ANNEX 72

EBC

Energy in Building and Communities Programme

International Energy Agency

Assessing life cycle related environmental impacts caused by buildings: Case study collection

Energy in Buildings and Communities Technology Collaboration Programme

February 2023

Technology Collaboration Programme by iea

International Energy Agency

Assessing life cycle related environmental impacts caused by buildings: Case study collection

Energy in Buildings and Communities Technology Collaboration Programme

February 2023

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Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international co-operation among the 30 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes (TCPs). The mission of the IEA Energy in Buildings and Communities (IEA EBC) TCP is to support the acceleration of the transformation of the built environment towards more energy efficient and sustainable buildings and communities, by the development and dissemination of knowledge, technologies and processes and other solutions through international collaborative research and open innovation. (Until 2013, the IEA EBC Programme was known as the IEA Energy Conservation in Buildings and Community Systems Programme, ECBCS.)

The high priority research themes in the EBC Strategic Plan 2019-2024 are based on research drivers, national programmes within the EBC participating countries, the Future Buildings Forum (FBF) Think Tank Workshop held in Singapore in October 2017 and a Strategy Planning Workshop held at the EBC Executive Committee Meeting in November 2017. The research themes represent a collective input of the Executive Committee members and Operating Agents to exploit technological and other opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy technologies, systems and processes. Future EBC collaborative research and innovation work should have its focus on these themes.

At the Strategy Planning Workshop in 2017, some 40 research themes were developed. From those 40 themes, 10 themes of special high priority have been extracted, taking into consideration a score that was given to each theme at the workshop. The 10 high priority themes can be separated in two types namely 'Objectives' and 'Means'. These two groups are distinguished for a better understanding of the different themes.

Objectives - The strategic objectives of the EBC TCP are as follows:

- reinforcing the technical and economic basis for refurbishment of existing buildings, including financing, engagement of stakeholders and promotion of co-benefits;
- improvement of planning, construction and management processes to reduce the performance gap between design stage assessments and real-world operation;
- the creation of 'low tech', robust and affordable technologies;
- the further development of energy efficient cooling in hot and humid, or dry climates, avoiding mechanical cooling if possible;
- the creation of holistic solution sets for district level systems taking into account energy grids, overall performance, business models, engagement of stakeholders, and transport energy system implications.

Means - The strategic objectives of the EBC TCP will be achieved by the means listed below:

- the creation of tools for supporting design and construction through to operations and maintenance, including building energy standards and life cycle analysis (LCA);
- benefitting from 'living labs' to provide experience of and overcome barriers to adoption of energy efficiency measures;
- improving smart control of building services technical installations, including occupant and operator interfaces;
- addressing data issues in buildings, including non-intrusive and secure data collection;
- the development of building information modelling (BIM) as a game changer, from design and construction through to operations and maintenance.

The themes in both groups can be the subject for new Annexes, but what distinguishes them is that the 'objectives' themes are final goals or solutions (or part of) for an energy efficient built environment, while the 'means' themes are instruments or enablers to reach such a goal. These themes are explained in more detail in the EBC Strategic Plan 2019-2024.

The Executive Committee

Overall control of the IEA EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA EBC Executive Committee, with completed projects identified by (*) and joint projects with the IEA Solar Heating and Cooling Technology Collaboration Programme by (☼):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: ☼ Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: ☼ Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: ☼ Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: ☼ Towards Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis and Evaluation Methods (*)
Annex 54: Integration of Micro-Generation and Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance and Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy and CO2 Emissions Optimization in Building Renovation (*)
Annex 57: Evaluation of Embodied Energy and CO2 Equivalent Emissions for Building Construction (*)

Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)
Annex 59: High Temperature Cooling and Low Temperature Heating in Buildings (*)
Annex 60: New Generation Computational Tools for Building and Community Energy Systems (*)
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings (*)
Annex 62: Ventilative Cooling (*)
Annex 63: Implementation of Energy Strategies in Communities (*)
Annex 64: LowEx Communities - Optimised Performance of Energy Supply Systems with Exergy Principles (*)
Annex 65: Long-Term Performance of Super-Insulating Materials in Building Components and Systems (*)
Annex 66: Definition and Simulation of Occupant Behavior in Buildings (*)
Annex 67: Energy Flexible Buildings (*)
Annex 68: Indoor Air Quality Design and Control in Low Energy Residential Buildings (*)
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale
Annex 71: Building Energy Performance Assessment Based on In-situ Measurements
Annex 72: Assessing Life Cycle Related Environmental Impacts Caused by Buildings
Annex 73: Towards Net Zero Energy Resilient Public Communities
Annex 74: Competition and Living Lab Platform
Annex 75: Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables
Annex 76: ☼ Deep Renovation of Historic Buildings Towards Lowest Possible Energy Demand and CO_2 Emissions
Annex 77: ☼ Integrated Solutions for Daylight and Electric Lighting
Annex 78: Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications
Annex 79: Occupant-Centric Building Design and Operation
Annex 80: Resilient Cooling
Annex 81: Data-Driven Smart Buildings
Annex 82: Energy Flexible Buildings Towards Resilient Low Carbon Energy Systems
Annex 83: Positive Energy Districts
Annex 84: Demand Management of Buildings in Thermal Networks
Annex 85: Indirect Evaporative Cooling
Annex 86: Energy Efficient Indoor Air Quality Management in Residential Buildings

Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)
Working Group - HVAC Energy Calculation Methodologies for Non-residential Buildings (*)
Working Group - Cities and Communities
Working Group - Building Energy Codes

Introduction

The content of the report serves as a collection of case studies gathered from the participants of the IEA EBC project Annex 72 dealing with the “Assessing Life Cycle Related Environmental Impacts Caused by Buildings”. The overall goal of the project is the harmonization of the methodology and solvation of issues which arise when applying LCA approaches on buildings.

The objectives of EBC Annex 72 are:
- To establish a common methodology guideline to assess the life cycle based primary energy demand, greenhouse gas emissions and environmental impacts caused by buildings;
- To establish methods for the development of specific environmental benchmarks for different types of buildings;
- To derive regionally differentiated guidelines and tools for building design and planning such as BIM for architects and planners;
- To establish a number of case studies, focused to allow for answering some of the research issues and for deriving empirical benchmarks;
- To develop national or regional databases with regionally differentiated life cycle assessment data tailored to the construction sector; share experiences with the setup and update of such databases.

Objectives and Contents of the Report

The purpose of this report is to provide a collection of case studies that cover different topics that are handled in the project of IEA EBC Annex 72 and which can be used as examples and referred to in other reports of Annex 72.

The collection of case studies consists of 25 different cases from 11 countries submitted by participants of Annex 72. If further information is needed than what is described in this collection of cases, the original publications with the case studies can be accessed.

This report mentions terms related to the life cycle of buildings and construction product and materials. According to EN 15643:2021, the life cycle of buildings can be divided into life cycle stages and corresponding modules. This is illustrated in Figure 1. The life cycle modules A1-3 in the production stage considers environmental impacts related to the production of construction materials. The construction process stage considers modules A4-5, which are environmental impacts from transport and construction of the building. In the use stage B1-7, the impacts from processes during the use of the building is considered including the operational energy use (B6). In the end-of-life stage, environmental impacts associated with de-construction, transport, waste processing and disposal of materials are considered (modules C1-4).

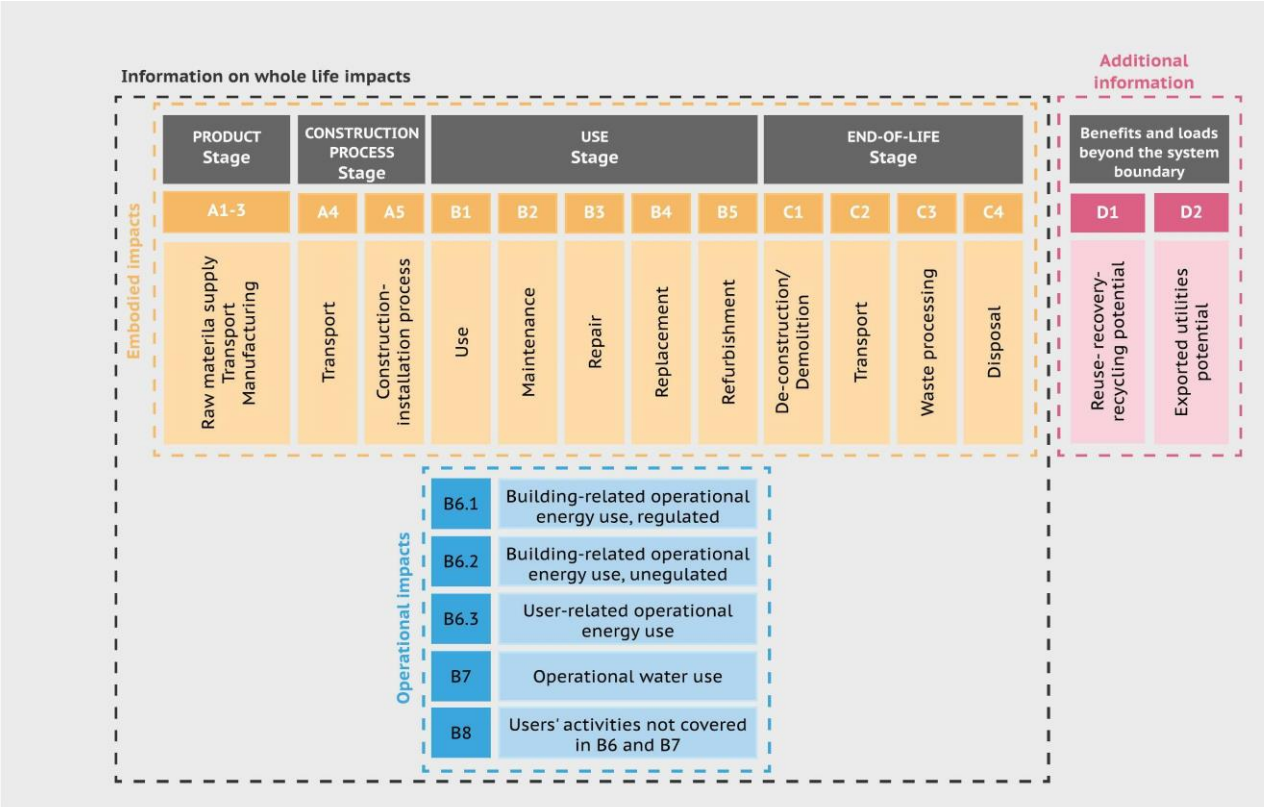

Figure 1: Display of modular information for the different stages of the building assessment as adapted from EN 15643:2021.

Contents

Abbreviations

Abbreviations	Meaning
ADPE	Abiotic depletion potential for fossil fuels
A72	IEA EBC Annex 72
BIM	Building Information Modelling
BIPV	Building-integrated Photovoltaic
C2C	Cradle to Cradle
CED	Cumulative Energy Demand
EM	Electricity mix
EoL	End-of-Life
GHG	Greenhouse Gas Emissions
GO	Guarantee of Origin
GWP	Global Warming Potential
HVAC	Heating, Ventilation, Air-conditioning
IDM	Information delivery manual
IEA	International Energy Agency
IFC	Industry foundation classes
KBOB	Koordinationsgremium der Bauorgane des Bundes
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCIA	Life Cycle Impact Assessment
MVD	Model view definition
ODP	Ozone Depletion Potential
PE-NRe	Primary energy non-renewable
POCP	Photochemical Ozone Creation Potential
PV	Photovoltaic
SIA	Schweizerischer ingenieur- und architektenverein

1. LCA related studies

Case Study 01

Modelling Operational Electricity Consumption of Residential and Office Buildings

Corresponding case study author: Livia Ramseier, treeze Ltd., Switzerland (ramseier@treeze.ch)
Original publication: Frischknecht R., Alig M. and Stolz P. (2020) Electricity Mixes in Life Cycle Assessments of Buildings. treeze Ltd., Uster. https://treeze.ch/fileadmin/user_upload/downloads/Publications/Case_Studies/Building_and_Construction/8169-2020.12.18_ELCAB_treeze_final_report_e_EC_v1.0.pdf.

Abstract

Purpose/aim

The influence of the choice of models used to represent the production and supply of electricity used during the operation of buildings on the life cycle environmental impacts was assessed.

Method

The electricity mix was established matching the hourly electricity consumption of residential and office buildings with the hourly Swiss production and trade profile. These mixes were compared to electricity mixes based on Guarantees of Origin (GO), a future and a marginal Swiss electricity mix.

Results

The life cycle based environmental impacts of the residential building are presented in Figure 2 (Abbreviations see under Figure 3). The impacts do hardly differ between the options national electricity mix and building specific mix. The environmental impacts of operation are significantly lower when applying GO mixes and the expected future mix. PV self-production reduces the environmental impacts, whereas local storage does not.

Conclusion

The assessment shows that the national electricity mix based on production and commercial trade is very similar to a building specific electricity mix. Thus, there is no need for building specific electricity mixes. GO are used to convert nuclear electricity into renewable electricity. GO mixes are prone to double counting.

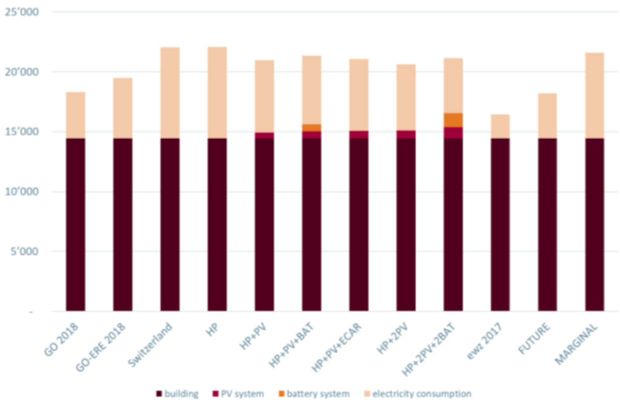

Figure 2: Environmental impacts (in Swiss eco-points 2013, see case study 1.3D3-01 from original publication) per m^2 and year of construction (building, PV system and battery, including end of life) and operation (electricity consumption) of the residential building Rautistrasse, Zürich, CH.

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Explanation of Figure 3

The electricity mix profile related to the consumption pattern of a residential building (HP) is very similar to the Swiss mix (ANNUAL). Self-production with PV, battery storage and electric car charging lead to a moderate increase of non-renewable energies in the electricity mix supplied to the building. The national electricity mix based on guarantees of origin has less nuclear and more hydroelectric power. European hydropower GOs are used to convert domestic nuclear power to renewable power.

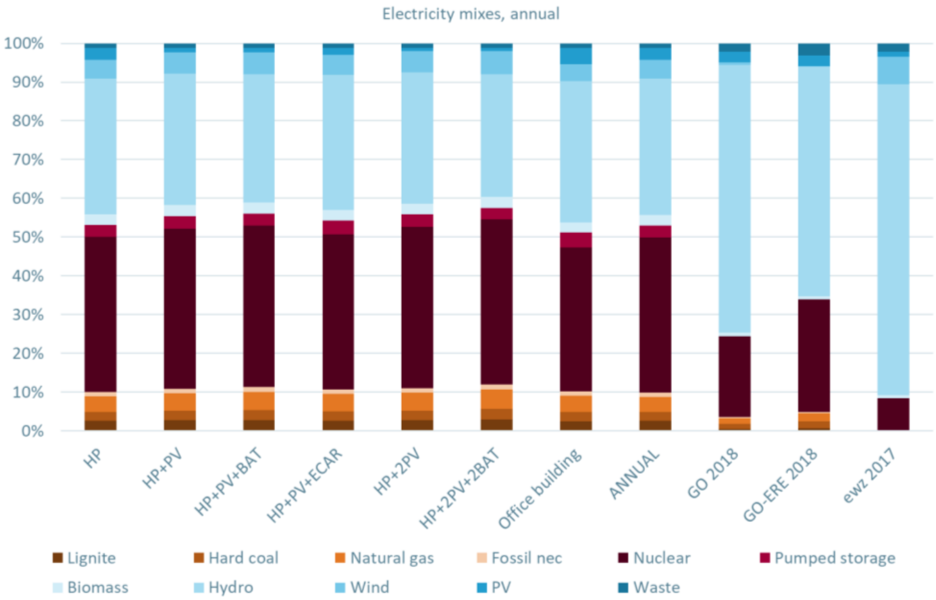

Figure 3: Technology shares of the annual Swiss electricity mixes for the different load profiles of the residential building Rautistrasse, the load profile of the ARE office building, the annual Swiss electricity mix (national load profile) and the Swiss consumer electricity mix 2018 according to guarantees of origin.

Abbreviations

HP: heat pump for space heating and hot water; HP+PV: incl. 32 kWp PV system; HP+PV+BAT: including 32 kWp PV system and 32 kWh battery system; HP+PV+ECAR: including 32 kWp PV system and 7 electric car charging stations; HP+2PV: incl. 64 kWp PV system; HP+2PV+2BAT: incl. 64 kWp PV system and 64 kWh battery system; ANNUAL: Swiss annual mix (national load profile); GO 2018: Swiss supply mix 2018 based on guarantees of origin; GO-ERE 2018: Swiss consumer mix 2018 (excluding electricity products based on renewable energy sold separately); ewz 2017: supply mix of the utility of the city of Zürich.

Additional references:
[1] Krebs L. and Frischknecht R. (2021) Life Cycle Assessment of GO based Electricity Mixes of European Countries 2018. treeze Ltd., Uster.

Case Study 02

Modelling Building Integrated PV-systems

Corresponding case study author: Rolf Frischknecht, treeze Ltd., Switzerland (frischknecht@treeze.ch)
Original publication: Stolz P., Krebs L., Frischknecht R., Urena Hunziker D. and Muntwyler U. (2021) Life Cycle Assessment of Active Glass Façades. Commissioned by the Federal Office for the Environment (FOEN), the Federal Office of Energy (SFOE) and the City of Zurich, Office of Building Construction (AHB), Uster and Burgdorf, Switzerland. https://www.bafu.admin.ch/dam/bafu/en/dokumente/wirtschaft-konsum/externe-studien-berichte/life-cycle-assessment-of-active-glass-facades.pdf.download.pdf/674-LCA-Active-Glass-Facades-v2.1.pdf.

