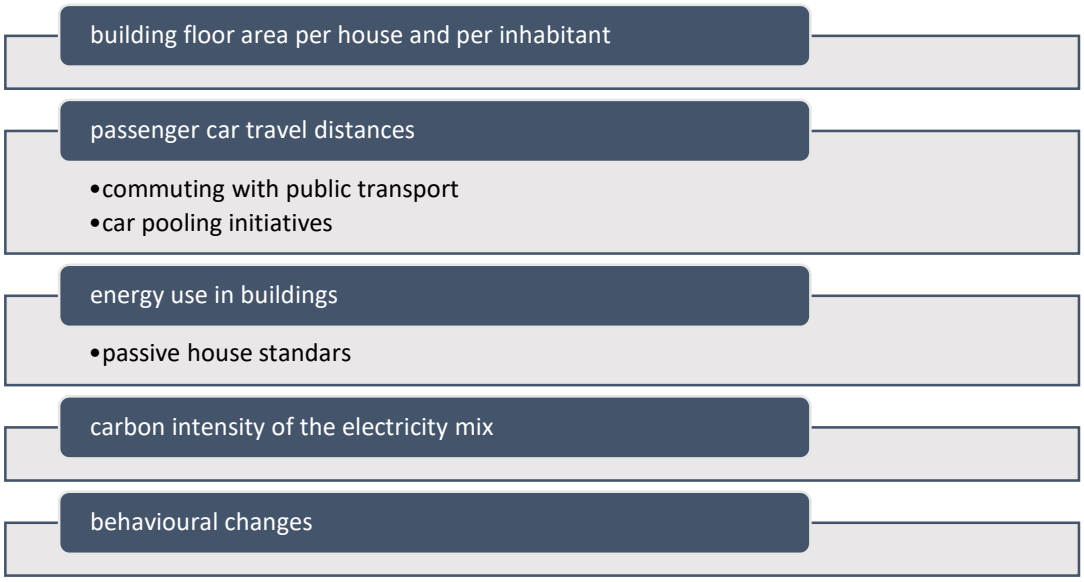


Figure 30 Factors to consider in the ZEN development to create significant effect (Lausselet, Ellingsen, Strømman, & Brattebø, 2020)

NTNU neighbourhood level calculation tool was also utilized for a second neighbourhood development project located in Ydalir. Target of the neighbourhood development was to reach net-zero level in operation and manufacturing. Target was tried to be reached with different scenarios. For mobility was created two enhancements: design include no parking near school and kindergarten, and secondly design include limited parking in periphery of the neighbourhood (effects according to the Institute of Transport Economics). For electricity upscaling local energy production with DH, PV and CHP wood chips was studied. The baseline result produced in total 141 kton CO2-eq (0,95 kCO2-eq/capita per year), final scenario result concluded to 54 % reduction from the baseline. Important factors to reduce mobility baseline were design and mode share (-17%), mobility technology and car sharing (-43 %). Results indicated that mobility is a great source of GHG with 62 % in the baseline version, operation phase contributing to 44 %. Reducing private car travel distances was the most important measure and promoting car-sharing and use of public transport were assessed to be the best ways to reach this target. For buildings was done material improvements, mainly shift to wood, however the effect was small (-2 %), sine the baseline was already developed model. For energy PV panel doubling produced 3 % increase to emissions when emissions were calculated with Norwegian grid electricity and 8 % decrease when calculated with European average grid electricity. Results

indicated that upscaling of the electricity production with PV panels would contribute to significant reduction only in case it substitutes use of fossil fuels in power generation and/or in mobility. Study of other renewable energy production alternatives was also recommended. For example, production with local wind, biomass, and geothermal sources. (Lausselet, Lund, & Brattebø, 2021)

Study concluded that in neighbourhood level LCA features density, transportation, infrastructure, and consumption should be included. However, it was noted that in many projects, density may be a given feature. Also, it was noted that interconnections between the buildings become more important when buildings are within the same system boundaries. System complexity increases but building cluster system also allow assessment of innovative solutions for local energy supply, energy storage, and energy flexibility. Simpler energy improvements recommended in the study were peak shaving; households and companies reduce the use during the peak hours, and increased battery storage. However, regardless of used enhancements and scenarios the results in this study concluded that Ydalir does not achieve the net-zero target. It was noted that neighbourhoods are important areas to assess from the emission reduction perspective, but that net-zero target is hard to reach. (Lausselet, Lund, & Brattebø, 2021)

6.3 Example calculation with HAVA, OneClick NS3720 and OneClick 3D Carbon Designer

Neighbourhood level LCA is relatively new topic. Areal calculation is complex entity and requires significant amount of data and well-structured calculation process. Several areal calculation tools have been developed, while common use is still limited. Such it was decided that when considering the workload, it is more useful to utilize existing tools rather than develop new tool for this study. However, there is limited amount of neighbourhood level LCA calculations completed with the existing tools. Also, the number of experts on the field is limited. Such it was decided that is it better to include hands-on calculation to study, rather than use existing calculation results and/or expert interviews as an information source. When tools are not in wide and common use, there is a risk, that possible interviewees have been too deeply involved to development of the tools and are such providing too biased answers of the use of a tool. Also, it was estimated that completing a calculation hands-on will increase the understanding of the topic, and that will be advantageous when interpreting usefulness of the tools and results received.

Calculation forms of three phases. In the first phase is completed areal calculation with HAVA. HAVA produces a baseline for the neighbourhood area in question. Tool is used to test which features are important on areal level (impacts level check). With HAVA is also studied the sensitivity of transport

and energy features (sensitivity check). This part is aimed to produce magnitudes of most important features, to see, where to direct low-carbon planning. In second phase impact magnitudes of most important features; buildings, transport (including use phase), and energy, is checked with OneClick LCA tool based on NS3720 (reliability check). NS3720 tool includes also land use and land use change, which are recommended to be calculated in areal level LCAs. Tool is based on valid standard used in Norway for building LCA and such it is estimated to provide reliable comparison results. However, when interpreting results, it must be understood, that tool is developed for neighbouring country and not to the test area location. Sensitivity of transport and energy features is studied also with this tool (sensitivity check). Since tool is developed to building level the area in question will be divided to buildings and their plots, and results for the area will be a sum of all building level calculations. Including building level approach gives a change to assess the benefits and disadvantages of completing neighbourhood level LCA with areal or building level approach. Calculation process for phases one and two is described in the figure below. See also annex A for more detailed process description and study area description.

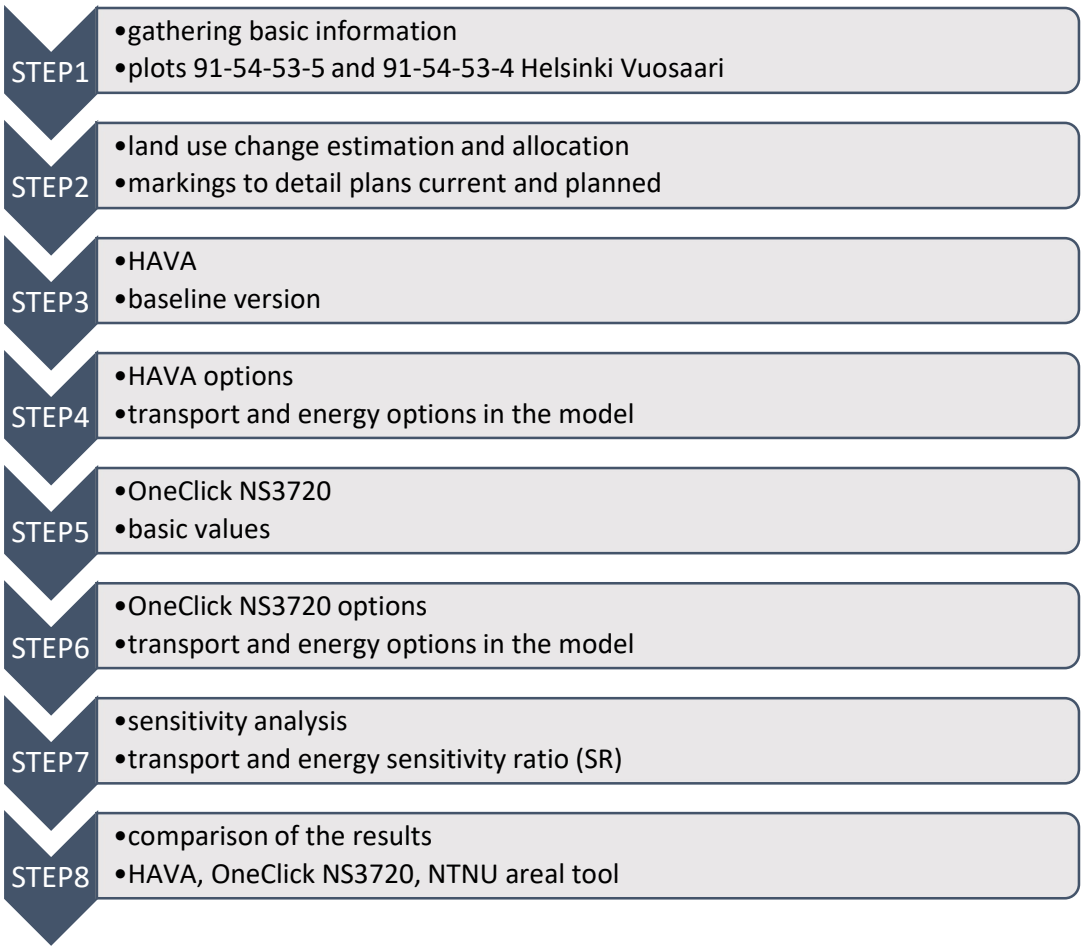


Figure 31 Calculation process description for phases one and two

Third phase of the calculation is completed with OneClick 3D Carbon Designer. Since buildings and their energy consumption have been noted to be often the most significant features in neighbourhood level LCA literature, buildings are studied to more detail. Building options are created with existing tool offering easy-to-use and quick-design options for early-phase planning. Tool and its usefulness are tested with using Finnish Ministry of Environment reference values. There was an option to include fourth step to the calculation process with OneClick Infrastructure tool. However, to limit the scope of the study it was decided that the study will be done with typical infill area focusing on features buildings, energy consumption and transport, which have been detected to be the most significant features in the literature. Tool is applied to three use-types: residential, office and school. For each use-type is calculated four design options. Varying parameters for design options are presented on figure below.

Figure 32 OneClick 3D Carbon Designer calculation option parameters

Energy consumption used for this phase is estimated based on HAVA reference values. See also annex B for more detailed description of the calculation phase and used values. Results for different use-types are also be compared to data gathered from previous building level carbon footprint calculations completed by representatives of Raksystems Insinööritoimisto Oy Green Building Services / Green Building Partners Oy.

7 Results

7.1 Example calculation: Comparison of areal results

When comparing results, it is evident that the background data of the tools have effect on the results. However, in the early phase planning the results do not present the end solution to detail. Such assessment of the results should in any case be done on magnitude level, rather than studying details, which are expected to differ from the end solution. Still, when background data creates significant differences, this must be acknowledged.

In the table below is presented the total results of the example areal calculation for HAVA and OneClick NS3720, as well as per floor square meter and per resident results also for NTNU tool from the Zero Village Bergen. Since NTNU results present different area, results should be used only to estimate the reliability of the result magnitude received from the example calculation.

Table 4 Total emission results of example calculation in kgCO2-eq

	total	*per GFA per a*	*per resident per a*
HAVA	31 919 133	16,3	735
NS 3720	46 595 344	23,8	1 073
NTNU		21,2	1 500

Areal calculations provide reasonable results, and difference is understandable when considering different reference values and features included. However, interestingly HAVA produces smaller values than OneClick NS3720 even though HAVA includes preconstruction, infra and common spaces and soil and vegetation, while OC NS 3720 includes only land use and land use change. While NTNU results are calculated for different area and the system bordering is different, the per floor square meter and per resident results settle between HAVA and OC NS 3720 results. Though the results are not comparable as such, this proposes that results magnitude of the example calculations are on correct level and significant features are included in the calculation. Difference between HAVA and OC NS3720 results require more detailed comparison. In the table below is presented total, use phase transport, energy consumption, buildings and plot, and land use for OC NS3720, and preconstruction, infra, common spaces and soil and vegetation for HAVA results.