Abstract

Purpose/aim

Building integrated photovoltaic systems provide two functions: building skin and electricity production. The environmental impacts of BIPV systems integrated in 6 buildings are assessed. The share of impacts attributable to the building and the electricity produced are determined.

Method

Environmental life cycle assessment is applied on BIPV systems integrated in six residential and office buildings. The environmental impacts are quantified with the Swiss eco-points 2013 based on the ecological scarcity method. Physical causality is used to allocate between the building and the electricity production functions of BIPV.

Results

The life cycle-based greenhouse gas emissions of the BIPV systems are presented in Figure 4. The total emissions vary significantly. Major contributors are the PV panel, the inverters and power optimisers and the mounting structure. Some of BIPV systems are coloured which significantly affects the annual yield.

Conclusion

The study showed that electricity produced with BIPV systems tends to cause higher specific greenhouse gas emissions and environmental impacts than optimally oriented building attached PV systems. Main reasons are their application on all façades (including north oriented façade) and their colouring.

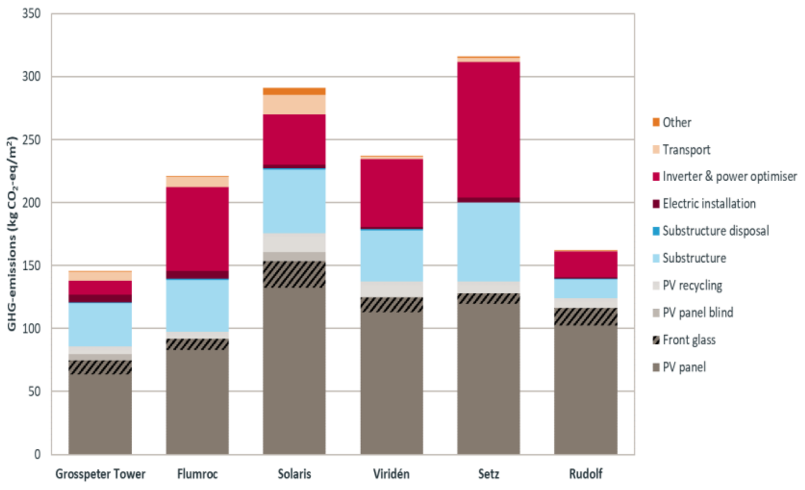

Figure 4: Greenhouse gas emissions per m² active glass façade of the six selected buildings divided into the impacts associated to PV panels, blind PV panels, substructure, disposals of PV panels and substructures, balance of system (BOS), transport and other (edge seals, joints). Note: Office buildings: Grosspeter Tower, Flumroc. Residential buildings: Solaris, Viridén, Setz, Rudolf.

Explanation of Figure 5

The greenhouse gas emissions per kWh of electricity produced by the six BIPV systems vary between 40 and 270 grams CO_2-eq, and the environmental impacts vary between 60 and 550 eco-points. The share of greenhouse gas emissions and environmental impacts attributable to the building vary between 18 and 32%, and between 8 and 20%, respectively.

The highest gross overall environmental impacts per kWh produced electricity is caused by the façade-integrated PV system of the Grosspeter Tower due to a comparably low specific electricity yield of 386 kWh/kWp and the type of panel used (CIS). The CIS panel cause relatively high environmental impacts but relatively low greenhouse gas emissions. The building Viridén has a low specific electricity yield of 289 kWh/kWp because the entire façade (including parts with low solar irradiation such as the north façade and balcony niches) is covered with active PV panels and the panels are coloured. This leads to comparably high specific environmental impacts and greenhouse gas emissions.

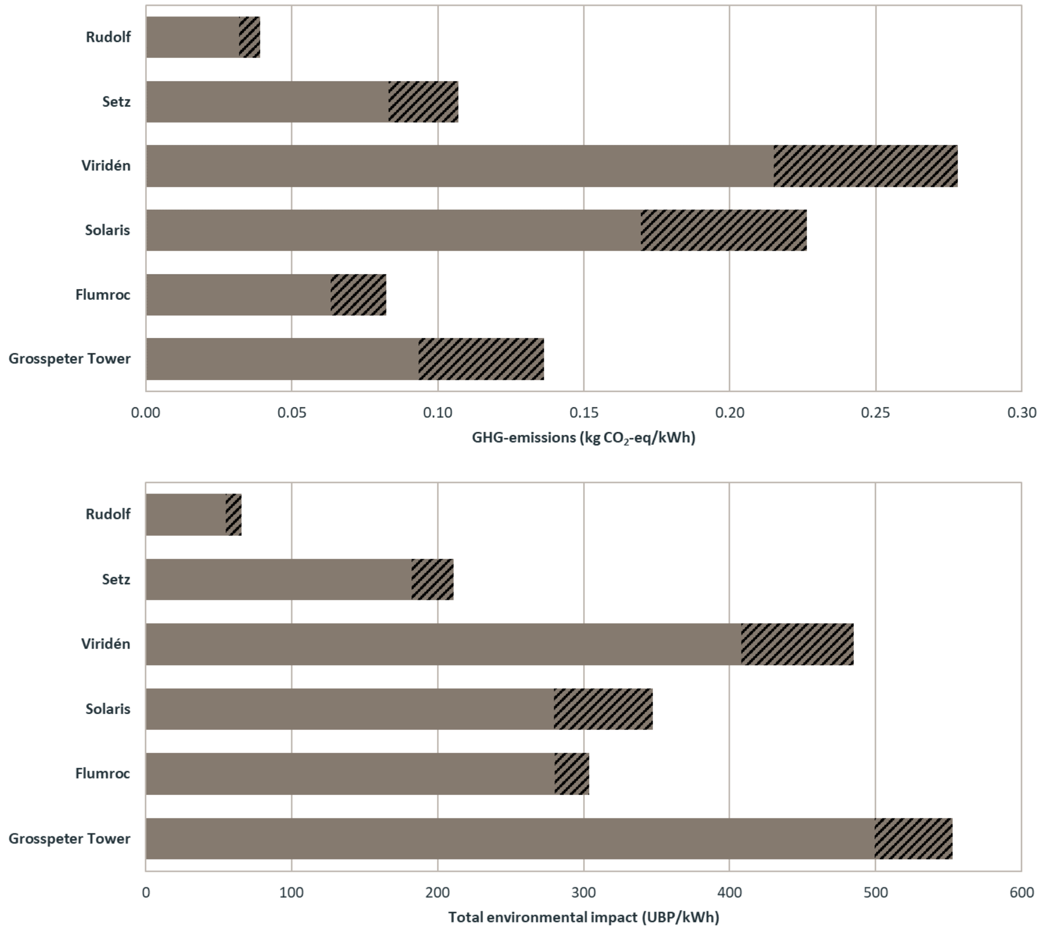

Figure 5: Gross greenhouse gas emissions (in kg CO_2-eq, top) and gross environmental impacts (in eco-points, bottom, see also case study 1.3D3-01) per kWh electricity produced by the active glass façades of six BIPV buildings. The shaded area can be attributed to the building (impacts of front glass and supporting structure) and not the electricity production.

Additional references:

[1] Frischknecht R., Krebs L. (Ed.) (2021) Factsheet: Environmental life cycle assessment of electricity from PV systems. International Energy Agency, Photovoltaic Power Systems Programme, IEA PVPS.

Case Study 03

Environmental, Economic and Energy Life Cycle Assessment "From Cradle to Cradle" (3E-C2C) of Flat Roofs

Corresponding case study author: José Silvestre, CERIS, Instituto Superior Técnico, University of Lisbon, Portugal (jose.silvestre@tecnico.ulisboa.pt)
Original publication: Gomes, R., Silvestre, J. D.; de Brito, J. (2020). Environmental, economic and energy life cycle assessment "from cradle to cradle" (3E-C2C) of flat roofs. Journal of Building Engineering. 32, 101436, November; https://doi.org/10.1016/j.jobe.2020.101436

Abstract

Purpose/aim

Evaluate the environmental, economic and energy (3E) performance of different flat roofs solutions, from "cradle to cradle" (C2C).

Method

The 3E dimensions were assessed individually using the 3E-C2C method and the 3E cost-C2C methodology, which considers Eco-costs monetisation method, and was used for their aggregated assessment. 114 flat roofs were studied for 50 years, including inverted (i.e. roof systems where the thermal insulation is applied over the waterproofing) and traditional ones, as well as different levels of accessibility (i.e. limited access, accessible to people, accessible to vehicles).

Results

Inverted solutions of flat roofs have, in general, worse environmental performance than traditional ones. Moreover, the 3E assessment confirmed higher costs of solutions accessible to vehicles and lower of those with limited access. Furthermore, solutions with higher initial costs demanded lower maintenance costs. Finally, the study confirmed the relevance of the economic cost (between 63%-77%) within the aggregated 3E cost-C2C, namely of the market acquisition costs, in year 0 (between 52%-76% within the total economic costs). Environmental costs showed an influence from 12%-29% and the energy costs between 8%-13%.

Discussion

A sensitivity analysis of the results was performed for the following parameters: discount rate, energy needs, initial construction cost, service life of the waterproofing solutions and the hazard classification of waste.

Conclusion

Inverted solutions of flat roofs have, in general, worst environmental performance than traditional ones. This is due to the materials applied in the protection layer. Furthermore, the 3E assessment confirmed the highest cost of the solutions accessible to vehicles and the lowest of the ones with limited access. Moreover, solutions with higher initial costs demanded lower maintenance costs. The individual and aggregated assessment of the environmental costs of the 114 alternatives showed the worst environmental performance, in general, in the production (A1-A3) sub-stage for inverted solutions and the best for traditional solutions and, in opposition, the best performance of the inverted alternatives in the sub-stage of operational energy.

The 3E-C2C Method

– Allows the comparison of different building solutions that comply with all requirements (e.g., technical specifications, geometry, legal rules or regulations) but are not functionally equivalent (e.g., that do not have the same thermal performance), without having to change their characteristics to make them comparable (e.g., changing their insulation thickness);
– Quantifies different aspects (e.g., 3E) of the alternatives' performance in each stage of their life cycle and also from cradle to cradle (i.e., materials and products performance in the use stage; their expected service life; and their recycling potential (Table 1)), in accordance with LCA international and European standards;
– Allows for the simultaneous comparison of all these dimensions of the alternative's performance, by using suitable weights for each aspect, allowing their quantification in the same unit.

Figure 6 presents the NPV of the total environmental cost of the three flat roof alternatives with the best and worst performance within the total of the 114 alternatives assessed.

Table 1: Impact and life cycle stages of a flat roof solution in each module of the 3E-C2C approach.

3E-C2C Module Performance		Environmental	Economic	Energy
Product stage (A1-A3)		LCA	Initial costs	-
Transport to the building stage (A4)				
Installation in the building (A5)				
Use stage	Maintenance, repair and replacement (B2-B4)		Costs	
	Energy use for heating and cooling (B6)		-	Costs
End-of-life stage - transport, processing and disposal (C2-C4), and reuse, recovery and/or recycling potential (D)			Costs	-

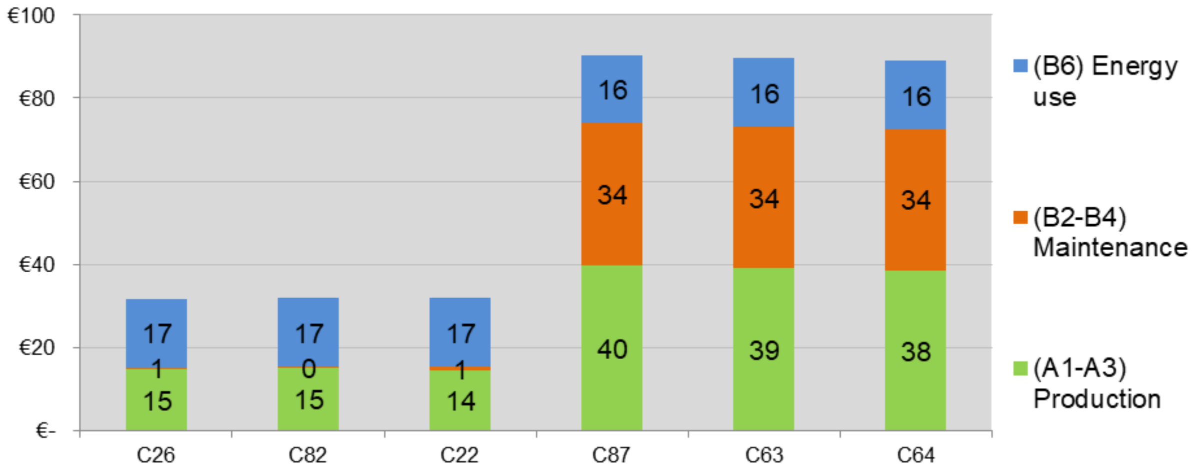

Figure 6: NPV of the total environmental cost of the three flat roof alternatives with best and worst performance (6 alternatives) within the total of the 114 alternatives assessed.

Case Study 04

The Role of Electricity Mix and Production Efficiency Improvements on Greenhouse gas (GHG) Emissions of Building Components and Future Refurbishment Measures

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Original publication: Tajda Potrč Obrecht, Sabina Jordan, Andraz Legat, Alexander Passer, 2021, *The role of electricity mix and production efficiency improvements on greenhouse gas (GHG) emissions of building components and future refurbishment measures,* Int J Life Cycle Assess, https://doi.org/10.1007/s11367-021-01920-2.

Abstract

Purpose/aim

An estimation of the environmental impact of buildings by means of a life cycle assessment (LCA) raises uncertainty related to the parameters that are subject to major changes over longer time spans. The main aim of the present study is to evaluate the influence of modifications in the electricity mix and the production efficiency in the chosen reference year on the embodied impacts (i.e. greenhouse gas (GHG) emissions) of building materials and components and the possible impact of this on future refurbishment measures.

Method

A new LCA methodological approach was developed and implemented that can have a significant impact on the way in which existing buildings are assessed at the end of their service lives. The electricity mixes of different reference years were collected, assessed and the main datasets and sub-datasets modified according to the predefined substitution criteria. The influence of the electricity-mix modification and production efficiency were illustrated on a selected existing reference building, built in 1970. The relative contribution of the electricity mix to the embodied impact of the production phase was calculated for four different electricity mixes, with this comprising the electricity mix from 1970, the current electricity mix and two possible future electricity-mix scenarios for 2050. The residual value of the building was also estimated.

Results and discussion

In the case presented, the relative share of the electricity mix GHG emission towards the total value was as high as 20 percent for separate building components. If this electricity mix is replaced with an electricity mix having greater environmental emissions, the relative contribution of the electricity mix to the total emissions can be even higher. When, by contrast, the modified electricity mix is almost decarbonized, the relative contribution to the total emissions may well be reduced to a point where it becomes negligible. The modification of the electricity mix can also influence the residual value of a building. In the observed case of a typical residential building from 1980, the differences due to different electricity mixes were in the range of 10 percent.

Explanation of Figure 7

In PHASE 1 the electricity mix (EM) must be re-modelled for the selected periods.

In PHASE 2, the life cycle inventory datasets were remodelled using the electricity mixes obtained in the previous phase. At this point, cut-off criteria were applied to avoid the re-modelling of the sub-materials that do not make a significant contribution to the end-results.

In PHASE 3, the residual value of the building is calculated using the re-modelled datasets.

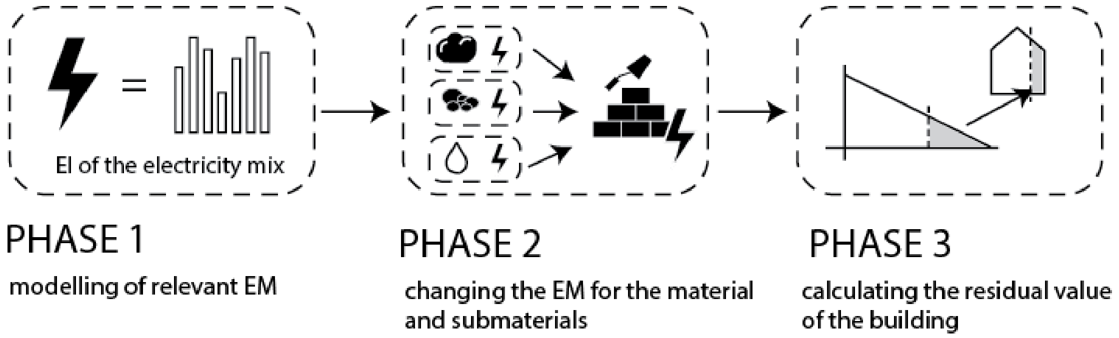

Figure 7: Three-phase approach to re-modelling the existing datasets and calculating the residual value of a building with the time-corresponding electricity mixes

Case Study 05

LCA of Future Construction Material Manufacture

Corresponding case study author: Livia Ramseier, treeze Ltd., Switzerland (ramseier@treeze.ch)
Original publication: Alig M., Frischknecht R., Krebs L., Ramseier L. and Stolz P. (2020) LCA of climate friendly construction materials. treeze Ltd., Uster, Switzerland. LCA of climate friendly construction materials (treeze.ch).

Abstract

Purpose/aim

Life cycle assessments of future production of construction materials relevant in structural engineering, namely mineral and metal materials, wood and plastics produced and/or used in Switzerland and of future transport services and energy supply were performed.

Method

Information about the technological development of manufacturing processes, transport services and energy supply were collected in interviews with representatives from associations and pioneering companies and with desk top research. Data were consolidated and complemented with assumptions. The study refers to the time period between 2030 and 2050.

Results and discussion

Figure 8 shows that with future construction materials manufacture, greenhouse gas emissions are reduced on average by 65 %, non-renewable primary energy demand by 48% and the total environmental impact by 38%. At building level, greenhouse gas emissions of construction (including building technology) and dismantling can be reduced by 50-60%.

Conclusion

Yet even with today's expected changes in production processes, substantial greenhouse gas reductions are within reach. However, this is not sufficient. Construction material industries need to reduce their greenhouse gas emissions (including supply chain) to close to zero. Such emission reductions require binding commitments to the 1.5°C target and substantial changes in the production processes.

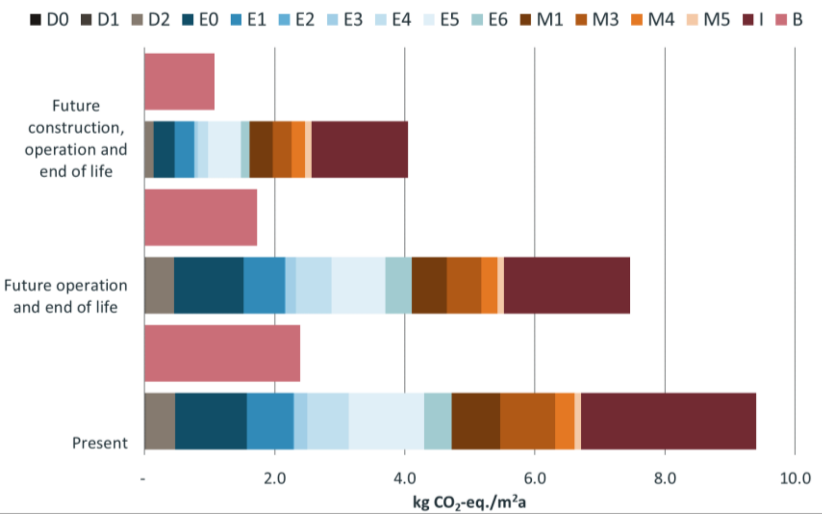

Figure 8: The greenhouse gas emissions per m² and year of the residential building "Rautistrasse" of building construction and dismantling are reduced by 57%. If only future data are used to model replacements, end of life treatment and operation, the reduction in GHG emissions is about 21%. The residential building Rautistrasse has 104 apartments and has been built according to the Minergie-Eco standard. All apartments have comfort ventilation and are equipped with underfloor heating, which is supplied with heat from geothermal probes and electric heat pumps. Note: The explanation of the abbreviation can be found in the original paper.

Explanation of Table 2

Different methods to select the electricity and district heating mixes for a building lead to different outcomes. The choice of method could determine which heating solution is seen as optimal. We discuss potential advantages and drawbacks of each method in terms of reliability, validity, ease of calculation and what type of practices the method encourages.

Table 2: Greenhouse gas emissions caused by manufacture and end of life treatment of kg of construction material and the reduction in emissions compared to the greenhouse gas emissions caused by today's manufacture and end of life treatment.

	Environmental impacts of 1 kg future building materials production [kg CO_2eq]	Improvements achieved with future building materials production
	GHG gas emissions	**GHG gas emissions**
Lean concrete	0.012	-76%
Building constr. Concrete	0.021	-77%
Civil eng. Concrete	0.023	-76%
Drilled piles concrete	0.025	-77%
Precast concrete, high perf.	0.042	-84%
Precast concrete, stand.	0.037	-77%
Bricks	0.036	-85%
Gypsum plaster board	0.17	-27%
Float glass	0.22	-80%
Aluminium	4	-56%
Copper	0.35	-89%
Nickel	0.15	-98%
Steel	0.63	-62%
Rolled steel	0.27	-63%
Zinc	1.2	-61%
3-layered lam. board	0.13	-65%
Glued lam. timber, outdoor	0.17	-50%
Glued lam. timber, indoor	0.14	-55%
Particleboard	0.35	-27%
Fibreboard	0.1	-76%
Glass wool	0.42	-41%
Rock wool	0.43	-59%
Linoleum	1.5	-41%
EPS	1.9	-55%
XPS	1.7	-85%
PE	1.8	-60%
PVC	0.55	-73%
PLA	1.3	-56%

Additional references:
[1] KBOB, eco-bau and IPB (2016) KBOB-Recommendation 2009/1:2016: Life Cycle Assessment Data in Constructon, Status as at September 2016. Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren c/o BBL Bundesamt für Bauten und Logistik, retrieved from: https://www.kbob.admin.ch/kbob/it/home/publikationen/nachhaltiges-bauen/oekobilanzdaten_baubereich.html.

Case Study 06

Biogenic Carbon in Buildings: A Critical Overview of LCA Methods

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Original publication: Hoxha, E., Passer, A., Saade, M.R.M., Trigaux, D., Shuttleworth, A., Pittau, F., Allacker, K., Habert, G. (2020). Biogenic carbon in buildings: a critical overview of LCA methods. Buildings and Cities, 1(1), pp. 504–524. DOI: https://doi.org/10.5334/bc.46.

Abstract

Purpose/aim

This case study investigates the possible discrepancies between results that arise when adopting different methods for biogenic carbon assessment in a timber building LCA.

Method

Carbon uptake and release were modelled through the 0/0 approach, the –1/+1 approach and through a dynamic approach. The '0/0 approach' is based on the assumption that the release of CO_2 from a bio-based product at the end of its life is balanced by an equivalent uptake of CO_2 during the biomass growth. Hence, there is no consideration of biogenic CO2 uptake (0) and release (0). The '–1/+1' approach consists of tracking all biogenic carbon flows over the building life-cycle. In this approach both biogenic CO_2 uptake (–1) and release (+1) are considered. In the case of the dynamic approach, two scenarios were considered: uptake before and after extraction.

Results

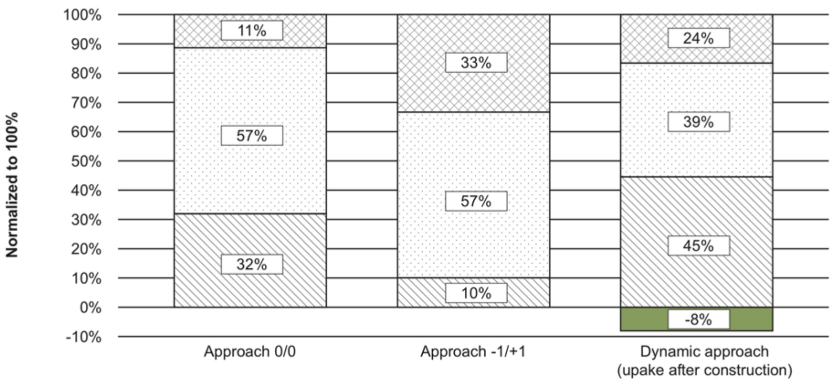
Differences are depicted in Figure 9 (0/0 vs -1/+1 vs dynamic after extraction) and Figure 10 (dynamic with uptake before vs after extraction).

Discussion

At a building level, the gap between results was of 29%.

Conclusion

Because it considers time aspects and rotation times, the dynamic approach seems to be a reliable method for the assessment of the biogenic carbon.



GW-score ($kgCO_2e/m^2/yr$)

C1-C4	(biogenic CO_2eq release)	0.00	4.66	1.55
	(building components)	2.22	2.22	4.83
B6		11.89	11.89	10.47
B1	(biogenic carbon uptake after construction)	0.00	0.00	-2.24
A1-A5	(biogenic carbon uptake befor construction)	0.00	-4.66	0.00
	(building components)	6.58	6.58	12.07
Total		**20.69**	**20.69**	**26.67**

Figure 9: Global warming (GW) scores calculated by different biogenic carbon accounting approaches.

Explanation of Figure 10

Global warming (GW) score results are presented as a function of time (dynamic approach). Biogenic carbon uptake is considered before construction versus after construction. To allow comparisons, the time boundary is extended to –100 years, to include the impact of forest growth before construction. The graph shows the influence of the time parameter in the evolution of impacts for stages A1–A5 and C1–C4 for building components and for the biogenic carbon uptake. With uptake occurring before construction the amount of absorbed carbon is significantly larger, for two reasons: (i) the wood in the forest has been harvested when the rotation period has been completed (full uptake); (ii) the 'time' parameter considered in the dynamic approach [1] leads to a continued positive effect even after harvesting. When uptake occurred after construction, carbon uptake quantity is lower, and its release happens after 50 years when the building reaches its EoL. Biogenic carbon uptake after construction should be preferred from a sustainable point of view to stimulate future forest re-growth.

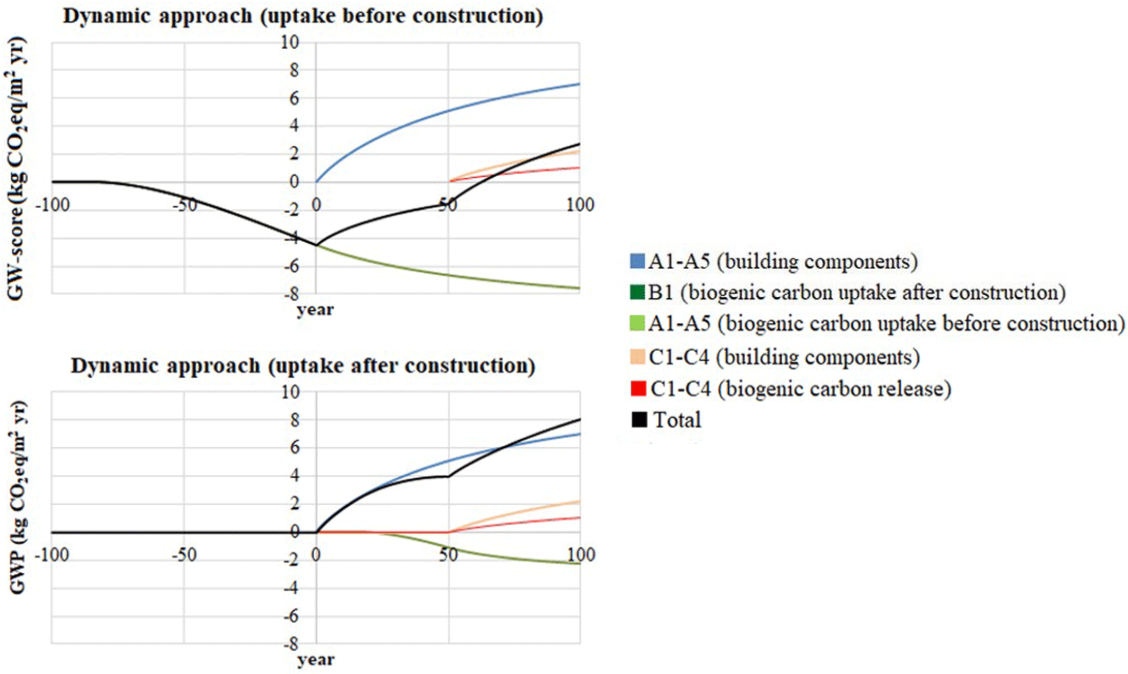


Figure 10: Global warming (GW) scores of the analyzed building as a function of the reference service life (year 0 is the construction of the building).

Additional references:
[1] Levasseur, A., Lesage, P., Margni, M., Deschênes, L., & Samson, R. (2010). Considering time in LCA: Dynamic LCA and its application to global warming impact assessments. Environmental Science & Technology, 44(8), 3169–3174. DOI: https://doi.org/10.1021/es9030003

2. Benchmarking related studies

Case Study 07

Single Score Environmental Benchmarks for Buildings

Corresponding case study author: Rolf Frischknecht, treeze Ltd., Switzerland (frischknecht@treeze.ch)
Original publication: Tschümperlin L., Frischknecht R., Pfäffli K., Knecht K. and Schultheiss M. (2016) Zielwert Gesamtumweltbelastung Gebäude; Ergänzungsarbeiten mit Fokus auf den Einfluss der Technisierung auf die Umweltbelastung von Büro- und Wohnbauten. Bundesamt für Energie, BfE Bundesamt für Umwelt BAFU, Uster, Zürich, Dübendorf: https://treeze.ch/fileadmin/user_upload/downloads/Publications/Case_Studies/Building_and_Construction/560-Zielwert_Gesamtumweltbelastung_Gebaeude_v1.1.pdf.

Abstract

Purpose/aim

This case study investigates the feasibility of single score environmental benchmarks for residential and office buildings and compares them to greenhouse gas emission benchmarks.

Method

An LCA was performed on energy efficient new and retrofit office buildings covering construction, operation and end of life. The environmental impacts were quantified using the Swiss eco-factors 2013 according to the ecological scarcity method.

Results

Figure 11 shows that the environmental impacts of both high- and low-tech office buildings are well below the recommended reference values.

Discussion

Retrofit office building HPZ causes significantly more environmental impacts during operation. The new office building be2226.

Conclusion

High- and low-tech office buildings assessed comply with the environmental benchmarks recommended. The single score indicator quantifying environmental impacts points to potential environmental trade-offs when used together with the climate change indicator "greenhouse gas emissions".

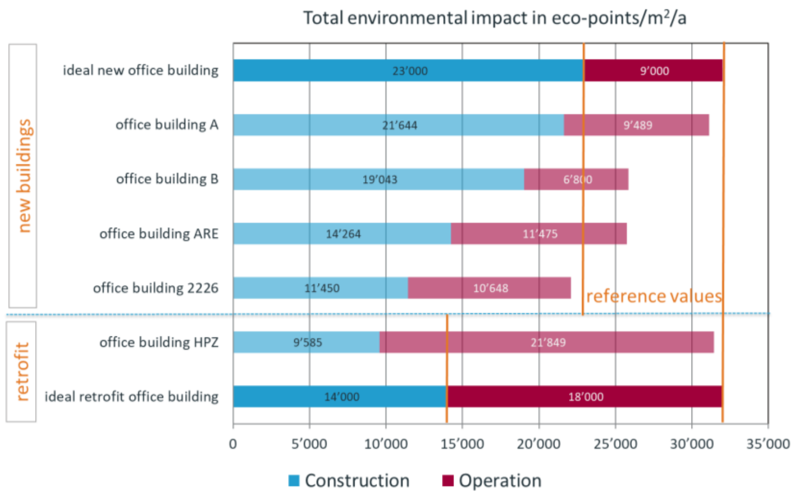


Figure 11: Total environmental impacts in Swiss eco-points 2013 according to the ecological scarcity method.

treeze
fair life cycle thinking

Explanation of Figure 12

The ecological scarcity method is a single score method. The weighting is based on the distance to target principle: Annual Swiss emissions and resource consumption today are compared to the emissions and resource consumption targets as defined in Swiss environmental legislation and international agreements adopted by Switzerland. The squared ratio between today's emissions and the emission allowances is used as weighting factors.

The ecological scarcity method covers the following environmental issues: water scarcity, energy resources, depletion of abiotic mineral resources, biodiversity losses due to land use, climate change, ozone layer depletion, air pollution, carcinogenic substances and heavy metals emitted to air, water pollution, persistent organic pollutants and heavy metals emitted to water, pesticides and heavy metals emitted to soil, carcinogenic effects of radioactive substances emitted to air and water, noise, landfilled non-radioactive wastes, radiotoxicity potential of radioactive wastes.

The method applies regionalized eco-factors for biodiversity losses caused by land use and for water scarcity.

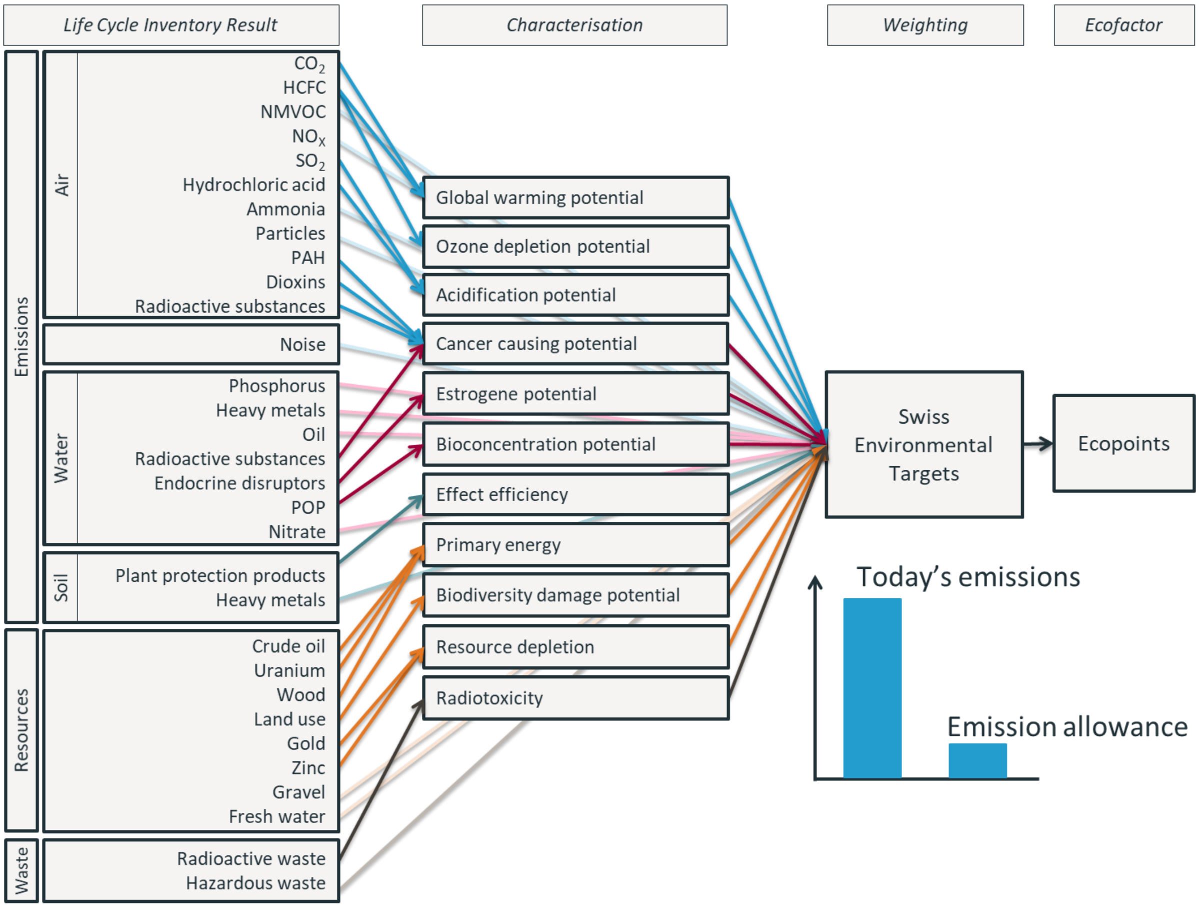


Figure 12: Basic concept of the ecological scarcity method, used to derive the Swiss eco-factors 2013.