Table 5 Example calculation feature results kgCO2-eq

	total	*transport*	*energy*	*buildings*	*land use etc.*
HAVA	31 919 133	8 073 402	4 839 921	18 517 768	488 042
NS 3720	46 464 968	5 063 546	21 607 436	19 793 986	13 0376
difference	-14 545 835	3 009 856	-16 767 515	-1 276 219	357 666

In the magnitude level the significant difference is in the energy feature. HAVA calculates consumption via scenario by Helen (current by Helen and Motiva data) (3 332 000 kWh) while OC NS3720 via TEK17 model (3 342 032 kWh). Energy emission intensity for HAVA is from DH scenario by Helen Oy and electricity scenario by TEM2020, and for OC NS3720 from EU + Norway electricity model. Energy emission intensity models are creating significant difference to the results. When comparing results further on feature level, there can be seen smaller, but still significant differences between transport, buildings, and plot features. See table below for percentages. In NTNU model transport is much more significant feature since it also includes replacements for vehicles. Replacements create 25 % of the emissions while use phase energy for mobility is 15 % (Lausselet, Borgnes, & Brattebø, 2019). In the energy category there is significant difference in the used energy emissions intensity scenarios. NTNU uses the Norway grid electricity emission intensity model.

Table 6 Feature percentages of total emissions

	transport	*energy*	*buildings*	*land use etc.*
HAVA	25 %	15 %	58 %	2 %
NS 3720	11 %	47 %	43 %	0 %
NTNU	40 %	31 %	22 %	7 %

Tools' results were also studied with changing parameters. For HAVA trip length and energy consumption increase with 25 % was tested. As well as changing the transport zone to walking and then to car zone. Changes resulted to total emissions presented in the table below.

Table 7 HAVA scenario results

scenario	*total*	*ratio*	*SR*
original	31 919 133	100 %	
trip length +25 %	33 937 483	106 %	0,25
walking zone	28 200 968	88 %	N/A
car zone	33 733 239	106 %	N/A
e. consumption +25 %	33 089 299	104 %	0,15

Sensitivity ratio was calculated for trip length and energy consumption. For transport zones there were several changes in parameters; car use, bus use, rail use, and walking and biking, such sensitivity ratio was not possible to calculate based on available material.

For OC NS3720 studied scenarios included changing transport area from Vuosaari to Kamppi, increasing car and car-pooling emission intensity and trip length by 25 %, and for energy using Norway grid electricity and increasing energy consumption by 25 %. See table below for results.

Table 8 OC NS 3720 scenario results

scenario	*total*	*ratio*	*SR*
original	46 464 968	100 %	
Kamppi area	44 368 583	95 %	
car and car-pooling emission int.	51 928 470	112 %	0,10
trip length +25 %	47 730 853	103 %	0,11
NOR E	26 993 624	58 %	0,44
e. consumption +25 %	51 866 865	112 %	0,47

Sensitivity ratio was calculated for transport emission intensity, trip length, Norway grid electricity and energy consumption scenarios. For transport area there were several changes in parameters related to mode shifts, such sensitivity ratio was not possible to calculate based on available material. When comparing sensitivity ratio for trip length +25 % and energy consumption +25 % there are significant differences between the tools.

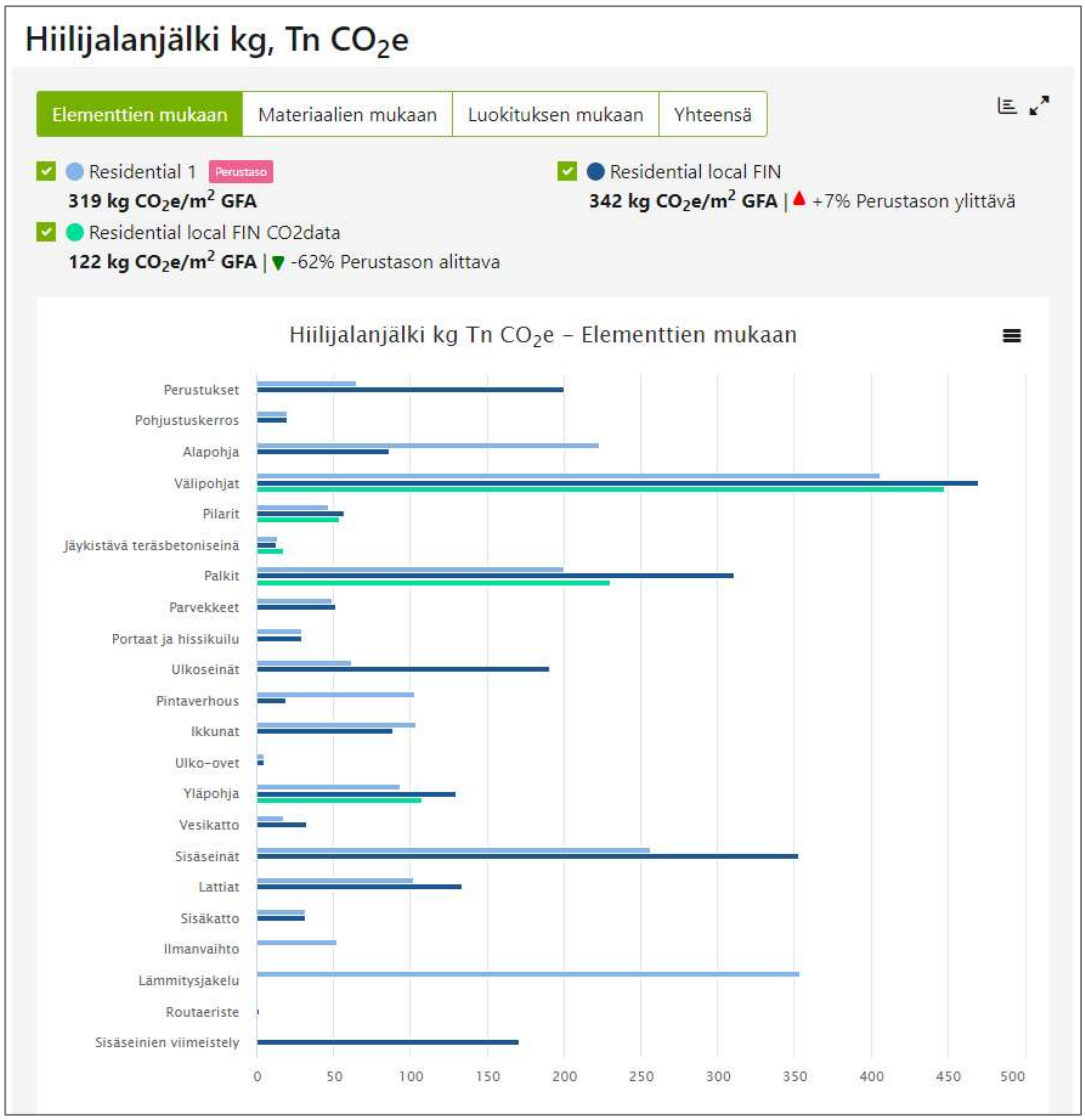
7.2 Comparison of building A1-A3 results

OneClick 3D Carbon designer was used for calculating different scenarios on building level. Scenarios included different foundation solutions, floor amount, warm or cold cellars, design options for load bearing structures and façade. Scenarios were limited to major features, while more design options would have been allowed by the software.

Figure 33 Scenarios results (kgCO2/m2 GFA) for 3D Carbon Designer

Scenarios are calculated with international reference building v2022.1., which uses Ecoinvent and generic OneClick LCA data. Software includes also Finnish national reference building v2022.1. which uses CO2data.fi and generic OneClick LCA data and does not include HVAC systems. There is also a Finnish reference building v2022.1. (CO2data.fi/SYKE data), however this refence includes only part of the main structures, for example residential reference includes intermediate floor, pillars, reinforced concrete walls, beams, and attic joints, but is expected to be updated to be more inclusive later. When residential example was calculated with same basic information

international reference building was 319 kgCO2/m2GFA and Finnish reference building 342 kgCO2/m2GFA. Reference building should be selected based on the aim of the calculation and comparison should be completed with the same reference building. Differences are illustrated in the picture below.



Picture 1 Screenshot from 3D Carbon Designer results for international reference building, Finnish reference building and Finnish reference building with only CO2data.fi

Table below presents A1 to A3 emissions from previous and 3D Carbon Designer calculations. GBP Average and GBP Interval are based on building specific LCA calculations completed by Green Building Partners Oy. Bionova Average and Interval are from “Carbon Footprint Limits for Common Building types” report completed by Bionova Ltd in 2021 for Ministry of Environment. To be noted, 3D Carbon Designer international reference building

results include HVAC systems (ventilation and heating distribution)(excluded in the table below) and Bionova results include building technology (Bionova Ltd, 2021). Results are presented as kgCO2e/m2.

Table 9 A1 to A3 result comparison

Type	GBP Av.	GBP Int.	Bionova Av.	Bionova Int.	3D FIN basic	3D global basic -HVAC	3D global Int.
Residential	290	248 – 331	278	268 – 287	342	261	262-319
Office	415	309 – 520	307	253 – 361	356	256	335-434
School	360	290 – 431	263	244 - 283	367	298	366-441

In 2021 there has been done a LCA calculation for detail plan phase of a Neitsytsaarentie residential development proposal. In the LCA assessment A1 to A3 emissions were calculated to be 407 CO2e/m2GF and 269 CO2e/gross area (m2) for a new construction. Calculation is done based on existing new construction building built a few years earlier in the block. Calculation included HVAC systems. (Rintala & Yli-Paunu, 2021) Calculation based on existing building is more detailed than an average building and may such sum up to slightly higher value. Comparison reveals that 3D Carbon Designer reference building provides reasonable comparison for Finnish residential building, and such can be used in early phase planning before more detailed information of used materials is available. Also, calculations done with 3D Carbon Designer Finnish reference building for office and school buildings provide results inside the GBP interval. However, in these categories there is more varying between the calculation results, and there may be need to adjust results for nontypical cases.

7.3 Answers to research questions

This chapter goes through the research questions created in the beginning of the study to sum up the results gained during the study.

The most well-known environmental assessment methods are presented in table 3 Summary of well-known environmental assessment methods. Table includes scorecard methods LEED and BREEAM, and actual value methods LCA, IOTS, CBA, MFA, MBA, and HERA. While comparing different assessment methods is complicated due their different features, some generalizations can be made of **the strengths and weaknesses of the environmental assessment methods**. Preferred methods are scalable, and in case of actual value methods more than one indicator can be included,

which lessens risk of problem shifting. System border setting is questionable with the methods, with different borders the results will explain different things, which must be informed to anyone utilizing the results. Data requirements, and possible lack or incorrectness of data is bound to create difficulties with all assessment methods. When utilizing extensive amount of data, the risk of not detecting errors in the data increases, when there are no resources to check all used data. Possible errors can be minimized be utilizing pre-checked databases.

When studying peer-reviewed literature, several methods to calculate neighbourhood level LCA can be found. There are early-phase calculation examples from Norway, land-use and transport methods from Belgium and USA, MSLCEA in Australia, and Nova-EQUER based multi-indicator calculations in Belgium. There are multiple methods, developed for different purposes and utilizing different tools. **In national (Finnish) context**, several tools have been created and tested, but areal calculations are not commonly done, and no single tool have been dominant or sophisticated. For example, city of Helsinki has calculated some area LCAs with internal process during the planning phase, but there is no requirement for a developer to provide areal LCA calculation and assurance than calculation would have been used to guide the planning towards low-carbon development.