Additional references:

[1] Levasseur, A., Lesage, P., Margni, M., Deschênes, L., & Samson, R. (2010). Considering time in LCA: Dynamic LCA and its application to global warming impact assessments. Environmental Science & Technology, 44(8), 3169–3174. DOI: https://doi.org/10.1021/es9030003

Case Study 08

Top-down Derived Benchmarks for Absolute Sustainability - Allocating the Share of “Safe Operating Space”

Corresponding case study author: Freja Nygaard Rasmussen, Aalborg University, Denmark (fnr@sbi.aau.dk)
Original publication: Pernille Ohms, Camilla Andersen, Freja Nygaard Rasmussen, Morten Ryberg, Michael Hauschild, Morten Birkved, Harpa Birgisdottir, 2019, *Assessing a building's absolute environmental sustainability performance using LCA,* submitted to the SBE19 conference in Trondheim: https://iopscience.iop.org/article/10.1088/1755-1315/352/1/012058/pdf.

Abstract

Purpose/aim

This case study illustrates different approaches to allocating the share of safe operating space (SoSOS) for evaluations concerning the absolute sustainability of a single-family stand-alone dwelling. SoSOS is the safe space for human development estimated via thresholds/ boundary levels for key Earth System processes, if we are to avoid unacceptable global environmental change.

Method

Six combinations of allocation principles are determined based on approaches reflecting egalitarian, utilitarian and acquired rights [1] principles of distribution.

Results

The examples of allocation principles are presented and explained in Table 3. The results are shown in Figure 13.

Discussion

The allocation principles applied in this study only represent a selection of ways the safe operating space can be shared.

Conclusion

The allocation principles can be used as a backbone for evaluating the absolute environmental sustainability.

Table 3: Examples of allocation principles. (continues on next page)

	Person **share out of** ***world*** **share**	***Household*** **share out of** ***person*** **share**	***Dwelling*** **share out of** ***household*** **share**
Allocation principle 1 (egalitarian + utilitarian)	Equal per capita $\frac{1}{\text{world}_{pop}}$	Final consumption expenditure $\frac{\text{FCE}_{HH}}{\text{FCE}_{person}} \cdot N$	Final consumption expenditure $\frac{\text{FCE}_{dwe}}{\text{FCE}_{HH}}$
Allocation principle 2 (egalitarian + utilitarian)	Equal per capita $\frac{1}{\text{world}_{pop}}$	Time spent $\frac{\text{H}_{home}}{\text{H}_{year}} \cdot N$	Final consumption expenditure $\frac{\text{FCE}_{dwe}}{\text{FCE}_{HH}}$
Allocation principle 3 (egalitarian + acquired rights)	Equal per capita $\frac{1}{\text{world}_{pop}}$	Energy consumption $\frac{\text{E}_{HH}}{\text{E}_{person}} \cdot N$	Energy consumption $\frac{\text{E}_{dwe}}{\text{E}_{HH}}$

Explanation of Table 4

Pop_{world} is the world population, FCE_{HH} is the final consumption expenditure for a household, FCE_{person} is the final consumption expenditure for a person, FCE_{dwe} is the final consumption expenditure for a dwelling, N is the number of persons in a household, H_{home} is the hours spent at home, H_{year} is the hours in a year, E_{HH} is the energy consumption for an average household, E_{person} is the energy consumption for one person, E_{dwe} is the energy consumption for a dwelling, $CO2_{HH}$ is the CO_2 emitted for an average household and $CO2_{world}$ is the CO_2 emitted worldwide. All factors are considered on an annual basis. The study distinguishes between a household and dwelling. A person's household includes all home-based activities and products, such as cooking, cleaning, relaxing, furniture etc., while dwelling refers to the building, and only the activities and products related to the building itself, i.e. paying rent, floorings, major appliances etc.

Table 4: Examples of allocation principles. (continued from previous page)

	***Household* share out of *world* share**	***Dwelling* share out of *household* share**
Allocation principle 4 (acquired rights + acquired rights)	CO2 emissions $\frac{CO2_{HH}}{CO2_{world}}$	Energy consumption $\frac{E_{dwe}}{E_{HH}}$
Allocation principle 5 (acquired rights + utilitarian)	CO2 emissions $\frac{CO2_{HH}}{CO2_{world}}$	Final consumption expenditure $\frac{FCE_{dwe}}{FCE_{HH}}$
	***Dwelling* share out of *world* share**	
Allocation principle 6 (utilitarian)	Final consumption expenditure $\frac{FCE_{dwe}}{FCE_{world}} = \frac{FCE_{HH}}{FCE_{world}} \cdot \frac{FCE_{dwe}}{FCE_{HH}}$	

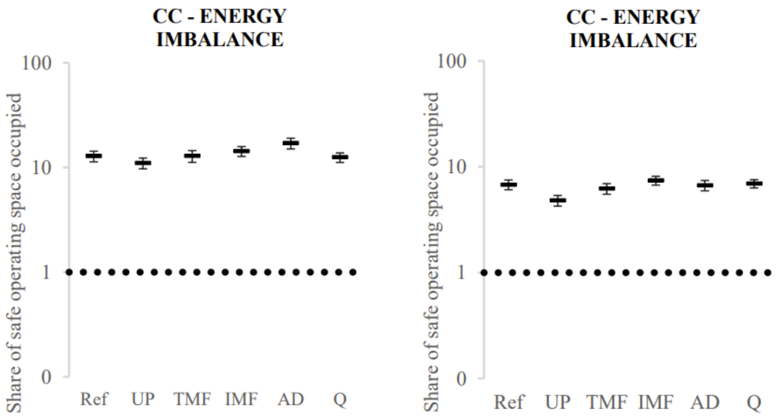


Figure 13: The impact potential for Climate Change - Energy imbalance relative to allocated share of safe operating space for each dwelling.

DTU Technical University of Denmark
UNIVERSITY OF SOUTHERN DENMARK
AALBORG UNIVERSITY DENMARK

Additional references:
[1] Ryberg, M. W., Owsianiak, M. and Hauschild, M. Z. (2018) 'Review of principles for assigning shares of the safe operating space to anthropogenic activities for absolute sustainability assessments in an LCA-context',

Case Study 09

Top-down Approaches for Setting Greenhouse Gas Emissions Targets for Buildings

Corresponding case study author: Chanjief Chandrakumar, Massey University, New Zealand (mtchanjief@gmail.com)
Original publication: Chandrakumar, C; McLaren, SJ; Dowdell, D; Jaques, R. 2020, *A science-based approach to setting climate targets for buildings: The case of a New Zealand detached house,* Build. Environ. 169; https://doi.org/10.1016/j.buildenv.2019.106560

Abstract

Purpose/aim

This study proposed an approach to assigning a share of the 1.5 ºC global carbon budget up to 2050 to a building and was applied to three New Zealand (NZ) residential dwelling typologies: detached (DH), medium-density housing (MDH), and apartments (AP).

Method

Using a combination of effort-sharing principles [1], a share of the 1.5 ºC global carbon budget for 2018-2050 is assigned to a country, its building and construction sector, and finally to a dwelling (see Figure 14). For this purpose, a stock model is used to account for the projected growth in the number of dwellings and associated carbon footprint in a country up to 2050. Afterwards, using Life Cycle Assessment methodology, the carbon footprint of the three residential dwelling typologies over a 90-year estimated service life (ESL) are quantified and benchmarked against the assigned carbon budget shares.

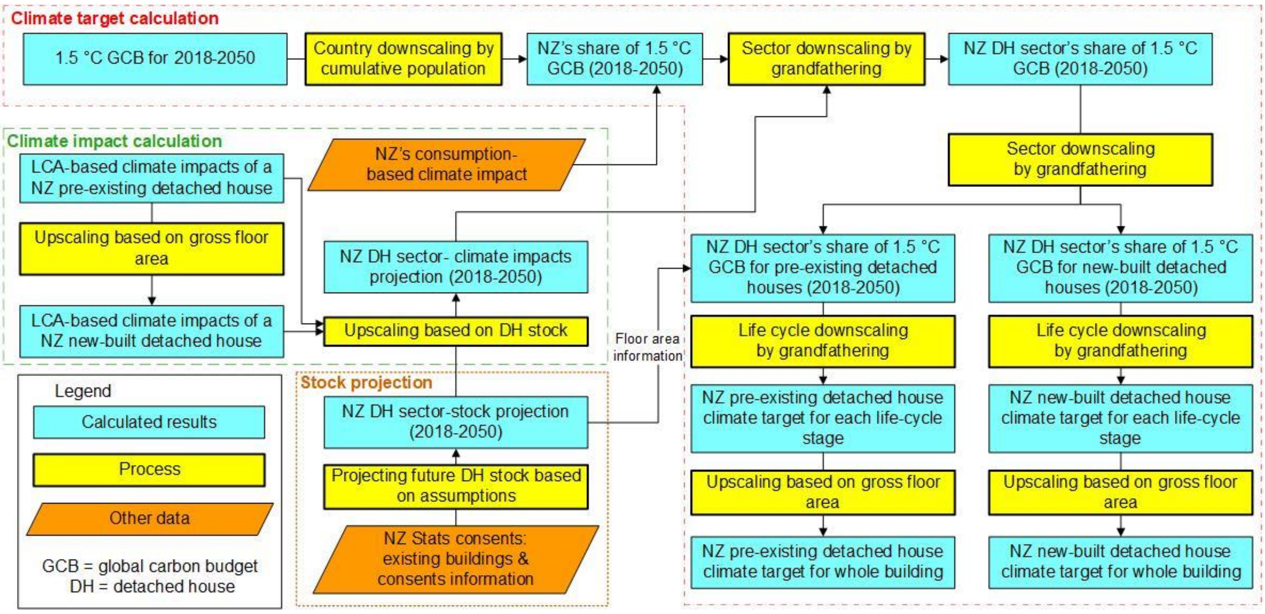


Figure 14: Proposed top-down approach illustrated to determine the share of the 1.5 ºC global carbon budget available for New Zealand detached houses.

Results

The carbon budget shares of the NZ new-built DH, MDH, and AP (over a 90-year ESL) are 35, 20, and 17 tCO_2eq, respectively [2]. Thus, the new-built dwellings exceed their 1.5 ºC carbon budget shares by a factor of 8.1, 8.3, and 16, as presented in Figure 15.

Discussion

The results indicate that substantial efforts are required to align the climate performance of NZ new-built residential dwellings with achieving the objectives of the Paris Climate Agreement, enshrined into law in the New Zealand "Zero Carbon Act". However, note that the proposed approach is only one potential way of assigning a carbon budget share to a building and there are alternatives. Furthermore, there is uncertainty associated with different modelling assumptions [1,3], which requires further investigation.

Conclusion

Overall, calculation of climate change planetary boundaries at the building scale has the potential to inform designers, architects, their clients and other stakeholders (e.g., government) about what level of greenhouse gas emissions are consistent with achieving no more than a 1.5ºC global temperature rise above pre-industrial levels. Many of these new buildings are likely to be occupied well after 2050, by which time New Zealand has committed to shifting its economy to net zero carbon (although currently excluding biogenic methane emissions).

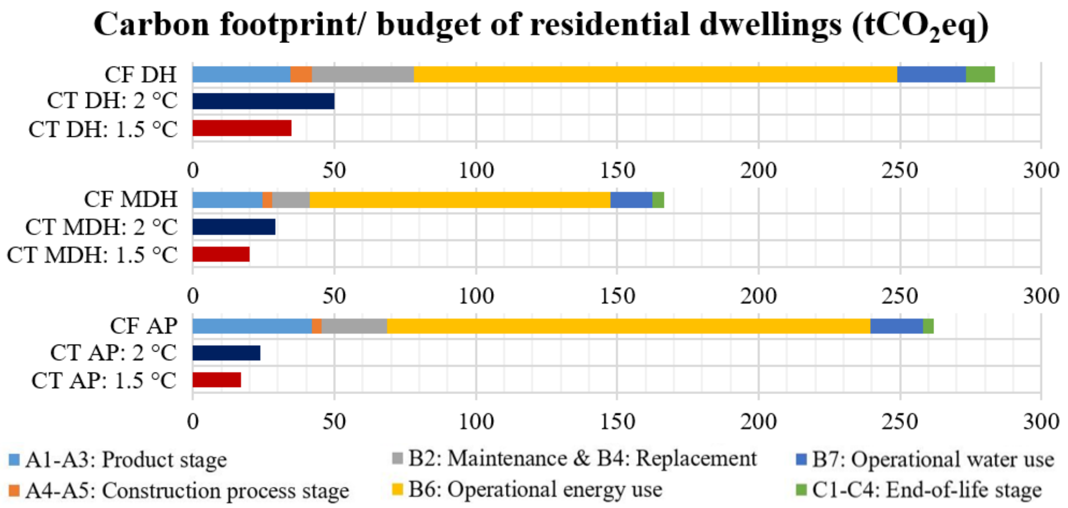


Figure 15: Carbon footprint and carbon budget of the New Zealand new-built residential dwellings over a 90-year estimated service life. CF= carbon footprint; CT= climate target; DH= detached house; MDH= medium density house; AP= apartment.

Additional references:

[1] Chandrakumar, C; McLaren, SJ; Dowdell, D; Jaques, R. 2019, *A top-down approach for setting climate targets for buildings: The case of a New Zealand detached house,* IOP Conf. Ser.: Earth Environ. Sci. 323 012183

[2] McLaren, SJ; Chandrakumar, C; Dowdell, D; Jaques, R. accepted, *Application of absolute sustainability assessment to New Zealand residential dwellings,* IOP Conf. Ser.: Earth Environ. Sci.

[3] Chandrakumar, C; Malik, A; McLaren, SJ; Owsianiak, M; Ramilan, T; Jayamaha, NP; Lenzen, M. 2020, *Setting better-informed climate targets for New Zealand: the influence of value and modeling choices,* Environ. Sci. Technol. 54(7)

Case study 10

Top-down or Bottom-up? – How Environmental Benchmarks can Support the Design Process

Corresponding case study author: Alexander Hollberg, Chalmers University of Technology, Sweden (alexander.hollberg@chalmers.se)
Original publication: Alexander Hollberg, Thomas Lützkendorf, Guillaume Habert, 2019, *Top-down or bottom-up? – How environmental benchmarks can support the design process,* Building and Environment, Volume 153, Pages 148-157; https://doi.org/10.1016/j.buildenv.2019.02.026

Abstract

Purpose/aim

The aim is to provide benchmarks that support two questions in the design process: 1) Is the building climate-friendly? and 2) How can the environmental performance of the building be improved through the choice of materials and construction principles?

Method

The concept consists in a dual benchmark combining top-down benchmarks derived from the capacity of the global eco system with bottom-up reference values for building components based on a statistical best-in-class approach (top 5%) using the market share of different construction products in Switzerland (see Figure 16).

Results

The resulting benchmark values can be used as a reference by designers.

Conclusion

The proposed approach can facilitate using LCA as a design-supporting method in design practice and promote the environmental performance optimization of buildings.

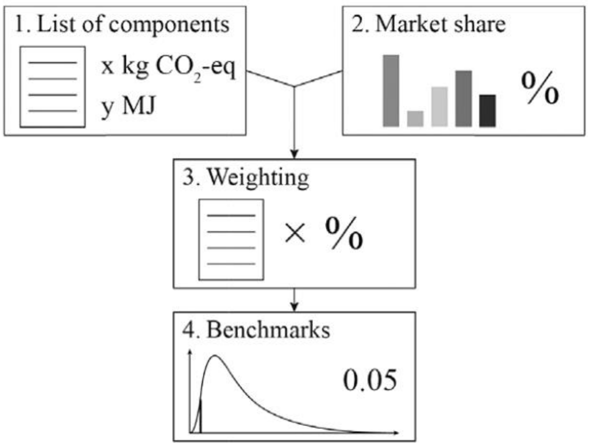


Figure 16: Simplified input on building level using the four categories as drop-down selections

Results

Based on the Swiss standard SIA2040 the top-down benchmarks for the operational and embodied GWP are calculated. The assumptions of SIA2040 are taken and adapted to the global target of 1 t CO_2-e per capita and year (see Table 5). The bottom-up benchmarks are calculated based on the typical construction components used and Switzerland that are available in a building component catalog. After weighting with the market share of materials used in Switzerland and statistical treatment the results in Table 6 are provided.

Table 5: Top-down benchmarks: Targets for GWP per capita and year for housing in Switzerland based on the global target of 1 t CO_2-e/(c·a).

GWP [kg CO_2-e/(c·a)]	
Embodied (including construction, replacement and demolition)	270
Operation	90
Total	360

Table 6: Bottom-up benchmarks: minimum, maximum and weighted mean and target values for GWP of different building elements.

Building element	Sample size	Reference unit	GWP [kg CO_2-e/(unit·a)]			
			Min.	W. mean	Max.	Target (0.05)
1. Base slab	80	$m^2_{element}$	1.32	2.23	2.82	1.87
2. Exterior walls underground	3	$m^2_{element}$	3.52	3.72	3.87	3.35
3. Exterior walls aboveground	404	$m^2_{element}$	0.82	2.11	3.82	1.37
4. Windows	16	$m^2_{element}$	1.49	3.16	5.57	1.85
5. Interior walls	35	$m^2_{element}$	0.59	1.28	4.46	0.82
6. Partition walls	30	$m^2_{element}$	0.58	1.05	3.97	0.83
7. Columns	7	piece	1.29	6.04	11.76	1.91
8. Ceilings	1260	$m^2_{element}$	0.66	2.24	4.69	1.37
9. Balconies	4	$m^2_{element}$	1.2	1.48	1.76	1.13
10. Roof	273	$m^2_{element}$	0.79	4.05	7.71	2.32
11. Technical equipment[a]	29	m^2_{AE}	1.18	–	3.36	1.18*

[a] Due to a small number of solutions in the building component catalogue, no benchmark is calculated, but the minimum is used. The target value is the sum of minimum values for electric equipment, heat generation, heat distribution and delivery, ventilation equipment and water (sanitary) equipment of residential buildings.