Current best practices for neighbourhood level LCA recommend including at least the most important features; buildings, energy, and transport. Calculation period is often around 50 to 60 years. From indicators GWP is always included, but it is recommended to consider also other indicators to avoid problem shifting between indicators. Many calculations are however completed with just GWP to avoid additional complexity, since the areal approach already makes the calculation relative complex. **LCA has been chosen over other analytical tools in neighbourhood level planning**, since LCA prevents problem sifting when several indicators are included. Compared to CBA, LCA provides territorial approach which allows spatial assessment and is such useful for neighbourhood level calculation. Building level LCA calculation is commonly used and standardized process to assess environmental impacts in many countries. To expand building level calculation to include also areal features has been found to be interesting possibility and has been tested with several tools in several countries.

Finnish Zoning and Building Law draft has vague requirements for area planning, including promoting of sustainable transport and centre development, and enabling renewable energy production. Proposed legislation does not include LCA or other environmental performance calculation to be completed in the general or detail planning phase. Climate mitigation will be

part of impact assessment, which is compulsory for significant construction developments. Impact assessment contains effects which are most likely significant. However, targets, scope and accuracy are allowed to be decided separately for each development. LCA calculation is required for buildings and to be done according to the national model. When considering if **Finland's building LCA declaration is compatible with drafted regulations for low-carbon neighbourhood development**, answer is not straightforward. As stated above areal developments, including a neighbourhood development, does not require CO2 calculation. However, since buildings are often the most significant emission origin in areal development, it is in the line with the requirement to calculate significant impacts for significant areal developments. However, other features are also significant on areal level. With developments including significant infrastructure (for example rails and bridges) or generating significant amount of traffic (for example logistic centre), it would be vital to require also other LCA calculations.

This study **calculated an example with Finnish neighbourhood LCA tool** HAVA developed by Sitowise Oyj and city of Helsinki. Tested HAVA version is a preliminary tool and will be developed further. However, test-version already offered an easy-to-use tool for calculating overall emissions for a neighbourhood. However, potential problems were detected for example in used energy scenarios, and results of the calculation should be interpreted with care. To gain more insight, **comparison was done with Norwegian tool**, Norway is aiming for sustainable neighbourhoods with zero GHG emissions. ZEN centre is the most important organization working towards this target. Organization does not provide legislation but research and innovations to be utilized for planning. There is valid LCA standard NS3720 for calculating building LCA. This study compared results from ZEN and NTNU areal LCA study and example was calculated with OneClick building LCA tool according to NS3720 including land use and use phase transport. There is synergy between building and neighbourhood level calculations in Norway. Methods are utilizing for example same energy data. Since there is already land use and transport included to the building standard, it would be interesting to see if other areal features could be allocated to buildings too. On the other hand, separate standard for early-phase planning phase with areal approach could be developed based on ZEN work. Comparison suggests that tools following the national guidance and localized data are **preferred by the users**. Also, databases and tools with frequent updates, often provided by separate provider like OneClick LCA Ltd. are often used. In general, easy-to-use tools which provide GWP indicator are preferred, and results are often reported as CO2e/GFA or CO2e/person.

This study compared calculation approaches to better understand **what the most feasible LCA calculation approach for early-phase planning**

is. Areal level approach was calculated with HAVA and building allocation with calculation tool based on NS3720 standard. Areal approach provided quick and basic calculation with several areal features. However, areal approach with HAVA offered only limited design features, foundations, wood-construction, and energy levels for buildings, and couple of transport design options with percentage change approximations. Building allocation allowed presenting the differences between separate buildings and land use areas in the neighbourhood. However, for large neighbourhoods building specific calculation may be too laborious. Also, building level calculation did not include areal features like infrastructure. Yard-areas were included as land use change of the building and its surroundings. There is no clear answer if areal or building approach is more feasible for neighbourhood development, but the answer depends on the aim of the calculation. If one wants to get the magnitudes of areal feature emissions and try different options with varying locations and building sizes areal tool offers faster approach. However, if number of buildings and location is set building-based approach allows presenting the difference between buildings with different use-types and construction materials.

From features, guiding transport planning with areal level LCA calculation proved to be difficult. HAVA has different transport zones, and NS3720 transport is calculated with specific locations or zones. With both approaches average trip lengths can be studied, and emission intensity and modal share as parameters are included to both approaches. However, neither calculation approach offered concrete design solutions on how to reach emission reductions through decreased trip lengths, trip amounts or trip emission intensity. HAVA includes planning features like enhanced biking and walking environments and separate parking facilities. However, how one design these correctly, so that they fit to the existing city structure and fulfil the emission reduction potential is out of the reach of the neighbourhood LCA tool.

From energy feature should be understood, that calculation can be based on approximated consumption, or actual consumption. Importance of the energy emission intensity became clear, since HAVA used scenarios where energy emission intensities decreased rapidly alongside carbon-neutral 2035 target. Both approaches would have benefitted from different energy supply options, and not just the energy consumption and energy emission intensity parameters. Areal approach provides general magnitude results for the area, while building specific allows assessing buildings with different use-types or other parameters. **The most important features to include in the neighbourhood level LCA calculation** were buildings, energy, and transport. Effect of land use and land use change, as well as infrastructure were small in the calculation area. Results was since the case was infill building development. Importance of above-mentioned features would increase

with bigger areas and when constructing on natural areas with no existing infrastructure.

When answering to **how well does the neighbourhood level LCA calculation reveal the magnitudes of the emissions per feature, and direct decision making and planning to those features**, there are couple of things to consider. Literature has revealed that buildings, transport, and energy are the most important features when considering the areal development GHG emissions. Including areal features like networks provides more information but is not as significant. Completed calculations and results used from previous calculation concluded to fairly similar results. Completed calculations would suit for opening the discussion of GHG emissions in early-phase planning and are such useful. They reveal the most important features and offer a possibility to discuss of these features and possibilities to affect them via planning solutions within a development area. However, both completed examples excluded vehicle production emissions while NTNU tool included this category and detected it to be significant. Vehicle production emissions example demonstrate the importance of a system border setting, which is needed to be done, but is complicated with a complex setting like areal emission calculation. When interpreting the results, one must understand what is included in the calculation and what is not. Border setting excludes features which might be useful in some cases and no areal model describes the reality to detail. Using a simplified model may ensure the use of any model at all, and such open the discussion for possible emission results. In later phases it may be useful to do a separate calculation for some features excluded from the original model or assessed with too many simplifications.

Answers to research sub-questions suggest that when properly done **neighbourhood level LCA can produce relevant information for low-carbon neighbourhood level planning by verifying the planning solutions which reduce the overall GHG emissions of the plan**. In the next chapter is presented an example process of how neighbourhood level LCA should be completed in early-phase to produce relevant information to support decision-making.

7.4 How to guide neighbourhood level low-carbon planning

This chapter provides a proposition for early-phase LCA process. Suggestion is based on tools used in this study. However, proposed tools can be replaced with local or more sophisticated options when available. Process is designed to be utilized before detail plan is accepted, for example as part of real estate owners' development proposal and detail plan appeal. Process is designed to be used by city planners, real estate developers and real estate owners, as well as environmental consultants. Organizations and owners may require external resources to complete the process due lack of resources or amount of

knowledge. To complete calculations required during the process calculation performer is required to have reasonable understanding of LCA in general as well as ability to assess the results and calculation system borders as well as to be able to report the results explicitly to stage holders without further understanding of calculation methods and used data. Proposed calculation process consists of five steps. Areal baseline calculation, areal case calculation, calculation with building approach, A1 to A3 building optimization, and additional assessment. See figure below for process description.

Figure 34 Early-phase LCA guiding process description

However, when utilizing previously developed LCA calculation tools, it is essential to evaluate the model system borders and used data and their suitability for current occasion and case. The following chapters goes through

potential parameters to be needed to adjust for proposed areal calculation tool HAVA and problematic features for building calculation tool 3D Carbon Designer, as well as briefly discusses the options for additional assessments. However, due to the complex nature of neighbourhood developments, adjustable parameters may vary between cases and do not limit to those presented below.

HAVA - Building carbon handprint

Depending on the building use type carbon handprint is 35 to 42 % of the carbon footprint in HAVA. Additional wood construction effect for increasing handprint is 285 kgCO2e/GFA for all use types, as well as decreasing footprint 70-115 kgCO2e/GFA depending on the use type. Carbon handprint calculation is based on (Bionova Ltd, 2021) report, where maximum reductions including low carbon, energy class and energy supply solutions were for example:

- residential buildings were estimated to be 36 %
- offices 30 %
- schools 34 %
- Not including an additional decarbonisation scenario which is defined in the §33 of the building energy performance decree.

Carbon handprint is shown in separate category in the HAVA results, which is according to the recommendations for carbon handprint. While calculating carbon handprint offers a possibility to discuss the material choices in structured way for net zero solutions, and maybe a motivating target, it does not come without problems. Handprint can be misused as presenting cases as net zero solutions when definitions and measured units are not clearly defined. Handprint may include hidden emissions originating from third partly actors earlier or later during the life cycle and handprint can be used for greenwashing, for example by covering high carbon footprint values. (Häkkinen, Nibel, & Birgisdottir, 2021) When doing an early-phase planning one can aim for decreasing the footprint and/or increasing the handprint. In HAVA parameter wood construction as planning ordinance, has a huge impact to the handprint, while assumed standard level handprint is already significant. This may lead to a simplified solutions where wood construction will solve the carbon footprint problem for the building. However, wood construction benefits should be studied together with carbon sink targets in national, but also on global level to reach a sustainable use of wood as a construction material in large scale.

HAVA - Energy electricity emission intensities gCO2e/kWh

In literature energy emission intensities have been detected to be one of the most significant parameters for neighbourhood developments. In HAVA energy emissions are calculated with analysis period average multiplied with

average or stated consumption. Emission intensity averages are based on target scenarios where Finland will be carbon neutral by 2035, and energy emission levels are in accordance with the target. District heating analysis period emission intensity average 36,5 (2025-2075) HAVA DH scenario is created by Helen Oy, align with this district heating emissions should be calculated with the local scenario.

For analysis period electricity emission intensity average is 23,8 (2025-2075). HAVA uses TEM scenario, used scenario should be according to national recommendations. Below is presented a graph presenting the used electricity emission intensities in FIN building declaration compared to HAVA. Note that values for HAVA are estimated from a graph in (Puurunen, Mattinen-Yuryev, & Soininen, 2021) page 33 and value points are here one per decade which changes the shape of the figure. However, figure demonstrates the significant difference between the used scenarios.

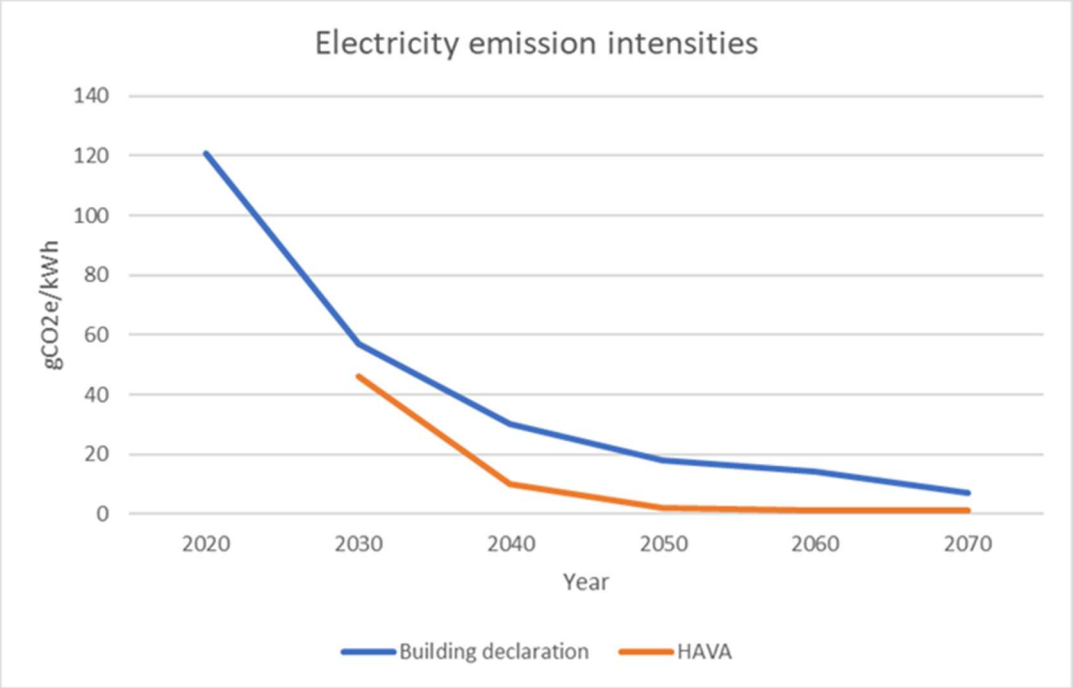


Figure 35 Electricity emission intensities according to building declaration and HAVA scenarios

Too rapid decrease in energy emission intensity scenarios during the next decades may reduce the incentive to consider energy efficiency or local sustainable energy production measures to the level they should be. Since scenarios for several decades include lot of uncertainties it is recommended that national scenarios would be used, but also to calculate comparative scenarios to demonstrate the effect of the scenarios.