Case Study 11

Using a Budget Approach for Decision-Support in the Design Process

Corresponding case study author: Alexander Hollberg, Chalmers University of Technology, Sweden (alexander.hollberg@chalmers.se)
Original publication: Alexander Hollberg, Thomas Lützkendorf, Guillaume Habert, 2019, *Using a budget approach for decision-support in the design process,* IOP Conference Series: Earth and Environmental Science, Volume 323, SBE19 Graz; https://doi.org/10.1088/1755-1315/323/1/012026

Abstract

Purpose/aim

The paper provides an example of using a dual benchmark approach in the design process of a residential building for decision making support.

Method

The concept consists in first calculating the target value based on the top-down benchmarks. If the environmental impact of the building is higher than the target value, the impact of each building element is compared to the bottom-up benchmarks to analyse the material-related improvement potential. If this potential is not sufficient to reach the target, a change to the design (shape, floorplan, etc) is proposed (see Figure 17).

Results

The result show that the building's impact in the case study is close to the target. Reaching the target only based on material improvement is difficult. Design changes looking at the sufficiency are more effective.

Conclusion

The proposed approach can facilitate using LCA as a design-supporting method in design practice and promote environmental performance optimization of buildings.

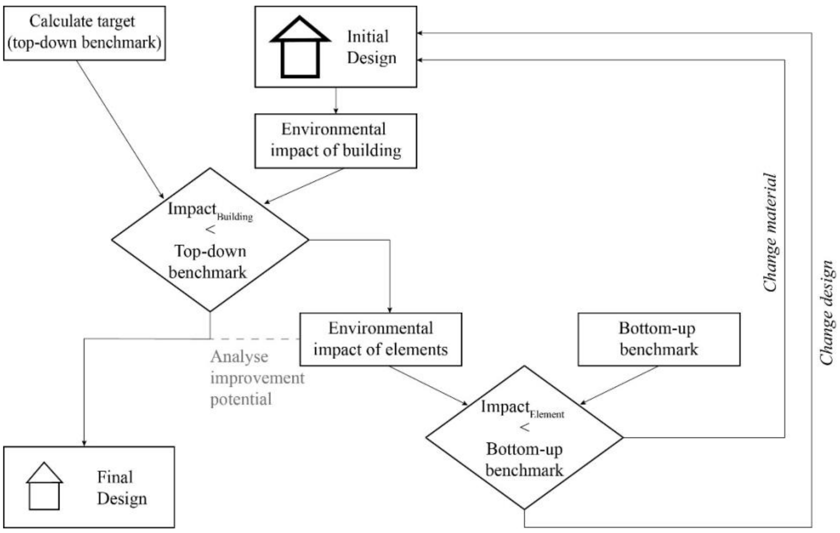


Figure 17: Proposed method of using the benchmarks in the design process

Results

A five-story timber building with a compact geometry (see Figure 18) is used as case study. The total life cycle GWP of 7591 kg CO_2-e/a is 14.6 % higher than the top-down target value of 6480 kg CO_2-e/a.

Figure 19 shows the GWP of each element related to the bottom-up benchmarks. As all selected solutions are close to the minimum, only the interior walls and the roof show a potential for improvement. Assuming the material of the internal walls could be exchanged to meet the benchmark this would save 289 kg CO_2-e/a. Doing the same for the roof would save another 9 kg CO_2-eq/a. This means that the optimization of the material could save 298 kg CO_2-eq. It is close, but not enough to reach the top-down target for the embodied part. Only, if the solutions with the minimum values are selected, the case study building achieves an embodied GWP of 4779 kg CO_2-eq/a and the top-down benchmark is met.

However, it is not clear whether this is technically feasible. Therefore, savings other than material optimization are needed. In this case study, the optimization potential of the building's shape is limited, because the building is very compact. One way to meet the top-down benchmarks is following a sufficiency strategy. If the floor area per resident can be reduced by 15% in this case study, for example through a higher efficiency of the floor plan, shared spaces or other design options, the top-down benchmark can be met.

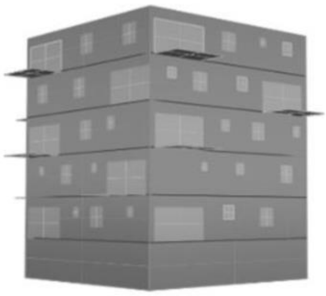


Figure 18: Case study building

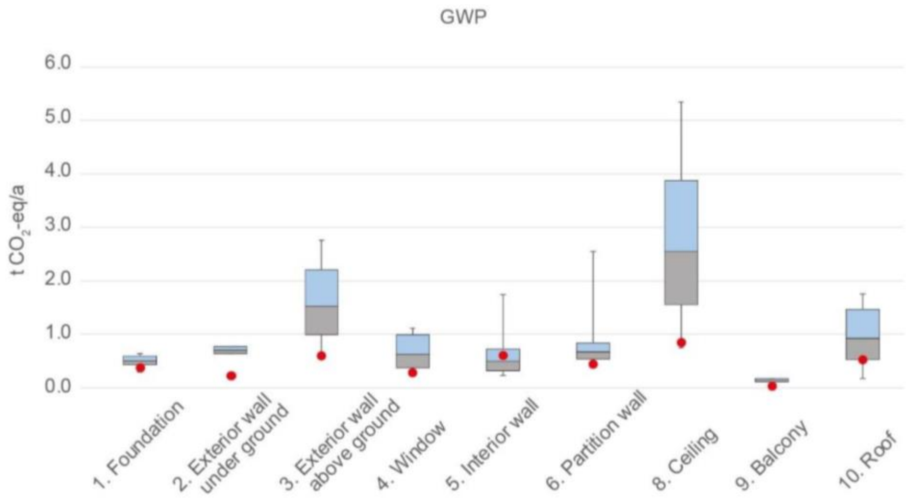


Figure 19: Benchmarks for the individual elements considering the surface areas of the building (points indicate the value for the specific material chosen in the case study)

3. Parametric related studies

Case Study 12

Statistical Method to Identify Robust Building Renovation Choices for Environmental and Economic Performance

Corresponding case study author: Alexander Hollberg, Chalmers University of Technology, Sweden (alexander.hollberg@chalmers.se)
Original publication: Alina Galimshina, Maliki Moustapha, Alexander Hollberg, Pierryves Padey, Sébastien Lasvaux, Bruno Sudret, Guillaume Habert, 2020, *Statistical method to identify robust building renovation choices for environmental and economic performance,* Building and Environment; https://doi.org/10.1016/j.buildenv.2020.107143

Abstract

Purpose/aim

Selecting an appropriate renovation strategy is challenging due to the long building service life and consequent uncertainties. In this paper, we propose a new framework for the robust assessment of renovation strategies in terms of environmental and economic performance of the building's life cycle.

Method

First, we identify the possible renovation strategies and define the probability distributions for 74 uncertain parameters. Second, we create an integrated workflow for Life Cycle Assessment (LCA) and Life Cycle Cost analysis (LCC) and make use of Sobol' sensitivity indices (a popular technique which quantifies how much of the variance in the model output each uncertain parameter is responsible for) to identify a prioritization strategy for the renovation. Finally, the selected renovation scenario is assessed by metamodeling techniques (application of Monte Carlo simulation using proxies of the original models) to calculate its robustness (see Figure 20).

Results

The results of three case studies of residential buildings from different construction periods show that the priority in renovation should be given to the heating system replacement, which is followed by the exterior wall insulation and windows. This result is not in agreement with common renovation practices and this discrepancy is discussed at the end of the original paper.

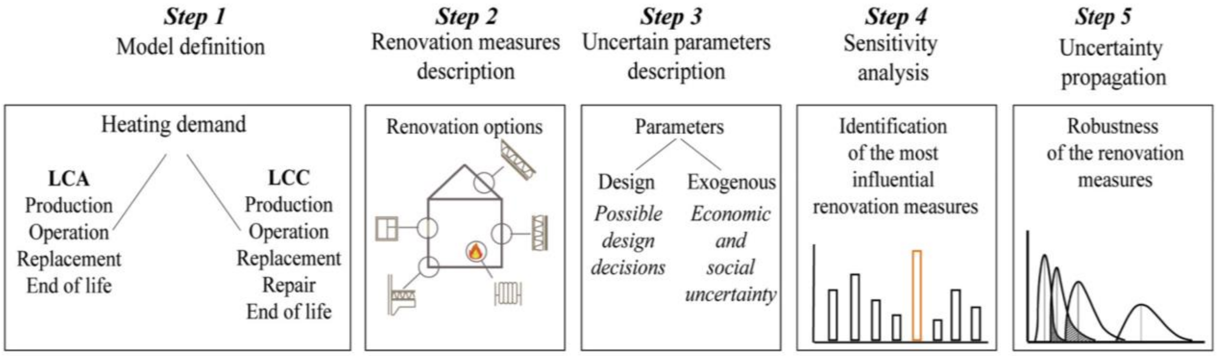


Figure 20: Proposed methodology.

Approach

The methodology of the paper is outlined in Figure 20. First, the heating demand of the building and a combined LCC and LCA is conducted. Second, possible renovation measures are selected. Third, the uncertain parameters are identified and described. This is followed by the Global Sensitivity Analysis, which is performed in several screening assessments to define the most influential parameters for the renovation. Finally, the uncertainties are propagated for the selected renovation measures and the solution robustness is compared to that of the non-renovated baseline case.

Figure 21: Building for case study 1.

Measure	Description
Step 1: Heating system	Heat pump, air-to-water, COP 2.8
Step 2: Exterior wall	12 cm rockwool insulation and plaster, U – 0.25 W/m^{2}K
Step 3: Windows	Wooden-aluminum window triple pane, frame part 10%, U – 0.8 W/m^{2}K
Step 4: Slab against unheated area	10 cm rockwool insulation and solid wood, U – 0.25 W/m^{2}K

Figure 22: Measures applied following each iteration of the sensitivity analysis.

Results for case study 1

Uncertainty propagation is carried out along each iteration of sensitivity analysis, i.e. once a renovation measure is selected, distributions of the corresponding GWP and costs are shown in Figure 23. The distributions of the non-renovated building lie on the right side of the figure. As renovation measures are applied, the curves gradually shift towards the left, which indicates a reduction in the mean values. The spread of the density curves is also getting smaller as renovation measures are applied, thus indicating an overall increase in robustness.

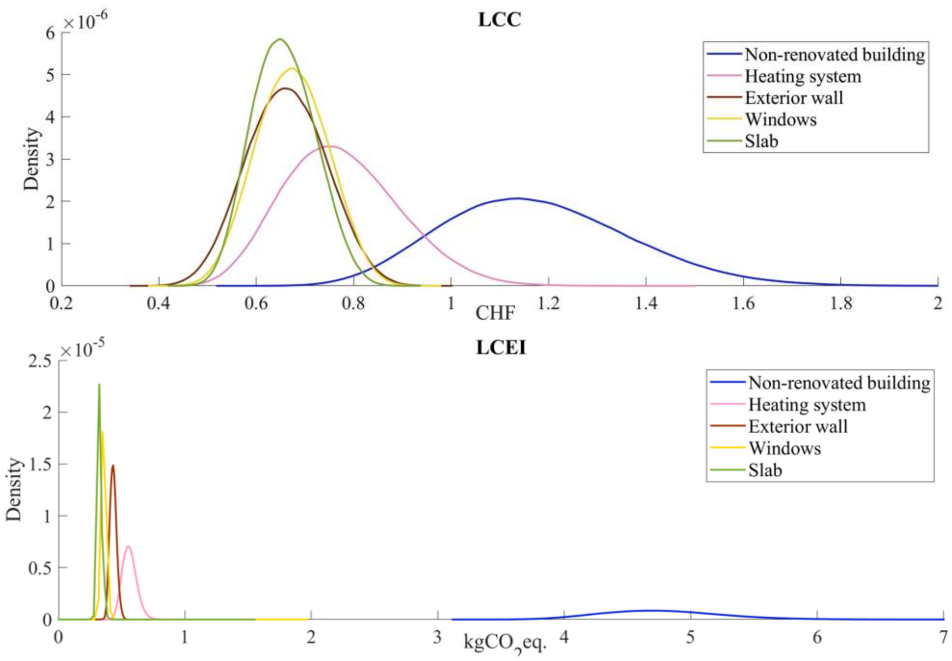


Figure 23: Measures applied following each iteration of the sensitivity analysis. The top graph shows results of uncertainty quantification for LCC in total CHF (Swiss Franc). The lower graph shows results of uncertainty quantification for LCEI (Life Cycle Environmental Impact) in total kg CO_2eq.

Case Study 13

A Data-driven Parametric Tool for Under-specified LCA in the Design Phase

Corresponding case study author: Alexander Hollberg, Chalmers University of Technology, Sweden (alexander.hollberg@chalmers.se)
Original publication: Alexander Hollberg, Deepshi Kaushal, Saso Basic, Alina Galimshina, Guillaume Habert, 2020, *A data-driven parametric tool for under-specified LCA in the design phase,* IOP Conference Series: Earth and Environmental Science, Volume 588, Beyond 2020; https://doi.org/10.1088/1755-1315/588/5/052018

Abstract

Purpose/aim

The goal of this paper is to adapt the method of structured under-specified LCA to the Swiss context and implement it in a design integrated tool. The users of the tool should be able to get a complete estimation of the life cycle impact based on very few inputs, such as building type, intended use and structural system.

Method

The paper describes the development of a structured database for the parametric LCA tool Bombyx. Furthermore, it exemplifies the intended workflow during the design process on a building design.

Results

The approach allows for quick feedback regarding environmental impacts over the whole life cycle in every design phase. From just defining four input parameters in the first building level, to finally defining each material, the approach makes sure that the LCA is calculated as accurately as possible in each stage.

Conclusion

The presented approach can be scaled up and adapted to other national contexts in the future. The visual output (Figure 24) facilitates environmental performance optimisation of buildings.

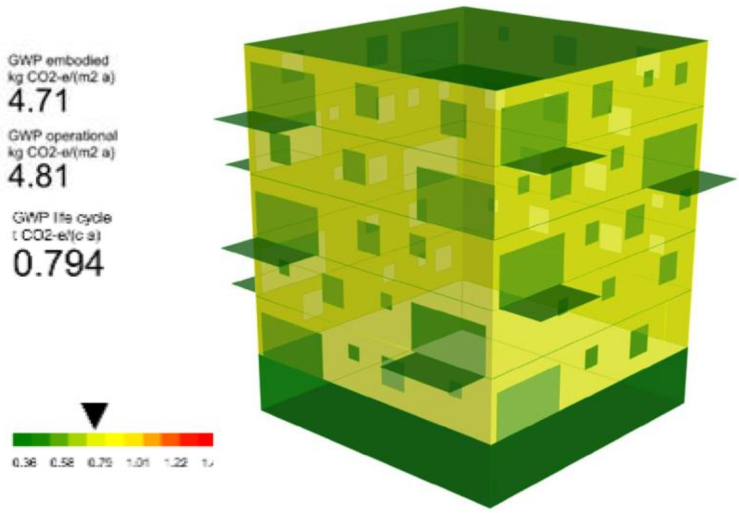


Figure 24: Visualisation of results (including total GWP and GWP per building component).

https://www.food4rhino.com/app/bombyx

ETH Zürich CHALMERS UNIVERSITY OF TECHNOLOGY Bombyx

Under-structured database

The material and component data used in Bombyx is stored in a SQL database. In addition to the LCA data, physical properties such as thermal conductivity are saved with the materials. In the future, further properties could easily be added. The four categories shown in Table 7 are added on component and element level to allow to filter the elements, components, and materials. The filtering occurs on different levels. If the material type timber is specified, only materials that belong to this category are used for example. If a Passivhaus standard is selected, only exterior walls with a u-value equal or below 0.15 W/(m^{2}K) are used.

Bombyx tool implementation

In the Grasshopper viewport, the specification of the materials and the technical system is done. On the building level, only the four inputs height, use, energy standard and main material are needed (see Figure 25). This provides all necessary information for the calculation of the embodied impact, but also the operational impact. For example, if the energy standard PassivHaus is selected, the tool filters the exterior walls that match the u-value of 0.15 or below. The u-value is mostly influenced by the thickness of the insulation layers in this case. For an ETICS system on a masonry wall, this would mean 24 cm of EPS insulation, for example. Based on the filtering, the average values of all construction that fulfil this criterion will be retrieved from the database. If the building should be specified in more detail in later design stage, the next level can be added. The calculation workflows stay the same.

Table 7: Visualisation of results (including total GWP and GWP per building component).

1 Height	2 Use	3 Energy standard	4 Material
Low rise	Residential SFH	Minimum	Concrete
Mid rise	Residential MFH	Above standard	Masonry
High rise	Office	Passivhaus	Timber
			Steel

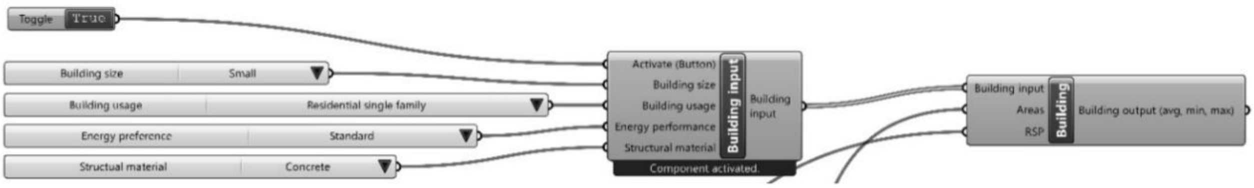


Figure 25: Simplified input on building level using the four categories as drop-down selections. SFH = single-family house; MFH = multi-family house

Case Study 14

Applying Multi-objective Optimization Techniques in a Modular Framework to Minimize Life Cycle Environmental Impact of Buildings I

Corresponding case study author: Benedek Kiss, Budapest University of Technology and Economics, Hungary (kiss.benedek@szt.bme.hu)
Original publication: Kiss, B., & Szalay, Z. (2020). Modular approach to multi-objective environmental optimization of buildings. Automation in Construction, 111. https://doi.org/10.1016/j.autcon.2019.103044

Abstract

Purpose/aim

Development of a modular framework that makes it possible to apply different optimization tools to early building design. Optimization of a case-study multi-apartment building in Hungary to minimize its environmental impacts through LCA.

Method

The procedure is based on the parametric definition of the case study building supported by various background datasets. The calculation step includes the quantification of material usage, as well as the operational energy impact (Figure 26). Results are used as objective values in the optimization module, while the building parameters comprise the optimization variables (Table 8).

Implementation

Grasshopper 3D (parametric modelling) with custom Python components (calculations) coupled with the Octopus plugin [1] (optimisation).

Conclusion

Through the optimization, significant environmental savings of 60–80% were achieved compared to the initial design options showing the potential for the application of such methods in architectural design.

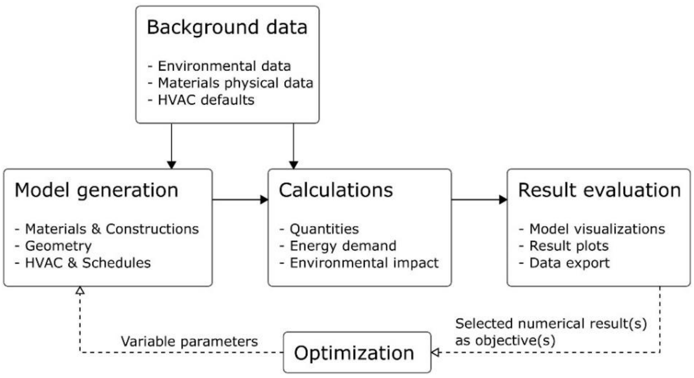


Figure 26: Example of a Pareto front.

Table 5: Optimization variables

Variable	Range/ discrete values	Unit
Number of storeys	1 - 8	-
Width of the building	5 - 30	m
Window-to-wall ratio N Window-to-wall ratio W Window-to-wall ratio S Window-to-wall ratio E	0.01 - 0.8	-
Glazing type N Glazing type S Glazing type E-W	double / triple glazed	-

Variable	Range/ discrete values	Unit
Wall insulation thickness	0.01 - 0.50	m
Wall insulation type	Cellulose, Rock wool, EPS, PUR, Glass wool, Wood wool, XPS	-
Roof insulation thickness	0.01 - 0.50	m
Roof insulation type	Cellulose, Rock wool, EPS, PUR, Glass wool, Wood wool, XPS	-
Shading	available / not available	-

Results

The results show that a relatively compact shape, large windows to south equipped with shading and very high levels of insulation are optimal from an environmental perspective (Figure 27). It was also proven that focusing only on the embodied or operational impact leads to a suboptimal solution (Figure 28), and the choice of the energy source for the operation of the building has a significant influence on the achievable optimum (Figure 29). The study showed that single-objective optimisation leads to different optima for different environmental indicators, which makes it difficult for the designer to decide between the options without explicitly assigning a weighting to the indicators. To overcome this issue, a multi-objective optimization should be applied, so the optimised options guarantee that no indicator will be neglected. At the same time, CED – GWP, CED – POCP and GWP – POCP turned out to be non-conflicting objectives in this case. This means that it may be sufficient to include only one of the three indicators as an objective in the optimisation, which would reduce the computation time in the results evaluation phase.

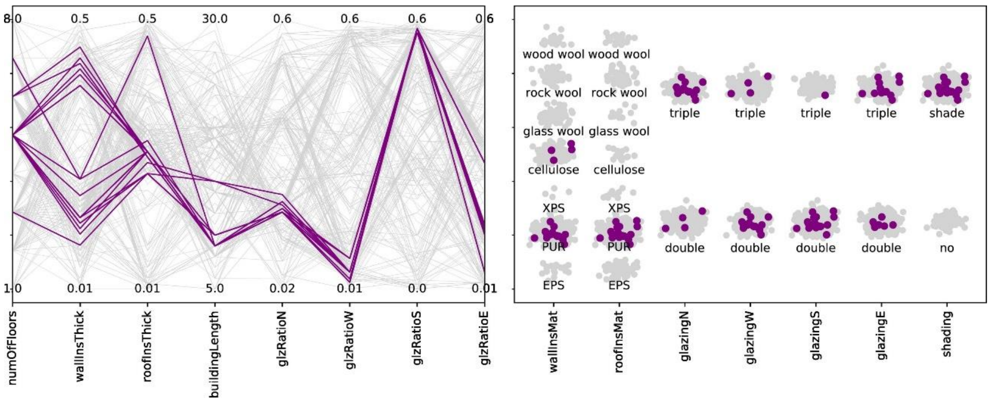


Figure 27: Example of a Pareto front.

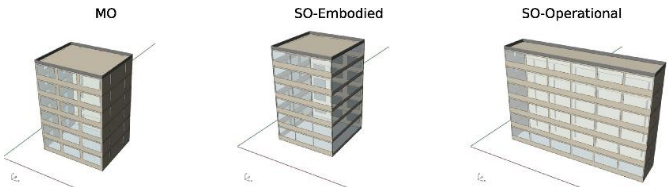


Figure 28: Optimized shape of the case study building depending on the objective (embodied / operational impact) and type of optimization (single-objective / multi-objective).

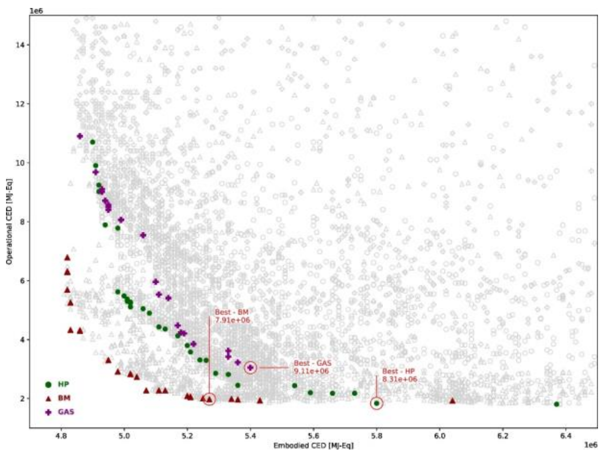


Figure 29: Optimized continuous variables (left), and discrete variables (right) of the multi-objective optimization

Additional references:

[1] Vierlinger, R. (2015). Master Thesis: Multi Objective Design Interface. (April 2013). https://doi.org/10.13140/RG.2.1.3401.0324

Case Study 15

Applying Multi-objective Optimization Techniques in a Modular Framework to Minimize Life Cycle Environmental Impact of Buildings II

Corresponding case study author: Alexander Hollberg, Chalmers University of Technology, Sweden (alexander.hollberg@chalmers.se)
Original publication: Alexander Hollberg, Jürgen Ruth, 2016, *LCA in architectural design—a parametric approach,* Int J Life Cycle Assess 21:943–960; https://doi.org/10.1007/s11367-016-1065-1

Abstract

Purpose/aim

This paper presents a parametric LCA approach, which allows architects to efficiently reduce the environmental impact of building designs.

Method

First, the requirements for design integrated LCA are analysed. Then, assumptions to simplify the required data input are made and a parametric model is established. The model parametrizes all input, including building geometry, materials, and boundary conditions, and calculates the LCA in real time. The parametric model was implemented in a parametric design software and applied using two cases: (a) the design of a new multi-residential building, and (b) retrofitting of a single-family house. Figure 30 provides an illustration of the procedure.

Implementation

We find that there is not one optimum insulation thickness, but many optima, depending on the individual boundary the chosen environmental indicator.

Conclusion

By incorporating a simplified LCA into the design process, the additional effort of performing LCA is minimized. The parametric approach allows architects to focus on their main task of designing the building and finally makes LCA practically useful for design optimization.

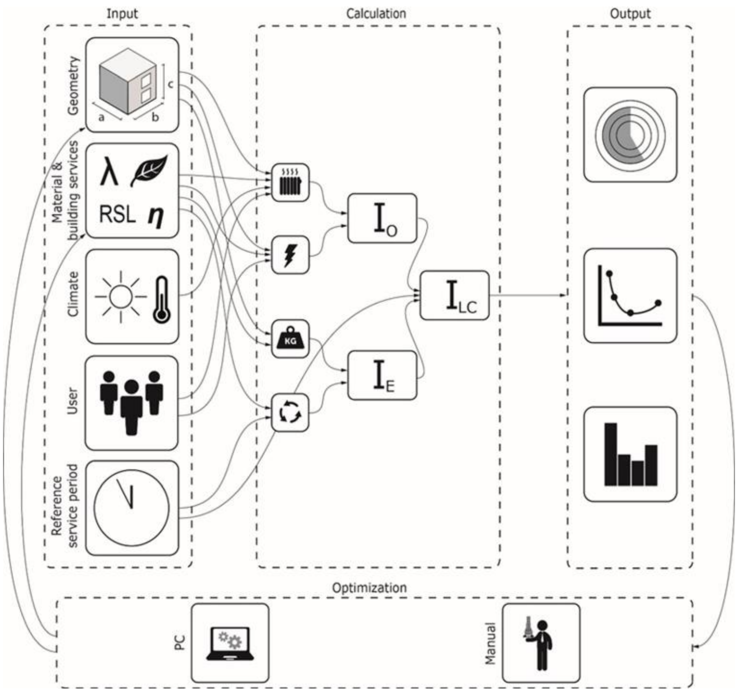
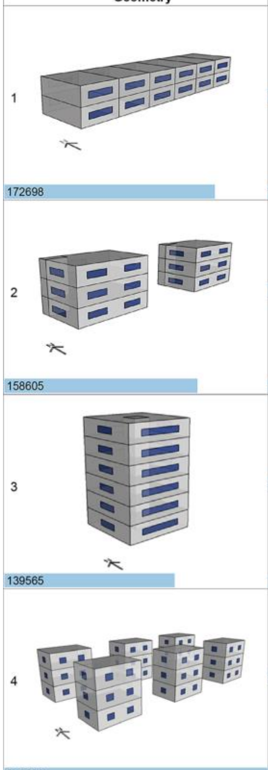


Figure 30: Concept of the parametric workflow

Case study results

We have successfully demonstrated the capability of the approach to find a solution with minimum environmental impact for both examples. In the first example, the parametric method is used to manually compare geometric design variants with regards to non-renewable primary energy (PENRT) (see Figure 31). The LCA is calculated based on assumptions for materials and building services.

In the second example, evolutionary algorithms are employed to find the optimum combination of insulation material, heating system, and windows for retrofitting. The results in Figure 32 show the minimum Life Cycle Impact (I_{LC}) for different environmental indicators.



Geometry	U-value	Material	Heat. System	
1 (172698)	EnEV (183440)	Wood (169332)	Gas	223040
			HP4.8	115624
		LSB (194240)	Gas	248944
			HP4.8	139535
		Concrete (186748)	Gas	242327
			HP4.8	131170
	Passivhaus (161955)	Wood (152326)	Gas	192203
			HP4.8	112449
		LSB (172177)	Gas	212477
			HP4.8	131877
		Concrete (161363)	Gas	201759
			HP4.8	120967
2 (158605)	EnEV (171192)	Wood (157359)	Gas	209233
			HP4.8	105486
		LSB (182215)	Gas	235107
			HP4.8	129323
		Concrete (174002)	Gas	228139
			HP4.8	119866
	Passivhaus (146018)	Wood (138312)	Gas	175575
			HP4.8	101048
		LSB (156355)	Gas	194135
			HP4.8	118575
		Concrete (143388)	Gas	181304
			HP4.8	105471
3 (139565)	EnEV (151505)	Wood (139361)	Gas	186288
			HP4.8	92434
		LSB (161790)	Gas	209540
			HP4.8	114040
		Concrete (153363)	Gas	202319
			HP4.8	104407
	Passivhaus (127625)	Wood (121331)	Gas	155420
			HP4.8	87242
		LSB (137298)	Gas	171853
			HP4.8	102742
		Concrete (124247)	Gas	158935
			HP4.8	89560
4 (215900)	EnEV (235768)	Wood (213929)	Gas	287165
			HP4.8	140693
		LSB (253762)	Gas	328608
			HP4.8	178916
		Concrete (239614)	Gas	316787
			HP4.8	162440
	Passivhaus (196031)	Wood (185215)	Gas	236640
			HP4.8	133791
		LSB (212912)	Gas	265242
			HP4.8	160582
		Concrete (189967)	Gas	242552
			HP4.8	137381

Figure 31: Case Study 1: Results for $PENRT_{LC}$ in MJ/a

Figure 32: Case Study 2: Results for minimum ILC depending on heating system and indicator

4. BIM related studies

Case Study 16

Embodied Carbon Assessment of HVAC Systems in Office Buildings Based on BIM

Corresponding case study author: Alexander Hollberg, Chalmers University of Technology, Sweden (alexander.hollberg@chalmers.se)
Original publication: Christina Kiamili, Alexander Hollberg, and Guillaume Habert, 2020, *Detailed Assessment of Embodied Carbon of HVAC Systems for a New Office Building Based on BIM,* Sustainability 2020, 12(8), 3372; https://doi.org/10.3390/su12083372

Abstract

Purpose/aim

This case study assesses the requirements and methods to perform a detailed life cycle assessment (LCA) for HVAC systems based on BIM (Figure 33).

Method

Linking external product data information using visual programming language (VPL) is tested using a detailed BIM model of a newly built office building in Switzerland. In addition, detailed project documentation is used to ensure the plausibility of the calculated impact.

Results

The embodied impact of the HVAC systems is 3 times higher than the targets provided by the Swiss Energy Efficiency Path (SIA 2040). It lies in the range of 15–36% of the total embodied impact of office buildings.

Conclusion

The results could contribute to defining better benchmarks for simplified LCA of HVAC system and for setting stricter targets in regulations.

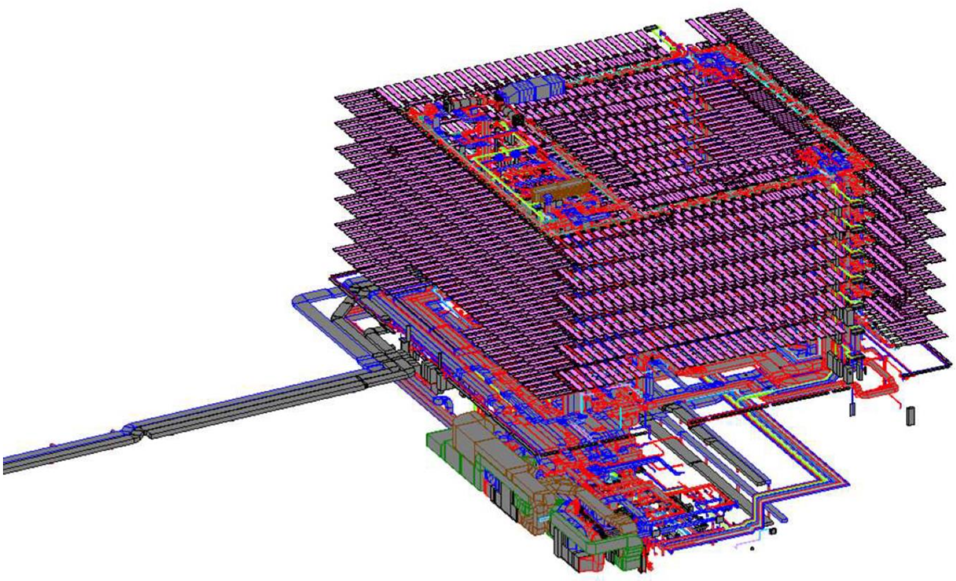


Figure 33: The BIM model of the HVAC systems of the case study building

Method

Three types of information are needed to perform the BIM-based LCA, namely geometrical data, material data (quantity and name), and LCA data. Geometrical and material information is extracted directly from the BIM model. If this information is not available in the model, product datasheets are used instead. In some cases, the quantity needs to be calculated by combining mathematical formula, e.g., for pipes and fittings. The integrated BIM and LCA workflow for the HVAC systems is described in Figure 34. Information from the BIM model (1), the product datasheets (2), and the LCA database (3) are combined in the VPL environment where the impact is calculated, and the results are exported in the desired format.

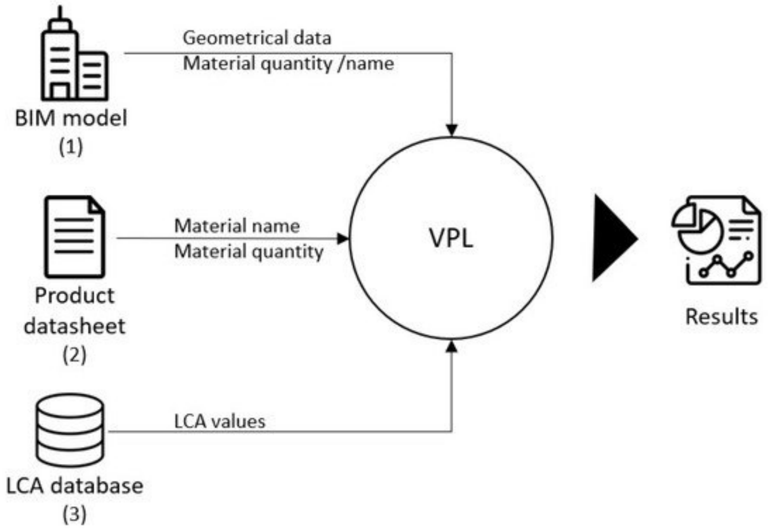


Figure 34: The BIM model of the HVAC systems of the case study building.

Results

The resulting GHG emissions show the importance of the replacement. The impact of the mechanical equipment is almost doubled during the use phase compared to its fabrication impact. Furthermore, it became clear that it is worth investigating the amount and the impact of the air filters that should be replaced every year according to the maintenance instructions. The total impact coming from the filters during the use phase of the building amounts to 11% of the total replacement impact.