HAVA – Transport

HAVA includes only gas pipe emissions, meaning not including electricity and fuel production emissions or vehicle production emissions, which leads to lower significance of transport emissions. Source for number of trips (trips/year) is Liikennetarpeenarviointi maankäytön suunnittelussa (transportation needs in land use planning) planning guide from year 2008 by Ministry of Environment. When using the tool, it may be required to assess the compatibility of used transport data and current situation.

In HAVA is used emissions per unit gCO2/pkm average for the whole calculation period

- personal vehicles 24,1
- public transport 4,4

NTNU background material provides well to wheel emissions snapshots gCO2/pkm for 2020, 2040, 2060 and 2080 shown in the table below.

Table 10 NTNU background material WtW emissions gCO2-eq/pkm (Lausselet, Borgnes, & Brattebø, 2019)

	2020	**2040**	**2060**	**2080**
PV gasoline	126,10	93,77	69,74	51,86
PV electric	3,10	1,50	0,81	0,60
bus diesel	65,46	48,09	35,33	25,96
bus electric	1,70	0,82	0,45	0,33

While the presented values above are not directly comparable with HAVA values demonstrate the possible problems created by the assumptions used for vehicle stock scenarios. Pace of transport electrifying has significant effect to the transport emissions and used unit emission for personal and public vehicles should be revised when new estimations are available.

3D Carbon Designer - YM

When completing the building level A1 to A3 calculation with OneClick LCA 3D Carbon Designer HVAC is not included to the Finnish reference building, while it is available for international reference building. According to the Finnish building declaration the main building service systems should be included in the assessment. Such, the current version of 3D tool is lacking this data, and the main HVAC systems need to be assessed separately. Also, it would be useful to utilize nationally recommended CO2data.fi data, but as previously stated, the reference building utilizing only this data is uncomplete.

There are multiple material choices for building parts and quantity can be modified for both building parts and main service systems (international reference building). Such if it is known that some material with especially low,

or high CO2e-level will be used, the emission amount can be included in the plan by modifying the material amount parameter for corresponding material, even when specific material is not available. In this study the 3D tool was utilized on superficial level, assessing the magnitude of building level emissions, and included building parts. Usefulness and accuracy of the tool in more detailed material level assessments is needed to be studied separately. This study used the tool only for the early-phase overall assessment, and such all material options for building parts were not tested. Such, while changing the materials from the given reference building structure it is recommended to test options widely to find the best solutions.

Additional assessments

Last step of the proposed early-phase planning LCA assessment process are additional assessments. Depending on the case some additional LCA studies may be useful. This study recommends considering at least four additional studies: transport, sustainable energy potential, pre-construction, and specific requirements for the buildings. One, or several additional studies may be useful, when the case has customized solutions, location or soil is special, local transport changes due the development, or use of the buildings require specific solutions, etc.

- Transport LCA assessment is recommended when the development creates significant change to the local transport. Possible reasons for assessment are, but not limited to, (1) significant change on the population which leads to a need for significant infrastructure developments, (2) area which creates additional transport like logistic centre plots, (3) significant infrastructure projects extending in the area, for example rail.

- Sustainable energy potential assessment is recommended when there is an option for other energy solutions than district heating and local electricity grid connection. Possible solutions can be heat-pumps, wind, solar power, waste-water heat recovery, and utilization of condensate heat from cooling processes.

- Pre-construction LCA assessment is recommended when development area is large, and such has significant pre-construction phase. Also, development areas with soft soil, requiring extensive foundation will benefit from early-phase pre-construction LCA. Pre-construction LCA is recommended to be done in Finland by utilizing co2data.fi infrastructure database. Content of the study is recommended to be modified case specifically, since pre-construction may have significant role in some cases, but solutions are not standardised due to the local site and its features.

- Specific requirements for the buildings may conclude to a need of more detailed building calculation already in early-phase. Specific requirements may be due to the use-type, material choices, recycling of building materials, etc.

7.5 Validation discussions

Neighbourhood level LCA is relative new concept, and such peer reviewed research material of the topic is limited. Furthermore, since the case study includes national (Finnish) approach, and there is hardly any peer reviewed research material available of the topic in national level, such additional validation of the study results is needed. Validation was done as validation discussions with six LCA and/or environmental management experts presenting Finnish municipalities, consultation companies and real estate investors.

Discussions included general discussion on LCA calculation on neighbourhood level, iterative calculation process for LCA, most important areal features; buildings, energy, and transport, role of built environment in preventing climate change, and a few other themes which were stated relevant during the discussions. Discussions were loosely structured around the most important themes but allowed experts to bring up themes and viewpoints based on their expertise also outside the preselected themes. Other option would have been a strictly structured interview, but due to the different backgrounds of the participants as well as complexity of the topic, it was assumed that less-structured format would allow participants to bring up more broadly the important lessons they have learned while working on the field.

LCA on neighbourhood level – general notices and iterative calculation process

Topic of the study has been perceived timely, role of GHG calculations is increasing also on neighbourhood level. Calculations are increasingly required also in the planning phase and not only as stating realized emissions afterwards. It was also brought up that many organizations and companies are currently developing and contemplating GHG calculation models and tools. From the calculation model should be explained what assumptions and simplifications were done in the model design. Not only what background data is used, but also to present most important data graphically, so data is easier to understand. When understanding the model and data better, it is possible to interpret the results better. Model should focus on revealing the magnitudes of emissions, and to focus on important features. While participants agreed with multiple things in the model design, there were also differences. Some said that different scenarios origin from different data may be good in the early-phase design, some argued that all design-steps should be

calculated with same background data, and no additional scenarios should be required.

Participants highlighted that calculations should be done to help decision-making, not calculating just for the sake of calculation. These calculations should promote areal development, which may lead to different calculation requirements on different areas. As example of special areal features pre-construction was brought up. One participant said that pre-construction may have summed up to 50 % of development GHG emissions in some cases, and in existing city structure significant land construction increases required transport when soil cannot be stored on the site. One of the disadvantages of HAVA was noted to be the lack of easy-to-do pre-construction assessment. Accuracy of used tools created discussions. If HAVA, or other tool designed for specific locations is used, it may create flawed results if applied elsewhere. Also, special features in certain areas should be included. Used model should optimize multiple indicators, not only GWP. This was since in early-phase planning environmental matters should be discussed more broadly than only focusing on the GWP. It was also wished that model would help to understand better the effectivity of a city structure, GHG calculation should be done to buildings and areas with different use-types, impression was that currently focus has been mainly on residential construction projects. Role of the owner was also noted. Owner's environmental targets direct the ambitiousness of the project. In detail plan phase changes are often generated by the real estate owner.

Neighbourhood level LCAs are still quite rare, so any calculation done is better than typical situation, where none is completed. There were however differing opinions of the current tools. While some said that already completing calculation with HAVA (or similar) is good, some were more doubtful, and suggested that it might be too simple to guide planning enough. Participants agreed that current neighbourhood level LCA tools are limited, and development should be done, however, clear direction where the calculations should be developed could not be formed. It was agreed that calculation should be easy enough in early-phase, but experts with different background valued different themes. Iterative LCA was mainly found interesting and good idea, however, there were worries, of how different tools can be integrated together during the calculation process.

Most important features: buildings, energy, and transport

For **buildings** in early-phase use of different reference buildings may not be a problem, different scenarios can also be good when estimating emissions. Using different refence buildings also gives a possibility to calculate an average of different options. However, it was noted that if early-phase results are not comparable with national building declaration system it may be

problematic. Also, if doing an iterative process, it was said that all steps of the process should use quite similar background data. It was brought up that via detail planning regulations building e-value and use percentage of recycled materials could be guided, while this has not been tested in practice. It was wondered, if the LCA tool could or should include these parameters.

Energy emission intensity over lifecycle has been detected to be a significant uncertainty in LCA. How to handle the uncertainty divides opinions. Calculation period is one matter. While some prefer longer calculation period than 50, it was noted here that longer period, like 100 years, increases uncertainties related to energy issues. On the other hand, it was noted that when energy emission intensity decreases in the future the significance of the uncertainty decreases for GWP calculation. One proposed solution was also to calculate with current emission intensities, while other solutions was to calculate several scenarios. From HAVA it was criticized that it uses different electricity scenario than national building declaration system. From the district heating perspective, it was stated that system in HAVA, calculating with local values, is more practical than national average. However, it was also proposed that for energy could be calculated both local and national average in the model. Also, possibility to include other heating options, like ground source heating pump, was recommended.

During general plan design **transport** planning has more significant role than in detail plan phase. In general, it was noted that transport calculations are challenging, future prediction is challenging, and they include lot of uncertainties in the early phase. Question of trips included to the calculation was discussed, since results will be different if they include only traffic from the area or also traffic to the area. Possibility to include logistics was also mentioned. Option to do a separate transport assessment was suggested, especially since free-time traffic increases and predictions are harder to make, also in case of having transport hubs like logistic centres in the area. Need to update commonly used data was also brought up. “Liikenteen tarpeen arvioinnin maankäytön suunnittelussa” guide from 2008, used example in HAVA, was stated to be a good source, however experts would have preferred more timely data, if it would be available. HAVA was criticized for including only gas pipe emissions, not fuel or vehicle production emissions, since different vehicle types produce emissions differently during the life cycle, comparing for example diesel and electric cars. However, it was noted that it is hard to determine, what is a correct detail level for transport in early-phase LCA. Some experts preferred also including vehicle and fuel production while some preferred including only the use phase. Against assumption done in some tools, it was also argued that after certain point density starts to create more traffic, and such should not be used as only parameter affecting traffic amount.

In early-phase design solutions like car and bicycle parking locations may not be decided, or they may change later during the process and such demand for recalculating may occur in later planning phases. Need for re-calculation also raised a question if calculation system borders should stay similar during the entire process, this would allow comparing the results of different planning stages better. Transport was noted to be an important feature also for service planning of the area; accessibility, electric charging stations, public transport, which should be considered in early-phase. Also, ensuring good accessibility with walking and cycling was noted. It was remained that bad planning of some elements in the area may ruin otherwise good accessibility in the area, which will affect to the realization of emissions in the area. There was also discussion of what should be optimized of the transport, emission intensity, traffic amount, or both. Traffic creates also other problems than just the GHG emissions.

Other valued themes: density, new construction vs. refurbishment and behavioural change

The most significant areal features were discussed with all experts, but also other themes were presented to see what themes were found important. **Density**, and possibility to study its effects, for example by changing m2/resident parameter, was valued by some experts. Experts did not have a clear answer if apartment size should be regulated on municipal level. It was noted that some areas, like student villages, are already created as denser areas. Results provided as GWP/m2, and GWP/resident were both understood as useful. It was stated that GWP/m2 result alone may not be enough, and it can be problematic if space efficiency does not affect the results. It was also wondered, if space efficiency would be a better parameter for offices, schools, etc., for other than buildings than those in residential use. However, **new construction** is only a part of the built environment sector. **Refurbishment** developments should also be discussed. Demolition and refurbishment cases were stated to be more complex. Economical aspect was stated to be challenging here. Building to existing structure was stated to be more expensive, so finding balance with economic and other parameters may be challenging. Results stated as GWP/m2 was valued with refurbishment developments.