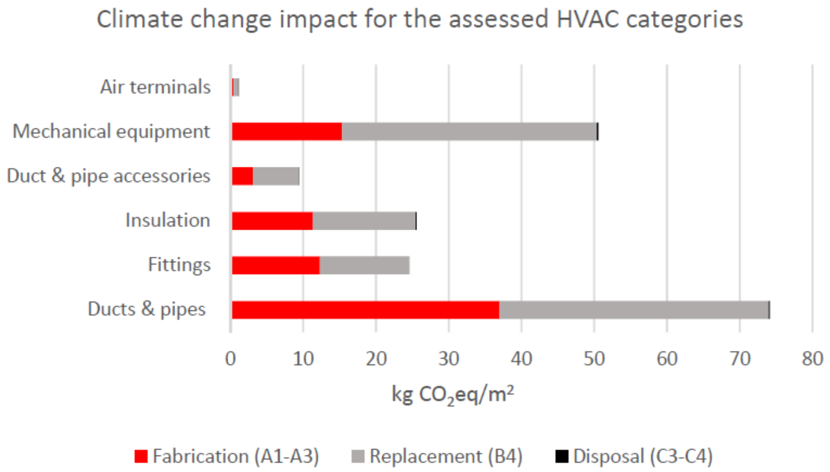


Figure 25: Climate change impact results for the assessed HVAC categories in $kgCO_2eq/m^2$.

Case Study 17

A Modelling Option of Transport to Guide Decision-making During Building Design Phases

Corresponding case study author: Bernardette Soust-Verdaguer, University of Seville, Spain (bsoust@us.es)
Original publication: Bernardette Soust-Verdaguer; Carmen Llatas; Antonio García-Martínez; and Juan Carlos Gómez de Cózar, 2018, *BIM-Based LCA Method to Analyze Envelope Alternatives of Single-Family Houses: Case Study in Uruguay,* Journal of Architectural Engineering, 24(3); https://doi.org/10.1061/(ASCE)AE.1943-5568.0000303

Abstract

Purpose/aim

This case study illustrates the incidence of transport impact in the decision making of building materials. It aims to identify which can be the best overall option: local but worst environmental performance materials or not local but better environmental performance materials.

Method

The modelling option defines five levels to quickly define the origin of the building materials, including: level 1 (up to 50 km), level 2 (up to 250 km), level 3 (up to 600 km), Level 4 up to 1500km), level 5 (up to 15000km). The method is used to compare 3 building material alternatives to a single-family house located in Uruguay. The examples of the modelling options are presented in Figure 36.

Results

Figure 37 show the incidence of transport impacts in the different material options. Figure 38 show that for the overall values (including modules A1-A3, A4 and B6) the transport impacts have similar influence both for local and no local building material alternatives.

Conclusion

The method can be used to compare different construction products and material and to get quick values of transport impacts and illustrate its influence in the entire life cycle environmental performance of the building.

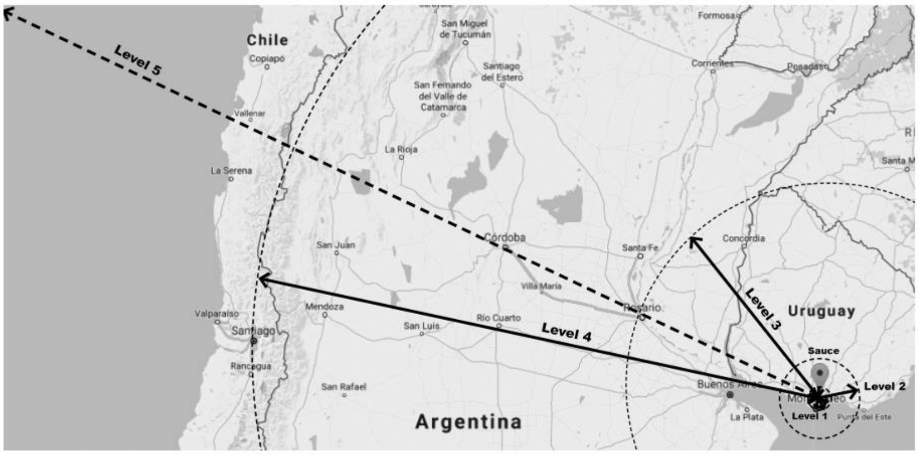


Figure 36: Examples of modelling option levels definition.

Explanation of Figure 37

Comparison of transport cradle to site of the three building design alternatives.

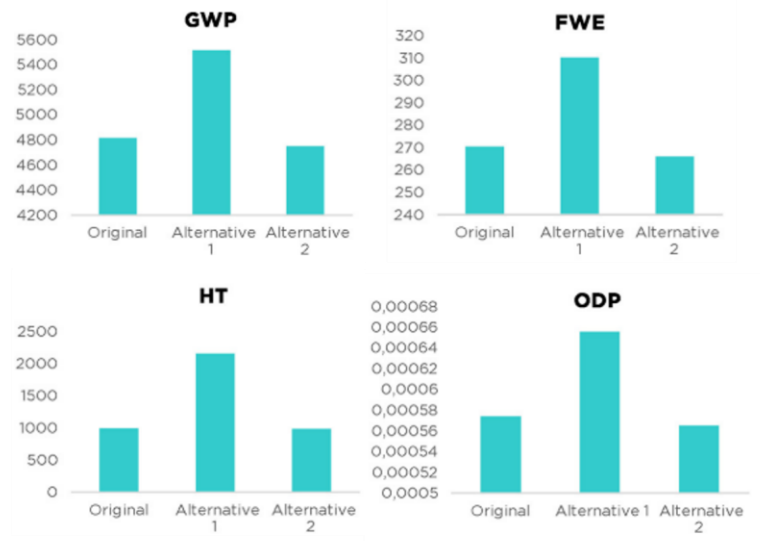


Figure 37: Examples of allocation principles.

Explanation of Figure 38

Comparison of the different scenarios considering the environment impacts GWP (global warming potential), FEW (Freshwater aquatic Ecotoxicity), HT (Human Toxicity), and ODP (Ozone depletion potential) for operational energy consumption (B6) and embodied impacts (including A1-A2-A3 and transport from cradle to site (A4)).

Figure 38: Examples of allocation principles.

Additional references:

[1] Bernardette Soust-Verdaguer; Carmen Llatas; Laura Moya, 2020, *Comparative BIM-based Life Cycle Assessment of Uruguayan timber and concrete-masonry single-family houses in design stage*, Journal of Cleaner Production, 227- 121958

Case Study 18

The BIM2LCA Approach: An Industry Foundation Classes (IFC)-Based Interface to Integrate Life Cycle Assessment in Integral Planning

Corresponding case study author: Rafael Horn, Fraunhofer Institute for Building Physics, Germany (rafael.horn@ibp.fraunhofer.de) and Sebastian Ebertshäuser, Karlsruhe Institute of Technology (KIT), Germany (sebastian.ebertshaeuser@kit.edu)
Original publication: Rafael Horn, Sebastian Ebertshäuser, Roberta Di Bari, Olivia Jorgji, René Traunspurger, Petra von Both, 2020, *The BIM2LCA Approach: An Industry Foundation Classes (IFC)-Based Interface to Integrate Life Cycle Assessment in Integral Planning,* Sustainability, 12, 6558: https://www.mdpi.com/2071-1050/12/16/6558.

Abstract

Purpose/aim

This study presents an approach for LCA integration in all phases of digital planning which aims at a DGNB certification based on the open BIM standard IFC. It allows one to consider both BIM and LCA software through a workflow based on a single data format.

Method

The planned object is created in a BIM-based authoring tool. The BIM-model is exported to the LCA system as IFCXML based on the LCA MVD. An LCA expert can adjust, complement, and specify the basic LCA input according to LCA-related requirements within an LCA expert software (e.g. GENERIS). LCA results are fed back into the BIM system through specification of results based on the use case requested in BIM, reintegration of LCA results in the IFCXML file, and import as well as result depiction in the BIM software. The general workflow can be seen in Figure 39.

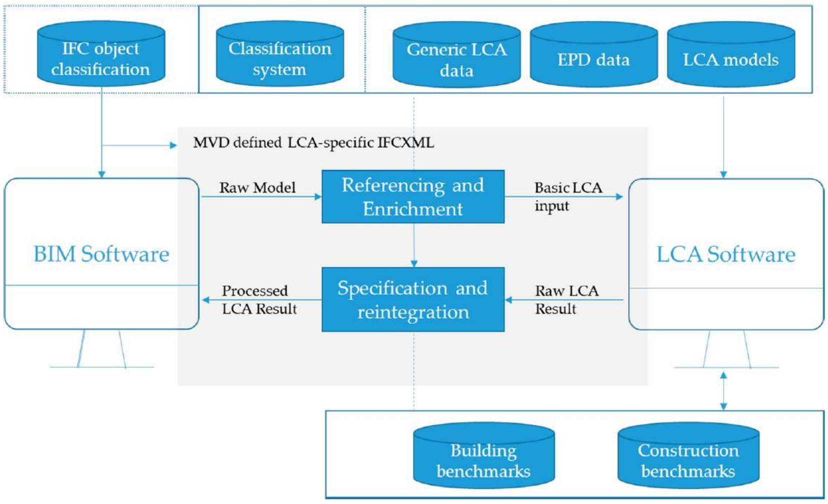


Figure 39: General workflow of the BIM2LCA approach as an extension of the strategies defined by [1] IFC-based bidirectional BIM-LCA integration.

Fraunhofer IBP
KIT Karlsruher Institut für Technologie
University of Stuttgart Institute for Acoustics and Building Physics
DGNB Deutsche Gesellschaft für Nachhaltiges Bauen German Sustainable Building Council

Results
Exemplified LCA settings in the structure of a life cycle element are presented in Figure 40.
Discussion
The XSD represents a specific solution for a submission process within the sustainable building assessment (SBA) tool GENERIS and the DGNB certification system but can be easily modified and extended for other SBA tools and certification systems.
Conclusion
BIM2LCA is the first open and fully modular and extendible approach to couple BIM and LCA.

Explanation of Figure 40

The exemplified LCA settings include the specification of the LCA database (e.g. Ökobaudat), the applied functional units (e.g. m³), the LCA type, and the applied indicators (e.g. GWP and ODP). Elements with solid lines are considered mandatory and dashed lines represent optional entries.

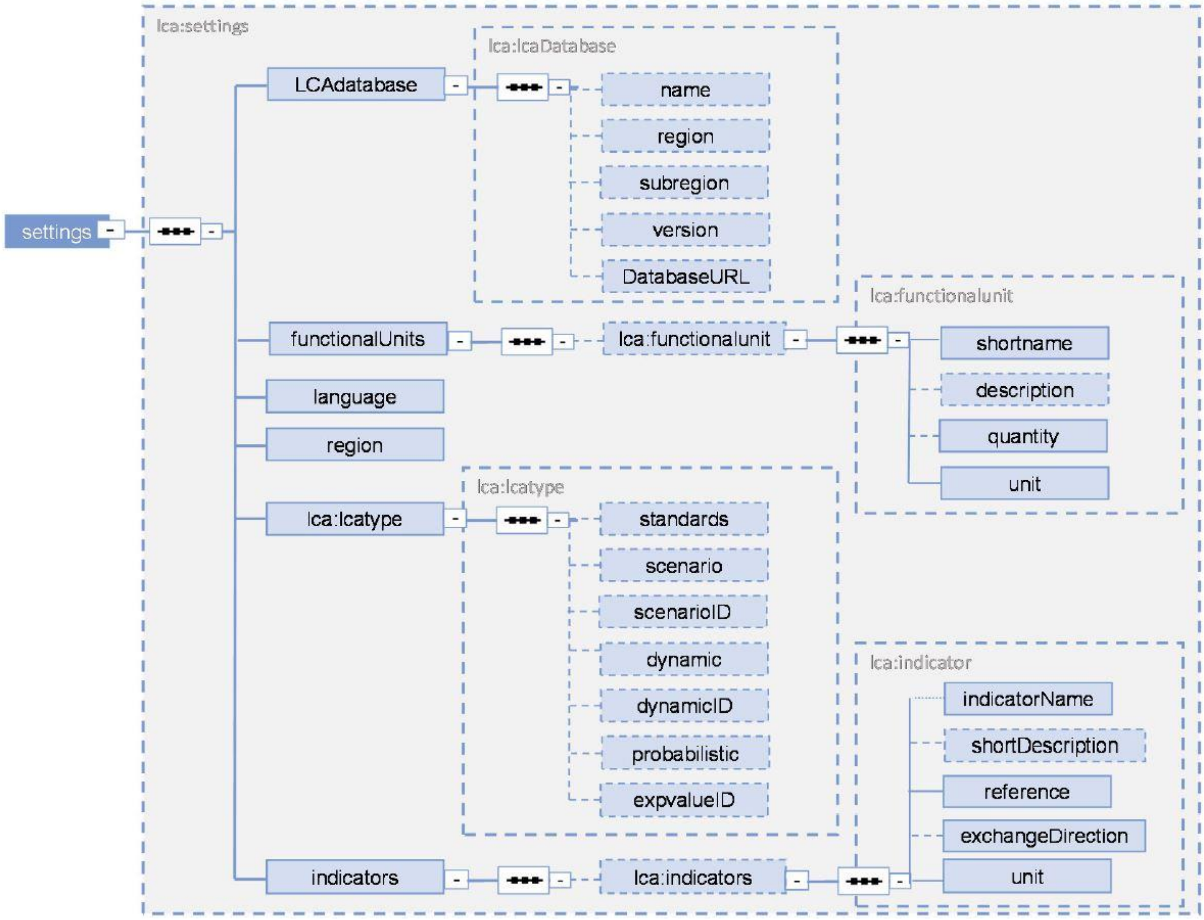


Figure 40: Example for LCA settings in the structure of a life cycle element.

Additional references:
[1] Wastiels, L.; Decuypere, R. Identification and comparison of LCA-BIM integration strategies. IOP Conf. Ser. Earth Environ. Sci. 2019, 323, 12101

Case Study 19

Integration of LCA and LCC Analysis Within a BIM-based Environment

Corresponding case study author: Rúben Santos, CERIS, Instituto Superior Técnico, University of Lisbon, Portugal (ruben.e.c.santos@tecnico.ulisboa.pt)
Original publication: Santos, R., Costa, A. A., Silvestre, J. D., & Pyl, L. (2019). Integration of LCA and LCC analysis within a BIM-based environment. Automation in Construction, 103, 127-149.
https://doi.org/10.1016/j.autcon.2019.02.011

Abstract

Purpose/aim

The present study explores the potential of BIM as a repository for the LCA and LCC information, and how that information should be used for an environmental and economic analysis.

Method

A BIM-LCA/LCC framework was proposed (Figure 41), which led to the development of an information delivery manual and a model view definition (IDM/MVD), using the industry foundation classes (IFC) schema, for the integration and exchange of information within a BIM-based environment.

Results

The authors verified that, to comply with the proposed framework, 137 IFC properties were required.

Discussion

Out of the 137 properties, the IFC4 schema already contains nine properties, all at the element level (eight for the environmental impact categories, in which the ADPE category is missing one property, and one for the economic impact). For a streamlined LCA/LCC analysis, the IFC schema does not require significant improvement, in contrast with the complete analysis. In this case, the IFC schema should add 17 mandatory properties apart from the previous nine (mostly at the material level), and 111 optional properties (at the material and project levels).

Conclusion

The proposed IDM/MVD allowed to identify the information exchange required to perform the LCA and LCC analysis within a BIM-based environment. This work contributes to the existing background knowledge necessary for future implementations of BIM-based LCA/LCC and for software developers to develop a suitable BIM-LCA/LCC tool.

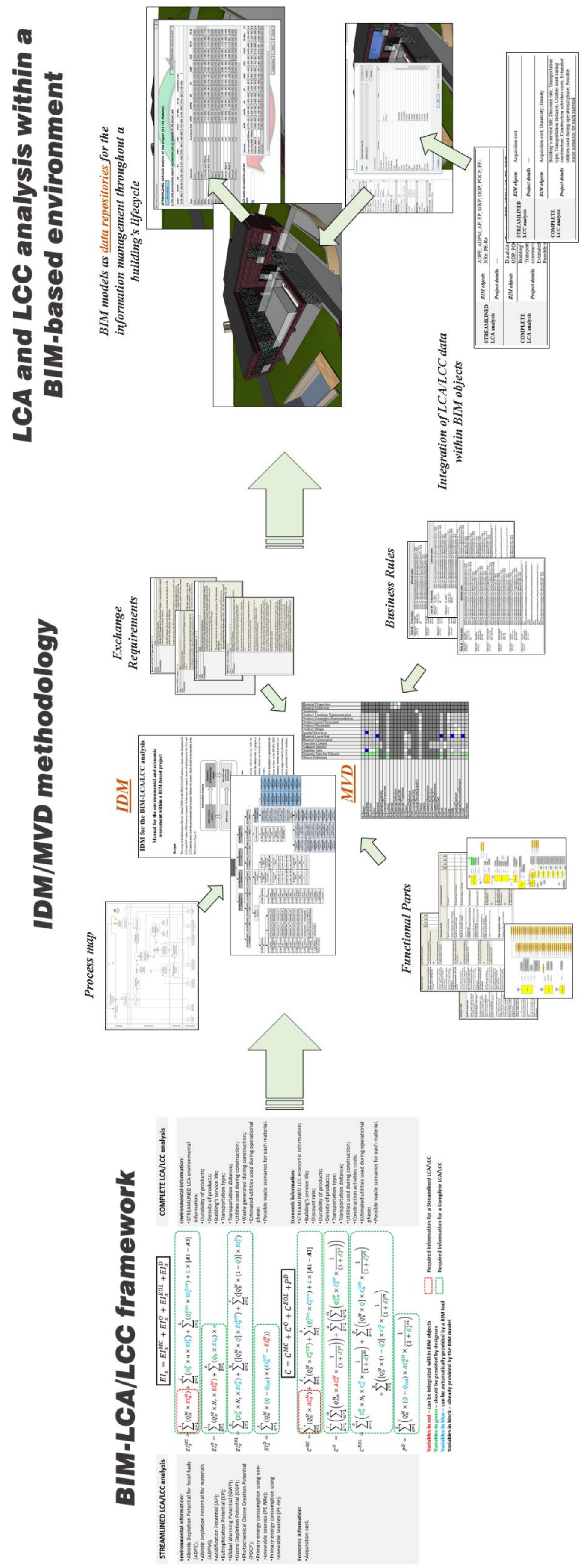


Figure 41: BIM-LCA/LCC Integration framework

Case Study 20

LCA and BIM: Visualization of Environmental Potentials in Building Construction at Early Design Stages

Corresponding case study author: Martin Röck, Graz University of Technology, Austria (martin.roeck@tugraz.at)
Original publication: Röck M, Hollberg A, Habert G, Passer A. LCA and BIM: Visualization of environmental potentials in building construction at early design stages. Build Environ 2018;140:153–61. DOI: https://doi.org/10.1016/j.buildenv.2018.05.006

Abstract

Purpose/aim

This case study showcases an approach using Building Information Modelling (BIM) to assess a wide range of construction options and their embodied environmental impact.