Complex theme **behavioural change** was found interesting by some experts. There was question of what should be regulated and what not. Changing construction process is already demanding, but even more so if behaviour of end users is wanted to be affected. Predicting how people act currently was already found hard to do, let alone trying to predict behaviour during the whole life cycle of a neighbourhood. It would be an advantage for a calculation tool to somehow measure change in the area, but, this was thought to be

too challenging. Only brought up solution was somehow to change and measure transport mode share.

Built environment and climate change

At the end of discussions experts were asked how they see the role of built environment in preventing climate change, and what they think of the current development. Experts shared the view that there are lot of uncertainties in the field and lot to do and change during the coming decades. Climate targets were seen ambitious, and decisions made, and solutions created, should be in line with those targets. However, it was noted that in built environment users tends to mix up things and things do not realize just as planned. Also, unclarity of carbon neutral area definition was noted be problematic. Definition is not regulated, and target setting can vary. It was stated that calculating emissions should be as precise as calculating costs, feature with highest value should be cut. Problem of how to calculate carbon sinks was also brought up, it was not felt to be well-regulated. However, it was reminded that in city areas carbon sink are not near as important as what they are in agriculture and forestry. It was felt that magnitude of carbon sink in city areas is not well-understood and such preserving green areas in cities may be reasoned illogically. Green areas were understood as important features of a city, but more for leisure, run off water management and habitats, than as carbon sinks. Such it was suggested that using different indicator, like green factor for them makes more sense.

National building declaration and carbon footprint limit values are coming into effect; however, it was reminded that these do not ensure carbon neutral areas, or even buildings. Building level evolvement was appreciated, however, it was stated that existing buildings should be guided more. LCA tool development was understood important. And other features, like transport, was stated to lack behind the building level guidance. It was suggested that other features should be optimized more in areal level. An expert also raised a fear that we may end up in situation where we should not build at all to be able to reach the climate targets. Fast actions including carbon footprint limits and carbon storage were seen beneficial to avoid future problems. Wood construction in coming decades rose mixed feelings. It was stated that used wood should be directed buildings, or other long-lasting structure. However, it was noted that new forests grow slowly, in those terms 2035 is close. So, it was also stated that maybe more existing forest should be preserved. Re-using and recycling of materials was seen important in future development.

8 Discussion and Conclusions

Study consists of seven phases. Context includes two phases, literature review of environmental assessment methods, and literature review of neighbourhood level LCA international best practices. The study part starts with legislation comparison of Finnish and Norwegian building and areal LCA and continues with study of Finnish and Norwegian neighbourhood level LCA tools. Study is completed with example calculation utilizing tools; HAVA, OneClick LCA NS3720 based tool and OneClick 3D Carbon Designer. Findings from the research phase are discussed with national experts via validation discussions at the end of the study. Study ends to a discussion and conclusions part to clarify and sum up the findings of the study. See process chart below.

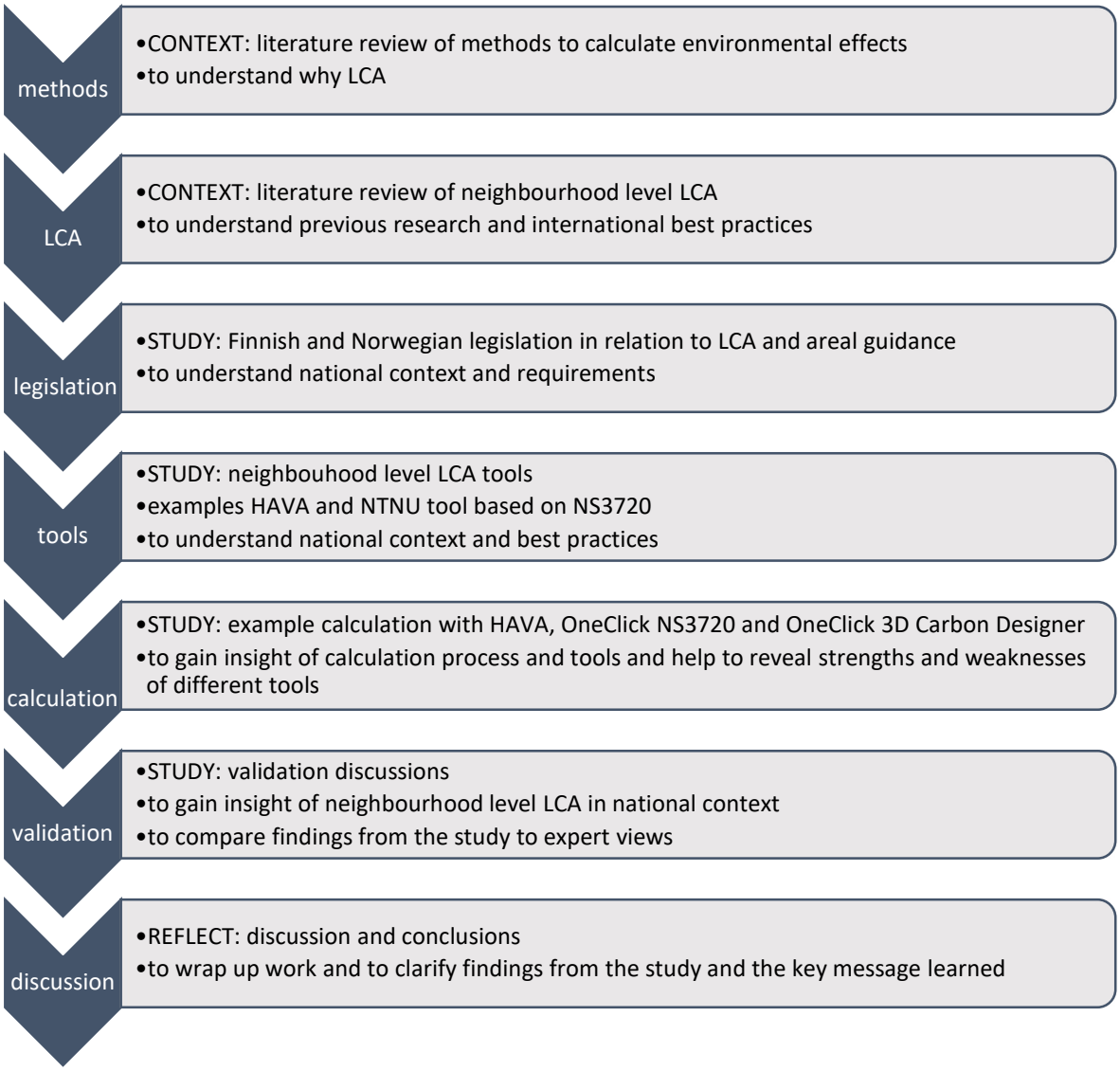


Figure 36 Study process chart

Climate change and agreed commitments to prevent alarming future scenarios require prompt actions. However, due to the complex nature of environment, economy and societies best practices are not always unambiguous. Multiple environmental assessment methods and tools have been created to help to understand and guide decision-making. Methods include different parts of natural and human made systems to explain certain parts of the larger system. LCA has been selected in many cases to be the method used for environmental assessing. LCA benefits from possibility to use several clear indicators, which with life cycle thinking, can be used to prevent problem shifting between indicators and life cycle phases.

Neighbourhood level LCA should be used already during the early phase planning to help to guide the decision making towards low-carbon planning. In early phase LCA calculation should reveal the magnitudes of the most important features in the area, to help to cut GWP of those features. Literature and completed study suggest that in the most areas buildings, transport, and energy consumption form majority of area's GWP. However, in early phase also land use change and infrastructure should be included in the LCA to bring up their effect and to stir up discussion also of those features and possibility to affect them with planning. To include land use in the calculation is especially important in cases where there is deforestation or restoration due neighbourhood development. In case of infrastructure objects like new roads, rails, and bridges should at least be considered.

However, in all cases overall areal calculation may not produce enough information to support decision making. Study suggests that LCA calculation in early phase should be an iterative process, targeting the calculation from an overall process towards more detailed planning of selected features. Process chart below presents typical case, when neighbourhood development is built within existing city structure, where buildings is the feature with most significant GWP, and being a feature, which planners can most effectively guide towards low-carbon solutions. Additional assessment can be done for example to transport, sustainable energy potential, pre-construction, or other relevant feature with significant GWP in the neighbourhood level. Transport LCA may be needed for example if area contains logistic centres, or other buildings which generate more traffic in use phase than average areas.

Figure 37 Iterative LCA process to support neighbourhood level planning towards low-carbon solutions

Process presented above is a LCA process, for calculating GWP. However, sustainable neighbourhood should consider also other indicators than GWP. LCA calculations with only GWP indicator are more vulnerable with problem shifting, however it can be justified to use only GWP in early-phase planning, and do more thorough, more complex and time consuming, calculation in later phase, when there are fewer varying objects. Even with multiple indicators LCA calculation alone does not tell enough of the neighbourhood's sustainability. It is often beneficial to use several calculations to explain the neighbourhood's sustainability. For example, combining LCA with consumption-based approach and biodiversity assessment produces additional information of neighbourhood's overall sustainability. Other choice could be using a scorecard method, like LEED communities. However, in early phase combining too many, or too complex methods may be a hindrance. It is often better to use simpler tools, which allow calculating several scenarios in shorter time and with less resources, than trying to complete one thorough calculation which in early phase uses preliminary data, not revealing the end results precisely, and does not provide comparison possibility.

When comparing to previous research, study concluded with same most significant features for neighbourhood level planning, including buildings, transport, and energy consumption. However, the research process where example calculation was completed with tools designed for use in different countries, here Finland and Norway, was less used. While using different tools impair the result comparison it is a good way to concretize difficulties and uncertainties in early phase LCA. The most significant difference in the LCA results between tools was due to the energy emission intensity scenarios used for the calculations. While real estate developer may not be directly able to affect for example district heating emission intensity, used scenarios for features during the life cycle may affect the status of the area. For example, if a neighbourhood is wished to gain a zero-carbon status, this kind of scenario setting affects significantly to the requirements for the area. When using scenarios, or any other estimated data often used in early-phase, it must be clearly stated, what kind of scenarios and data is used. Especially, when stating that a neighbourhood is a sustainable or a zero-carbon neighbourhood there should be clear, unified, and strict scenarios and data used for the calculation. During the past decades scientific community has been expressing worries of the fulfilment of environmental targets to prevent climate change and biodiversity loss. Environmental assessment methods and tools should not add to this burden by allowing greenwashing and presenting the calculation results in a form which diminishes the magnitude of created environmental effects.

However, despite the used environmental assessment tool the results, and even more the realization of the environmental effects due a development, are dependable on the people implementing the calculation and development project. On its part this study has been revealing the usefulness of early-phase LCA to encourage the use of LCA for neighbourhood level developments early-on when it is still possible to affect various features. Research hypothesis suggested that *neighbourhood level LCA can produce relevant information for carbon neutral zoning, and such assist decision-making, by answering to what kind of plan leads to low-carbon zoning and why, and such assists decision-making of city planner, landowner, developer, etc.* LCA points out the significant emission origin objects. However, LCA does not provide straight answers of how to design a neighbourhood. For example, LCA can tell that emission intensity of private transport has significant impact to overall emissions. But designers need to decide how to decrease the emission intensity. Can we promote the shift towards electric transport? Can we promote the shift towards next-generation vehicles, combustion vehicles which consume less? Or are these beyond our reach, and should we focus on reducing the amount of transport or trip lengths? Or both? While one answer is that we should affect all features, and all parameters towards low-carbon design, we also need to consider economic aspect and LCA can help us to target our resources to those design solutions which create the biggest impact.

There are still many unanswered questions considering the neighbourhood level LCA. Balancing between simplicity and useful information is something to which there is no clear answer at this point. While it is useful to have extensive selection of areal features in neighbourhood level LCA, the calculation should not become too detailed, too complex and such too time consuming and resource demanding. If early phase calculation is too demanding, risk of not using LCA as early phase guiding tool increases. However, since neighbourhoods can vary significantly on size, building use-types, new infrastructure, change in traffic amount, natural habitats in area, etc. it is difficult to create a one calculation process for all areas. Such, in this study is suggested the use of additional assessment when neighbourhood has special features. However, clearer instructions of when to complete additional assessment and what to include to them is still needed. Also, how to assess sustainability of a neighbourhood on more extensive level requires more research. Completing also for example CBA and biodiversity assessments would elaborate the understanding of neighbourhood plan affects to sustainability in an area. How to complete and merge these assessments with LCA should be studied more in the future.

Low-carbon and sustainable solutions in built environment are often complex, good effects somewhere may backfire elsewhere. Wood construction

and their relation to carbon sinks is just one example of sustainable solution, which while lessening the construction phase emissions, leads potentially harmful effects elsewhere. More research is needed from solutions which are claimed to be sustainable within built environment. These solutions should be inspected also outside of the built environment field. Sustainable solutions are also connected to problem of carbon neutrality and zero carbon definitions in areal developments, which requires clarification. In CEEQUAL net zero carbon definition consist of construction phase and operational energy with definitions presented below.

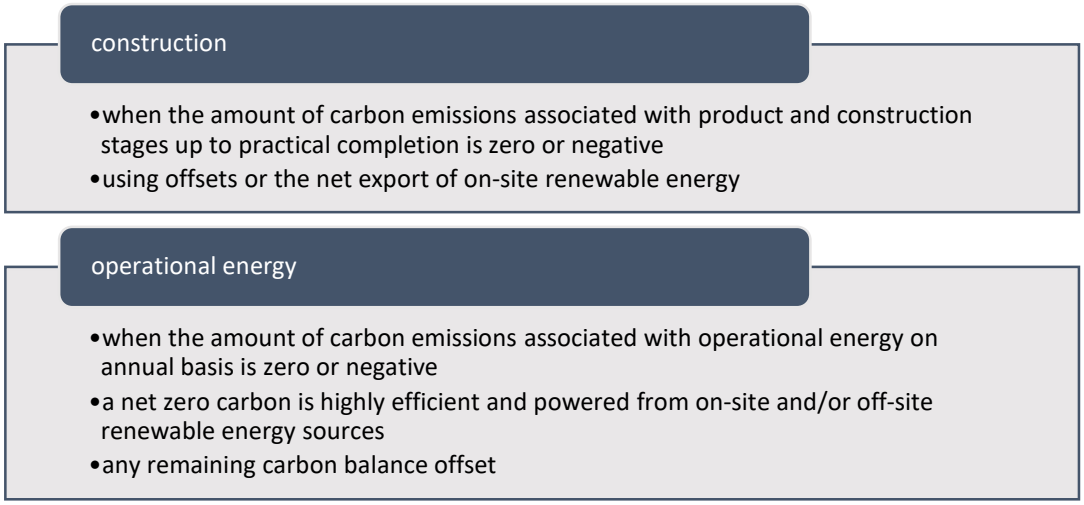


Figure 38 Carbon neutrality requirements (BRE Global Ltd, 2020)

Since Finland targets to be carbon neutral by 2035 and to become carbon negative after that, is it not a net zero carbon level, to which our new and refurbished neighbourhoods should be targeting? More research should be done on how a net zero carbon neighbourhood can be developed, but also which offsets should be allowed to be used when calculating a net zero carbon neighbourhood. In the validation discussions experts agreed that to reach the 2035 carbon neutrality and later targets, a lot needs to be done and there are still many uncertainties how these targets will be accomplished. LCA is a one method which can help us to verify if we stay within the limits, which will allow us to reach our environmental targets. Common use of LCA should be extended from building level also to neighbourhood level, and we should learn better to utilize the methods and tools which have been developed already.

When doing an early-phase LCA guiding one must understand that calculating the emissions once, or twice is hardly enough. To guide the development often several calculation phases is needed. This study suggests use of iterative process, where LCA is calculated for neighbourhood level, and then to most significant features in the area. Within the calculation of neighbourhood level

or single feature LCA it may be required to be calculated several times with different solutions to be able to reach sufficient GWP level. Figure below presents this calculation process within a level or feature. After target level setting and baseline calculation the case LCA should be calculated with different solutions until solution which enables the target is reached.

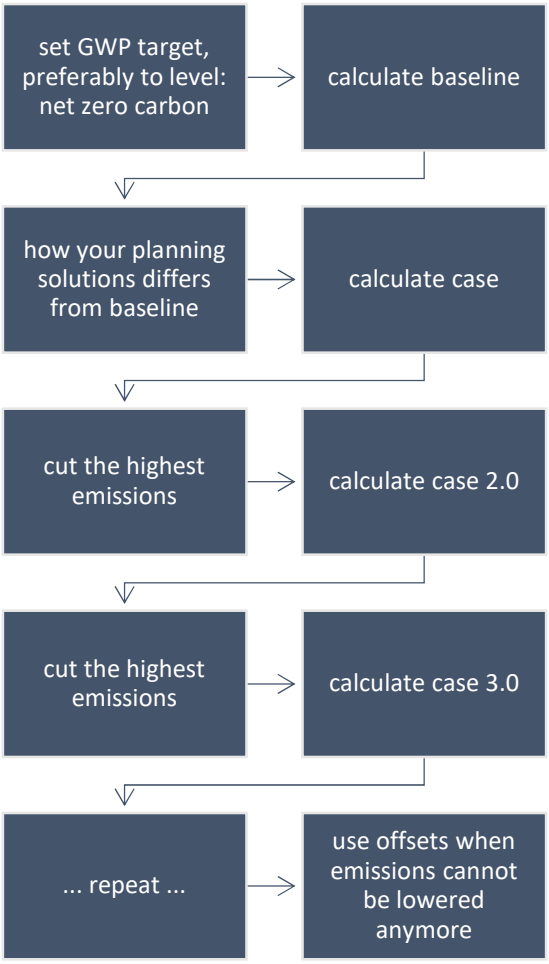


Figure 39 Process chart towards carbon neutral and net zero carbon development

LCA process should not end when the construction of a neighbourhood is ready. LCA should be monitored and improved during the neighbourhood's life cycle to verify the realization of the targets, as well as to encourage improvements during the life cycle. Also, since neighbourhood serves the population the habits affecting energy consumption, transport, etc. should be monitored and compared against the target, especially if neighbourhood claims to be a low-carbon or net zero carbon neighbourhood.

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A. Calculation process description for HAVA & OneClick NS3720 tool

Calculation process

STEP 1: Gathering basic information (see case description on page 105)

STEP 2: Land use change estimation and allocation

- Land use change
  - marking land use types and changes to detail plan maps (see case description)
- Building allocation
  - land use changes per building in the detail plan maps (see case description)

STEP 3: HAVA basic

- Excel version 1.1., 4.11.2021
- Calculate basic version according to the HAVA document instructions
  - Puurunen, E., Mattinen-Yuryev, M., & Soininen, S. (2021). *Helsingin asemakaavojen vähähiilisyyden arviointimenetelmä (HAVA)*. Helsingin kaupunki / kaupunkiympäristön toimiala, viewed 3 February 2023, https://api.watch.kausal.tech/documents/107/Asemakaavojen_v%C3%A4h%C3%A4hiilisyyden_arviointi_-raportti.pdf.
- Land use category simplifications
  - yard includes planted green spaces
  - streets and squares include parking, paved yard, and walking = paved yard area
- Transport according to the model
  - public transport zone
  - trip lengths according to the model
- Energy according to the model assumptions
  - not actual consumption

STEP 4: HAVA options

- Transport: options calculated with
  - car zone
  - walking zone
  - trip lengths +25 %
  - can be used to estimate different location of the planned area, trip lengths, effects of city structure, accessibility of services nearby

- Energy: options calculated with
    - model estimation for consumption +25 %
    - can be used for different energy supplies, but consumption need to be calculated separately, consumption sensitivity

STEP 5: OneClick NS3720 based tool

- Basic information selected for the calculation
    - information: concrete structure
    - phase: RIBA: Preparation and brief
    - greenhouse gas inventory basis
    - includes: foundation, structure, outer sheath, surface materials, building technology
    - default LCA parameters: material production, phase defaults, electricity IEA2019
- Carbon designer tool
    - Norwegian reference building
    - GFA (car parks not included)
    - floors above ground (number per building)
    - calculation period 50
    - heated underground floors (number per building)
        - note, car parks in 1 and 6, not showing in the results
    - 1 and 6: steel pipe piling, hard ground, 15 m, due parking
    - 2-5: footing foundation/hard ground, for sand, gravel, silt, clay
    - energy scenario: TEK17 and electricity EU + Norway, 60 years and consumption estimation, electricity-based heating
        - main requirements for TEK17 are low U-values of house constructions and airtightness of the structure
            - floor construction U-value - not more than 0,15 W/m2K
            - outside wall - not more than 0,18 W/m2K
            - roof - not more than 0,13 W/m2K
            - windows and doors (with frame) - not more than 0,8 W/m2K
            - according to: Ekobustas. (2023, February 20). *TEK17 and other energy-efficiency standards, A energy-efficiency class house*. Retrieved from https://www.ecobustas.lt/production/technology/TEK17-building-standards.
- Transport
    - Helsinki Vuosaari area: trip lengths and modal shares based on Matkat aluettain, HSL 2013. Liikkumistottumukset Helsingin seudulla 2018, HSL 2019.
- Construction process

    - averages by the tool
    - land use change categories selected
        - buildings and paved > from mineral soils to buildings
        - planted green areas > from buildings to park
        - forest > deforestation of sparse forest
- Shop (560 GFA) not separately assessed, tool allows only one use-type per building

STEP 6: OneClick NS3720 based tool options

- Transport: options calculated with
    - area Helsinki Kamppi
        - can be used to estimate different location of the planned area, trip lengths, effects of city structure, accessibility of services nearby
    - vehicle emission intensity
        - forecasted emission intensity changed to current emission intensity
            - calculated for all transport modes, separately only to private cars and car-pooling
        - can be used for technology development, and share of electric vehicles in vehicle stock
    - trip length +25 %
        - can be used for city structure, and service accessibility calculations
- Energy: options calculated with
    - Norwegian 60 years electricity emission intensity scenario
    - consumption +25 %
    - can be used for different energy supplies, but consumption need to be calculated separately, consumption sensitivity

STEP 7: Sensitivity analysis

- HAVA
    - trip length +25 % / SR 0,25
    - energy consumption +25 % / SR 0,15
- NS3720
    - emission intensity of cars and car-pooling modes / SR 0,10
    - trip length +25 % / SR 0,11
    - NOR energy emission intensity / SR 0,44
    - energy consumption +25 % / SR 0,47
- Most significant difference between tools:
    - HAVA energy consumption SR 0,15, where as in NS3720 SR 0,47

STEP 8: Comparison of results

- total emissions (HAVA and OC NS3720)
- per GFA per a (HAVA, OC NS3720 and NTNU tool previous results)
- per resident per a (HAVA, OC NS3720 and NTNU tool previous results)
- total emissions and emissions per feature
    - transport
    - energy
    - buildings
    - land use etc.
- emissions as percentages of total emissions per feature
    - transport
    - energy
    - buildings
    - land use etc.
- HAVA scenarios
    - total, ratio, sensitivity ratio
    - original
    - trip length +25 %
    - walking zone
    - car zone
    - energy consumption +25 %
- OC NS3720 scenarios
    - total, ratio, sensitivity ratio
    - original
    - Kamppi area
    - car and car-pooling emission intensity
    - trip length +25 %
    - Norwegian 60 years electricity emission intensity scenario
    - energy consumption +25 %

Case description

Location: Helsinki, Vuosaari, Neitsytsaarentie 2 to 8

Plot
Plots: 91-54-53-5 and 91-54-53-4
Plot area total: 34 765 m2

Buildings
Old buildings, building numbers: 8, 6, 2, 4a, 4b (5 pcs)
Old buildings: 17 089 m2
Old buildings: 12 886 GFA
New buildings, building numbers: 1, 2, 3, 4, 5, 6 (6 pcs)
Infill building, old buildings demolished: 58 261 m2
Infill building, old buildings demolished: 39 091 GFA
Average resident number in Helsinki 45 GFA/person

- Old: 386
- New: 869

Land use categories

Old:	Map markings
• buildings 4 783 m2	(orange)
• parking 6 174 m2	(light green)
• planted green areas 14 461 m2	(purple)
• city forest 4 914 m2	(bright green)
• street 197 m2	(red)
• yard 4 235 m2	(yellow)
New:	
• buildings 10 312 m2	(orange)
• parking 1 745 m2	(light green)
• planted green areas 13 697 m2	(purple)
• street 197 m2	(red)
• yard 8 814 m2	(yellow)

Picture 2 Old buildings areal map, layout City of Helsinki / https://kartta.hel.fi/

Picture 3 Old buildings allocated map, layout City of Helsinki / https://kartta.hel.fi/

Picture 4 New buildings areal map, layout Anttinen Oiva Arkkitehdit 10.5.2021

Picture 5 New buildings allocated map, layout Anttinen Oiva Arkkitehdit 10.5.2021

B. Calculation process description for OneClick 3D Carbon Designer

Basic information for calculation process

- International reference building
- Study period 50 years
- Project phase: preparation and brief
- Model: Finnish ministry of environment building declaration
- Type: new construction
- Structure: not defined
- Scope: foundations, structure and envelope, surface materials, outdoor areas, HVAC

Other project information for calculation process

- building process: construction site and demolition, based on building area
    - building type specific
- Energy consumption: based on HAVA kWh/k-m2/a (grid electricity 50a)
    - residential: 51,0 kWh/GFA (321 000 kWh) (warm net-area)
    - office: 69,3 kWh/k-m2 (311 850 kWh)
    - school: 60,9 kWh/k-m2 (109 620 kWh)
- Building area: construction size area
    - plot ratio (e)
        - residential: 0,6 (11 667 m2)
        - office: 1,25 (4 000 m2)
        - school: 1 (2 000 m2)
- Warm net-area 90 %
    - residential: 6 300 m2
    - office: 4 500 m2
    - school: 1 800 m2

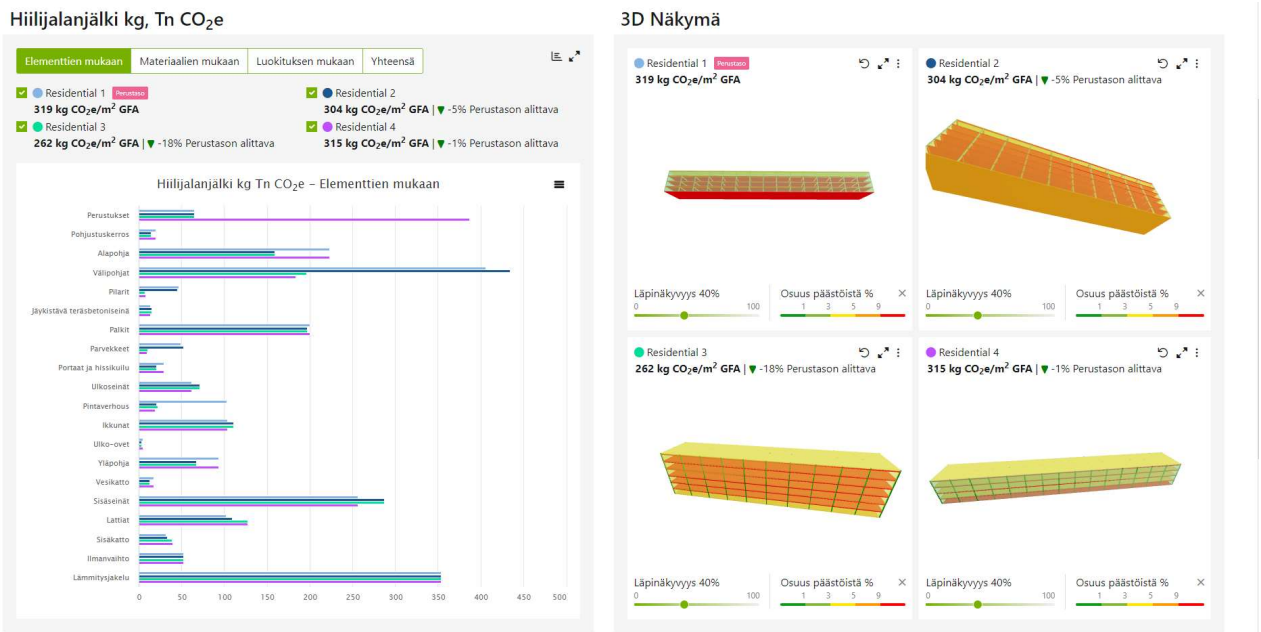
3D Carbon Designer calculation for A1 to A3

Residential building

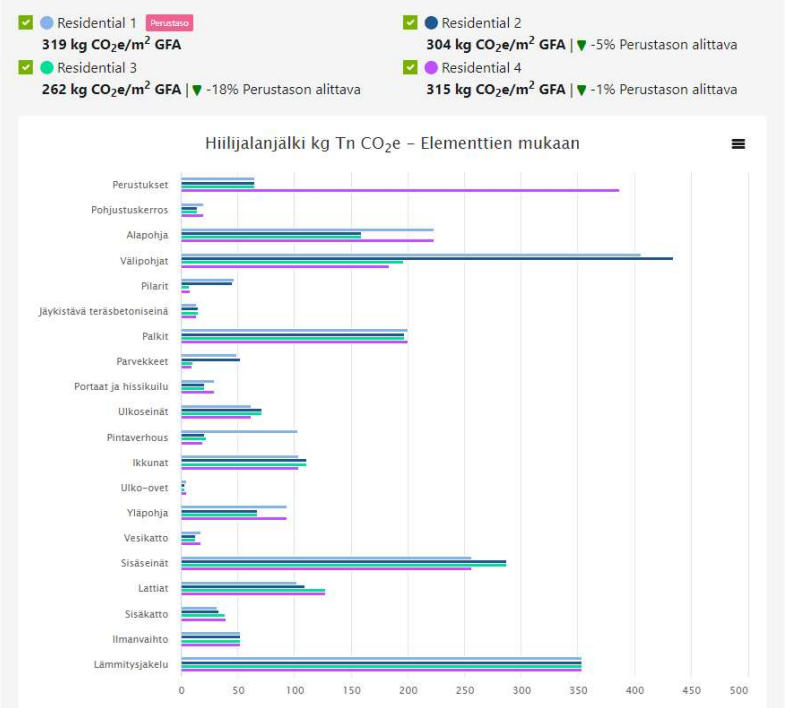
- Area 7 000 GFA
- Scenarios decribed on the table below

Table 11 Residential building scenarios for A1 to A3

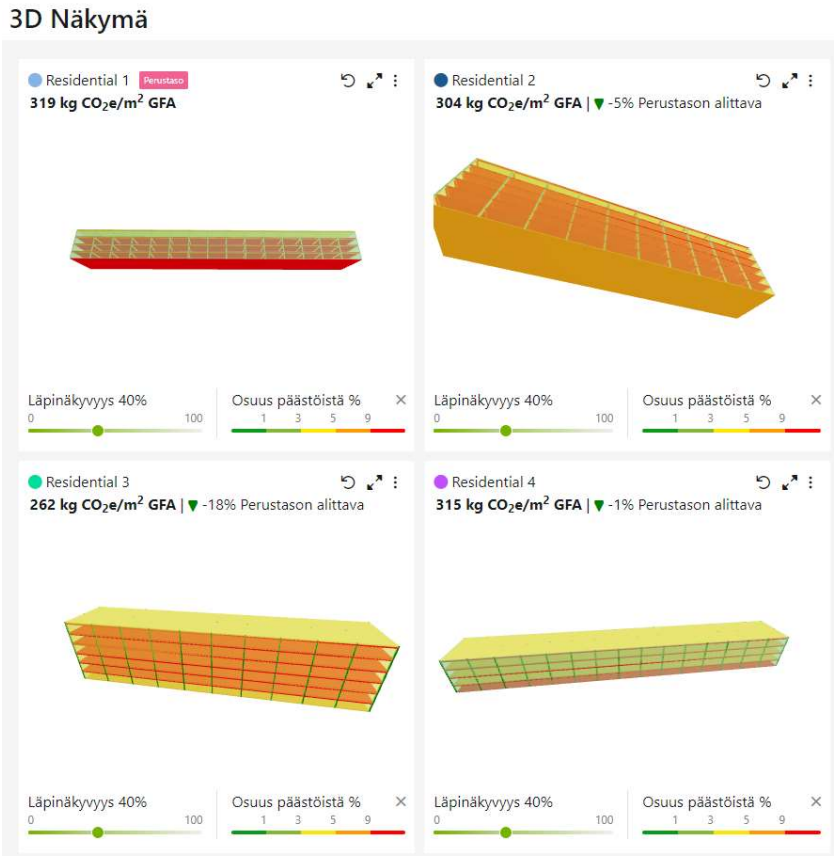
	cellars	above ground floors	foundation	structure	exterior wall surface material
1	1 cold	4	hard ground, footing	concrete	brick
2	1 cold	6	hard ground, footing	concrete	plaster
3	1 warm	6	hard ground, footing	wooden intermediate floors, pillars, balconies	wood
4	1 warm	4	soft soil, steel piles 15 m	wooden intermediate floors, pillars, balconies	wood



Picture 6 Overview of residential building 3D Carbon Designer scenario results



Picture 7 Residential building 3D Carbon Designer results per class



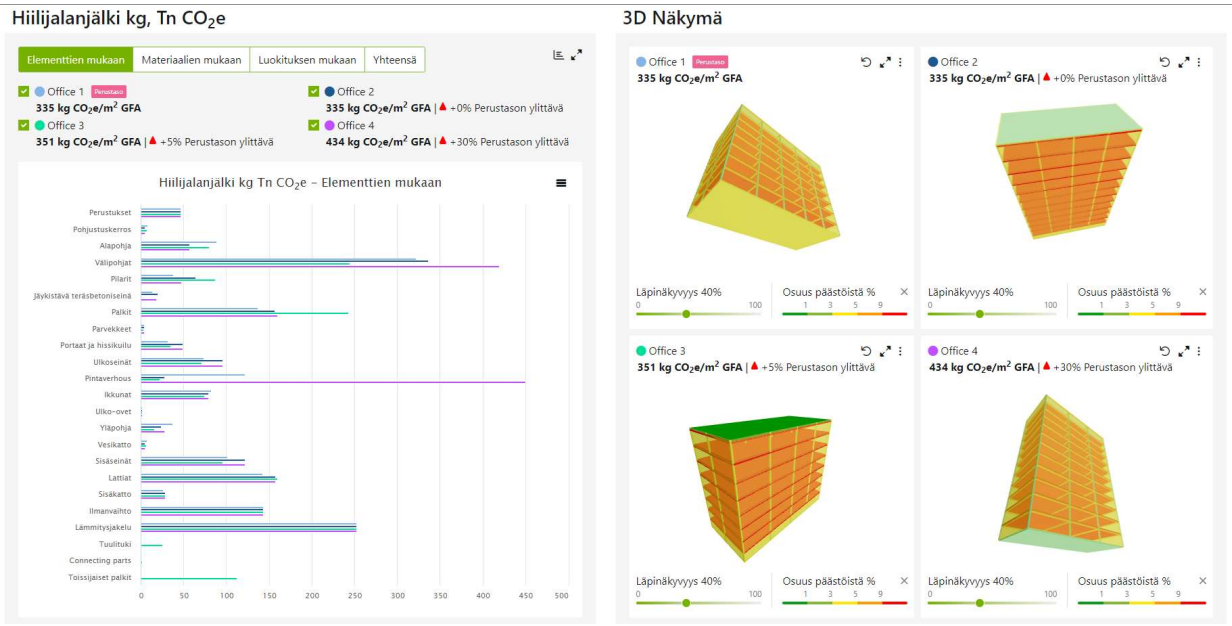
Picture 8 Residential building 3D Carbon Designer visualizations, green – red bar > increasing share of emissions

Office building

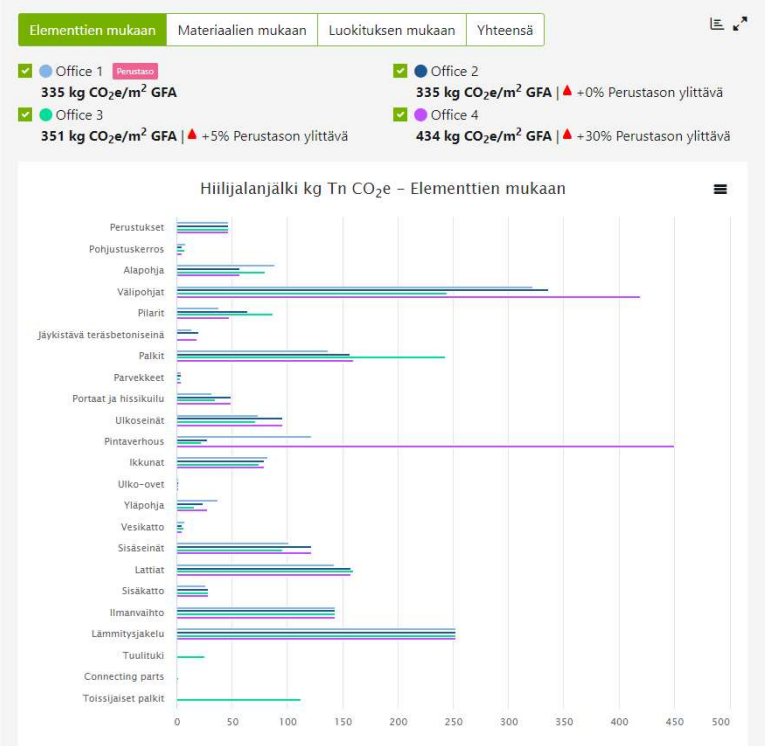
- Area 5 000 GFA
- Scenarios decribed on the table below

Table 12 Office building scenarios for A1 to A3

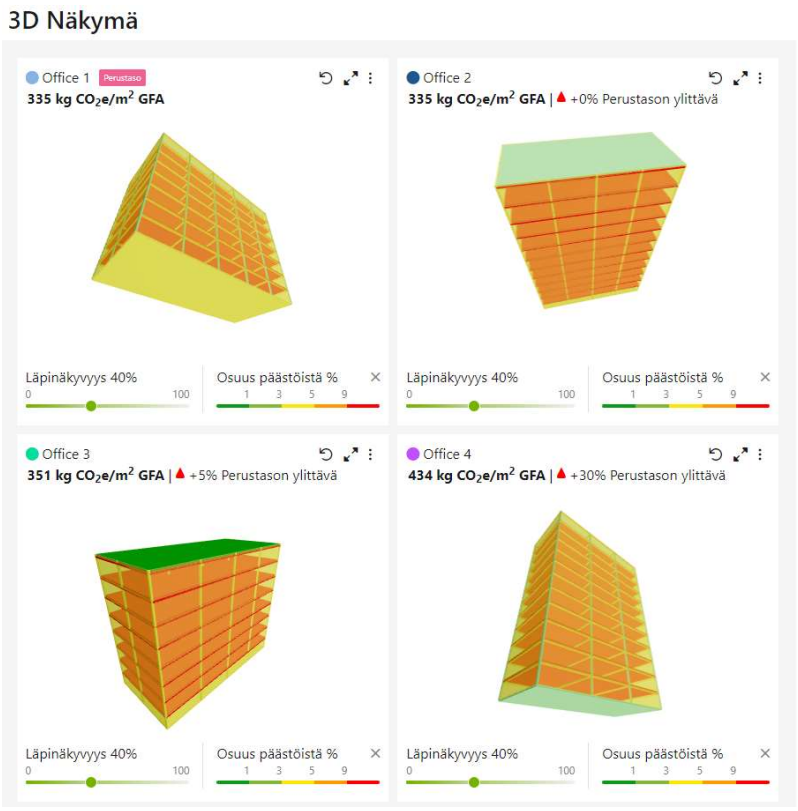
	cellars	above ground floors	foundation	structure	exterior wall surface material
1	1 cold	8	hard ground, footing	concrete	brick
2	2 warm	12	hard ground, footing	concrete	plaster
3	2 warm	8	hard ground, footing	steel	wood
4	2 warm	12	soft soil, steel piles 15 m	concrete element	glass + aluminum



Picture 9 Overview of office building 3D Carbon Designer scenario results



Picture 10 Office building 3D Carbon Designer results per class



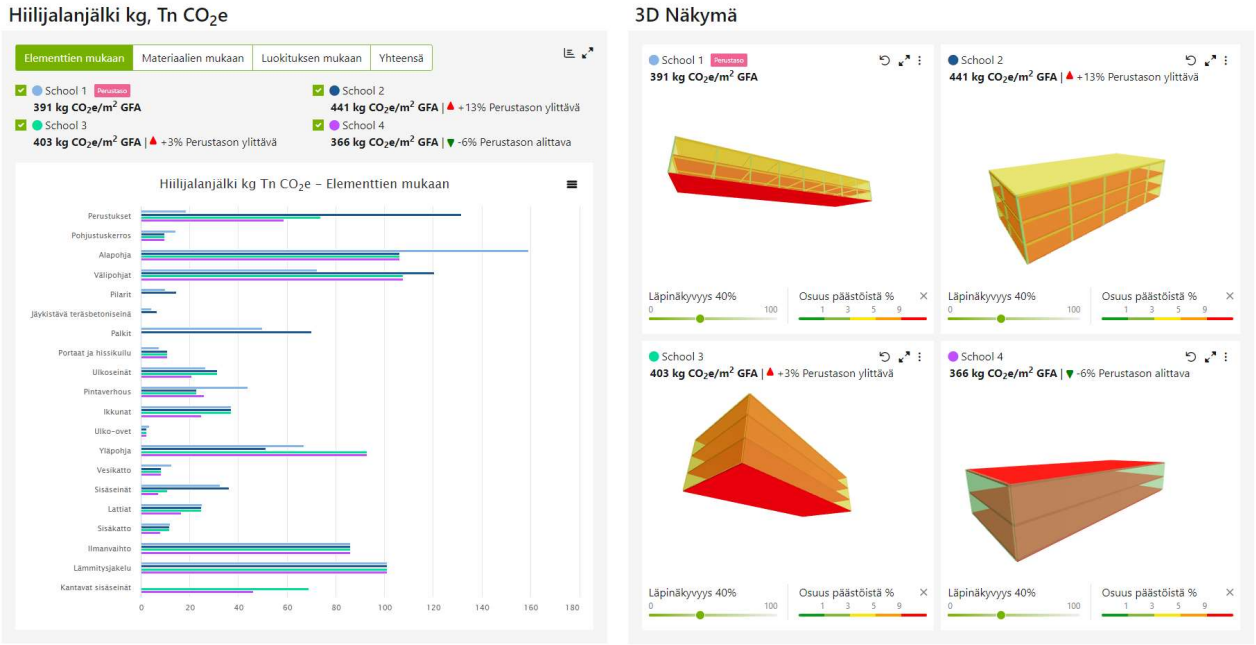
Picture 11 Office building 3D Carbon Designer visualizations, green – red bar > increasing share of emissions

School building (primary school)

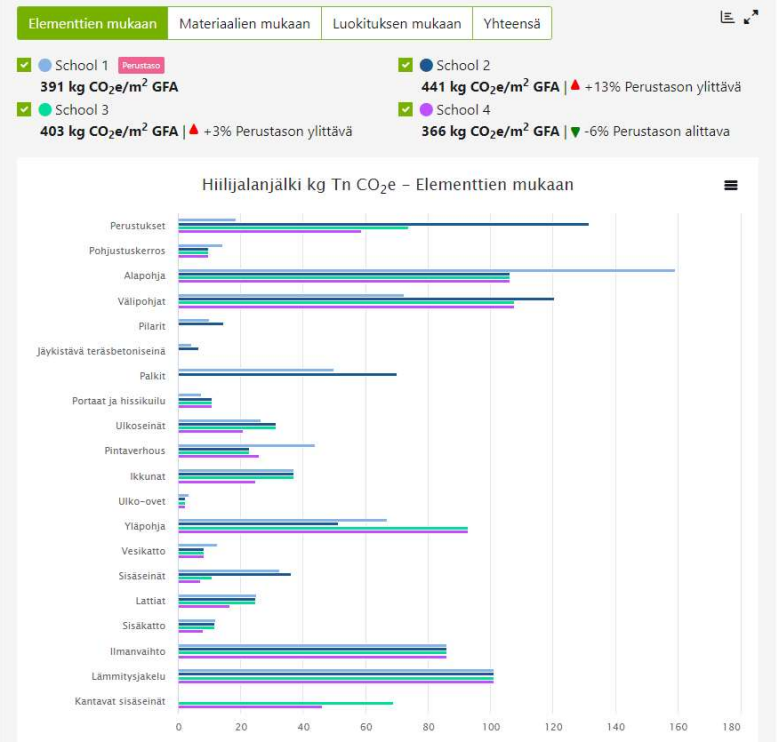
- Area 2 000 GFA
- Scenarios decribed on the table below

Table 13 School building scenarios for A1 to A3

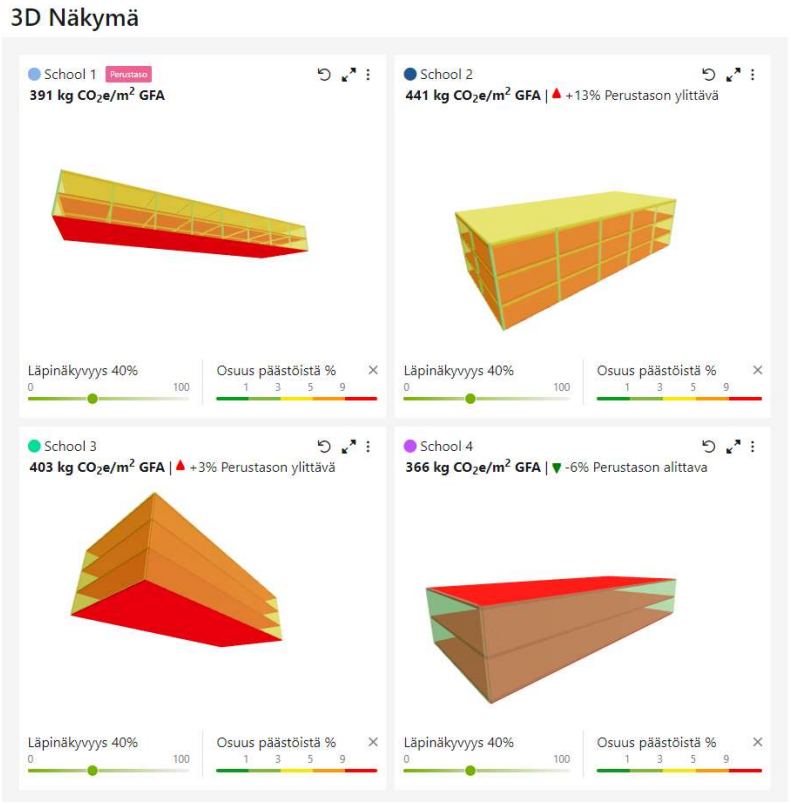
	cellars	above ground floors	foundation	structure	exterior wall surface material
1	no	2	hard ground, footing	concrete	brick
2	no	3	soft ground, point and strip footing	concrete element	fiber cement + wooden lathes
3	no	3	soft ground, core piles 10m	bearing walls	fiber cement + wooden lathes
4	1 cold	2	hard ground, core piles 10m	bearing walls	steel sheet + wooden lathes



Picture 12 Overview of school building 3D Carbon Designer scenario results



Picture 13 School building 3D Carbon Designer results per class



Picture 14 School building 3D Carbon Designer visualizations, green – red bar > increasing share of emissions