Method

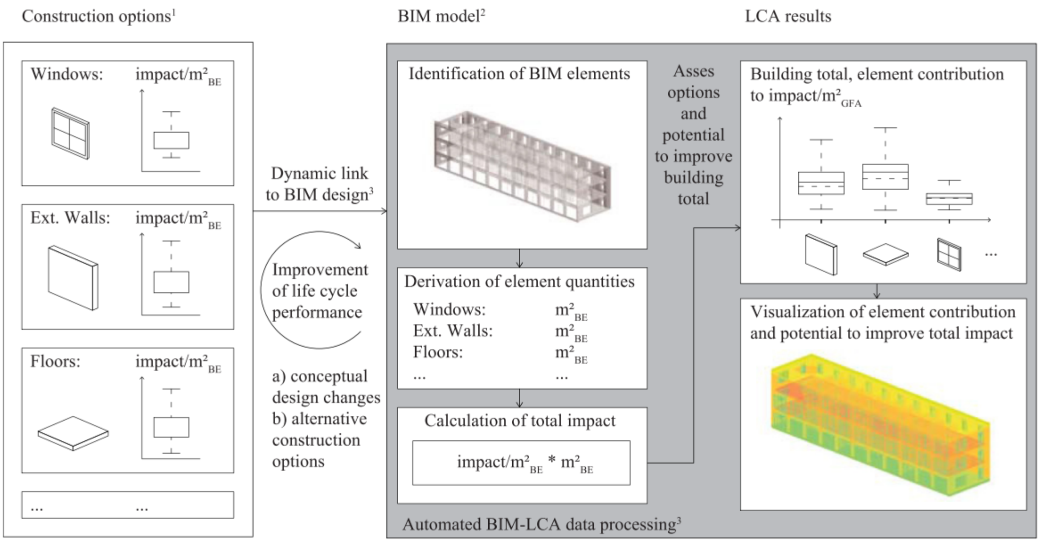
We use a conceptual BIM model to evaluate a variety of material compositions for different building elements and the potential contribution of elements to the total embodied impact of the building design.

Results

Applying the method to a case study we can see that it allows to quickly identify which element has the greatest potential for improvement at the building scale and where to focus during a conceptual design stage (Figures 42-44).

Conclusion

The BIM-integrated approach enables identification of design specific hotspots which can be visualized on the building model for communication of LCA results and visual design guidance.



¹ Aggregated LCA database for building elements, e.g. MS Excel
² BIM model, e.g. Autodesk Revit
³ Custom script, e.g. Autodesk Dynamo

Figure 42: Schematic workflow showing the link of aggregated LCA data for multiple construction options and BIM; Automated identification of element quantities and calculations of total embodied impact; Analysis and visualization of LCA results and improvement potential.

Conclusion

The presented workflow shows that it is possible to accomplish an integration of LCA in BIM when using a common granularity and data structure in both LCA data and BIM elements. Applying this approach allows a BIM-integrated calculation of embodied impacts of building materials in early design stages. Using a variety of possible construction options this integrated calculation enables a comprehensive analysis of individual building element's contribution to the total impact as well as the identification of design-specific hotspots and improvement potential from specific building elements.

Furthermore, the building model geometry can be used for visual design guidance by presenting various aspects of the results such as the contribution or sensitivity of specific building elements plus the changes from different design options to the total embodied impact of the building. This kind of visual presentation provides an intuitive way to communicate the impact and importance of material choices for individual building elements.

Finally, the proposed approach could thus make the application of LCA as a design-supporting method more accessible and especially improve assessment and communication of embodied impacts.

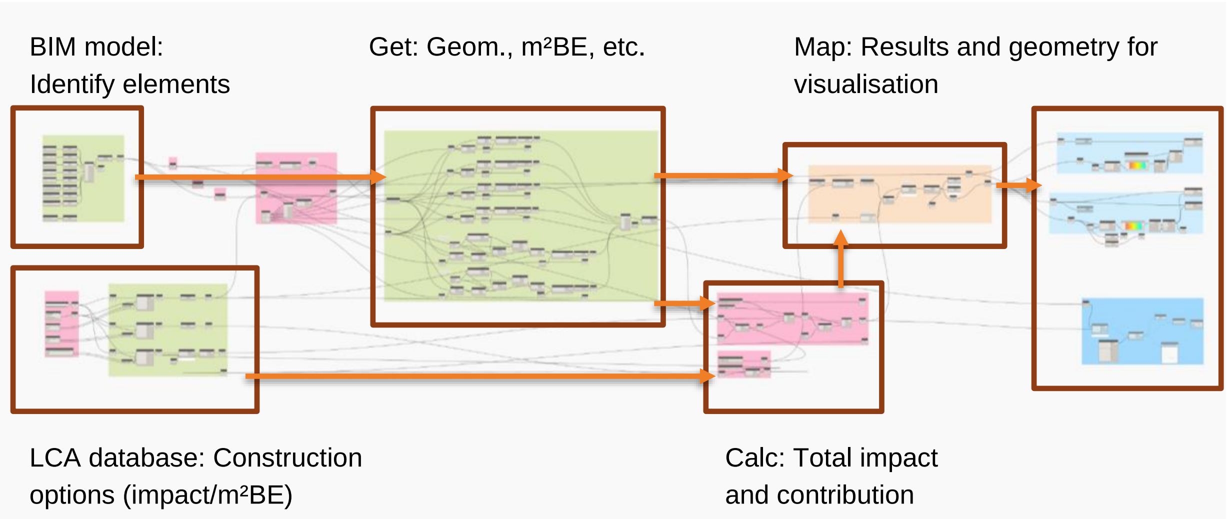


Figure 43: Custom script using a Revit BIM model and Dynamo for visual programming.

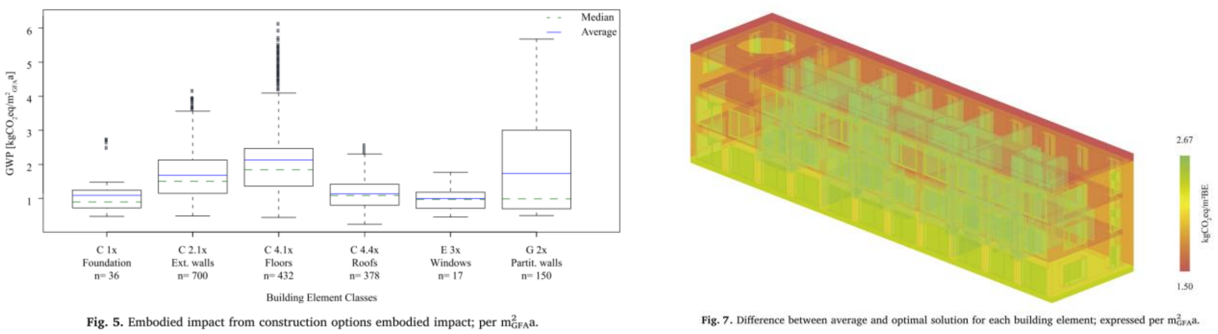


Figure 44: Optimization potential presentation options (boxplot, 3D model visualisation).

Case Study 21

Evaluation of BIM-based LCA Results for Building Design

Corresponding case study author: Alexander Hollberg, Chalmers University of Technology, Sweden (alexander.hollberg@chalmers.se)
Original publication: Alexander Hollberg, Gianluca Genova, Guillaume Habert, 2020, *Evaluation of BIM-based LCA results for building design,* Automation in Construction, 109; https://doi.org/10.1016/j.autcon.2019.102972

Abstract

Purpose/aim

Various tools using BIM for automatic quantity take-off as basis for LCA have been developed recently (Figure 45). This paper describes the first application of such a BIM-LCA tool to evaluate the embodied GWP throughout the whole design process of a real building.

Method

34 states of the BIM model of a case study (see Figure 46) are analysed using a Dynamo script that links the materials in the Revit model with the Swiss LCIA database for buildings KBOB.

Results

The results show that the embodied GWP during the design phase (see Figure 47, 48) is twice as high as for the final building. These changes can be mainly attributed to the designers' approach of using placeholder materials that are refined later (see Figure 49), besides other reasons.

Conclusion

By using the current BIM design workflow as it is, the embodied GWP is highly overestimated. A BIM-based environmental assessment during the design process could be misleading and counterproductive. Three alternatives to the established automatic quantity take-off are discussed for future developments (see the link to the full paper for this discussion).

Figure 45: BIM-LCA workflow

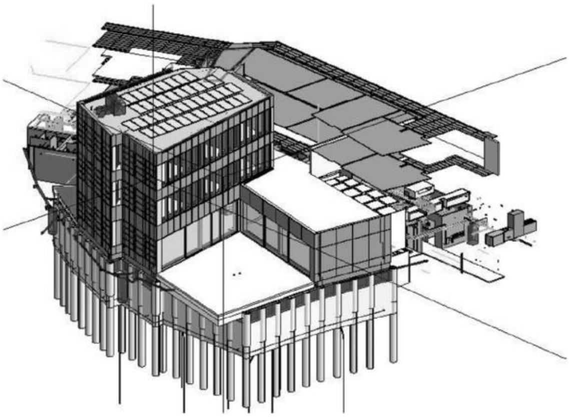


Figure 46: Example BIM model for the case study – the first office building in Switzerland built without printed plans

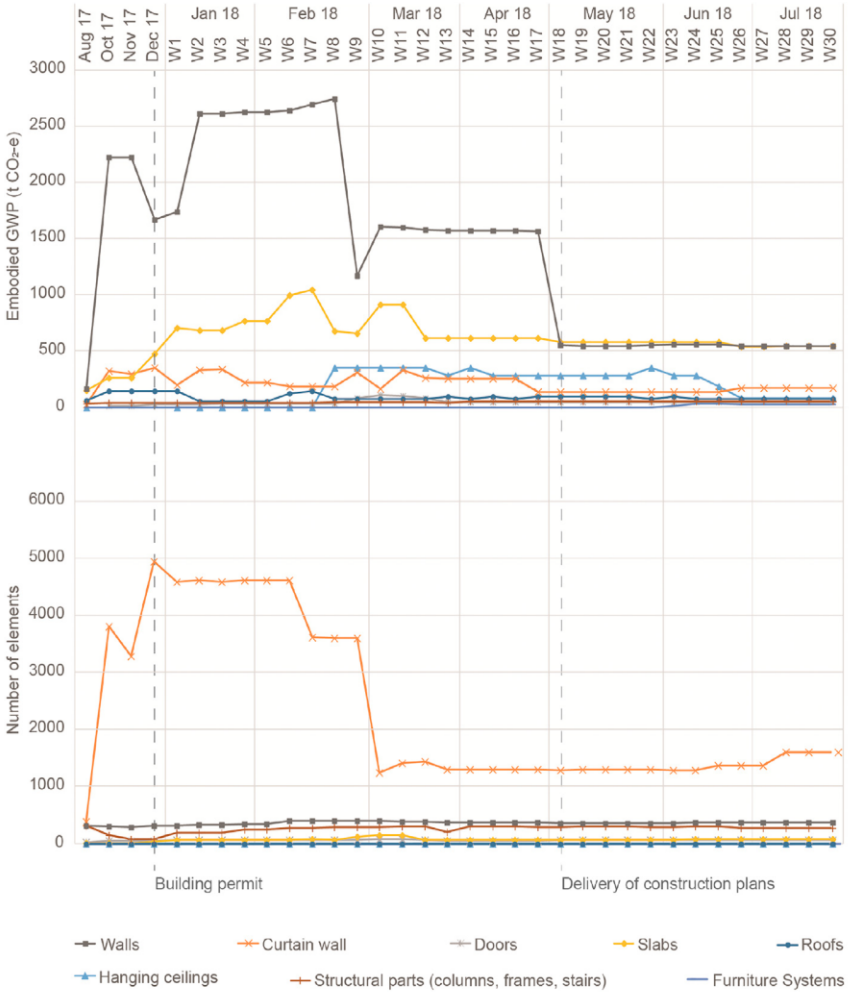
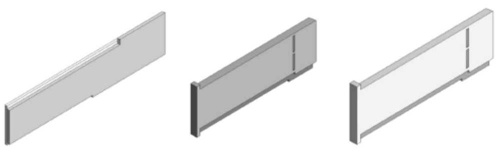


Figure 47: Evolution of results for embodied GWP in t CO_2-e for individual building elements and number of elements throughout the design process.

Figure 48: Evolution of total results for embodied GWP in t CO_2-e throughout the design process.



Date	October 2017	April 2018	July 2018
Number of elements	2	1	1
Number of materials	2	5	5
Area [m^2]	51.35	37.98	35.42
Volume [m^3]	12.82	18.79	11.45

Figure 49: Example for quantity take-off for a single wall.

Case Study 22

A Design Integrated Parametric Tool for Real-time Life Cycle Assessment – Bombyx Project

Corresponding case study author: Alexander Hollberg, Chalmers University of Technology, Sweden (alexander.hollberg@chalmers.se)
Original publication: Saso Basic**,** Alexander Hollberg, Alina Galimshina, Guillaume Habert, 2019, *A design integrated parametric tool for real-time Life Cycle Assessment – Bombyx project,* IOP Conference Series: Earth and Environmental Science, Volume 323, SBE19 Graz; https://doi.org/10.1088/1755-1315/323/1/012112

Abstract

Purpose/aim

The biggest potential for optimization and reduction of GHG emissions lies in the early stages of the design process (see Figure 50). Therefore, a design-integrated approach for LCA is needed. The goal of this paper is to describe the development of a parametric LCA tool for application in early design stages in the Swiss context.

Method

The integration of LCA throughout the design process is solved through a modular strategy. In the early stage, pre-defined components are selected to model a complete LCA. In the following design steps when more information is available, individual materials can be input with higher level of detail.

Results

The Bombyx tool is developed as a plugin for Grasshopper based on Rhinoceros3D, which is a 3D modelling software and includes an SQL material and component database. Users can choose different materials and building systems and quickly modify the building's geometry while continuously receiving the calculated environmental impact in real-time.

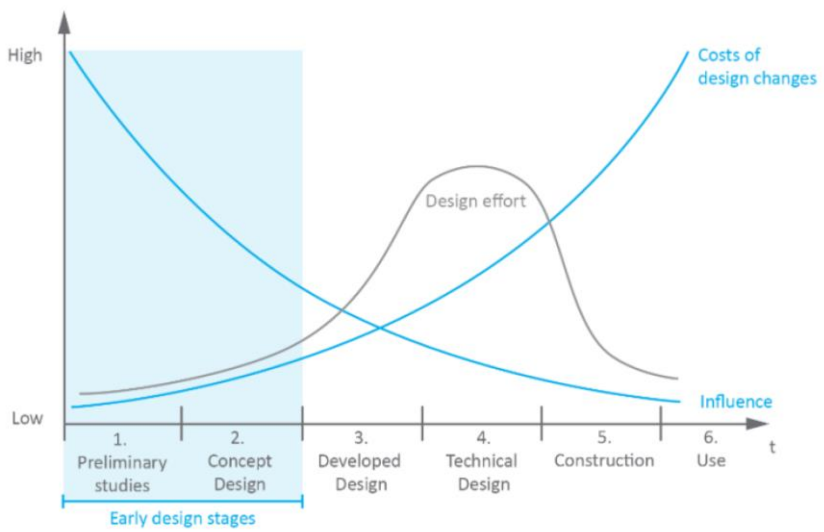


Figure 50: Influence of the early design stages

https://www.food4rhino.com/app/bombyx

Bombyx tool

The envisioned users of the tool are primarily architecture and engineering students, but also practitioners. The plugin for Grasshopper can be downloaded at https://www.food4rhino.com/app/bombyx. Figure 51 shows the approach to structure the building into element. Figure 52 shows the user interface in Grasshopper. The project is developed in open source (https://github.com/Bombyx-ETH/Bombyx) to broaden the user and developer community and foster new ideas, designs, and implementations in Bombyx.

Building element	BKP-H Component
1. Base slab	C1 Base slab, foundation
	G2 Floor covering
2. Exterior wall under ground	C2.1A Exterior wall under ground
	E1 Exterior wall finishing under ground
3. Exterior wall above ground	C2.1B Exterior wall above ground
	E2 Exterior wall finishing above ground
	G3 Interior wall finishing
4. Window	E3 Window
5. Interior wall	C2.2 Interior wall
	G3 Interior wall finishing
6. Partition wall	G1 Partition wall
	G3 Interior wall finishing
7. Column	C3 Column
8. Ceiling	C4.1 Ceiling
	G2 Floor covering
	G4 Interior ceiling/roof finishing
9. Balcony	C4.3 Balcony
10. Roof	C4.4 Roof
	F1 Roof covering
	G4 Interior ceiling/roof finishing
11. Technical equipment	D1 Electric equipment
	D5.2 Heat generation
	D5.3 / D5.4 Heat distribution and delivery
	D7 Ventilation equipment
	D8 Water (sanitary) equipment

Figure 51: Structure of building elements and components

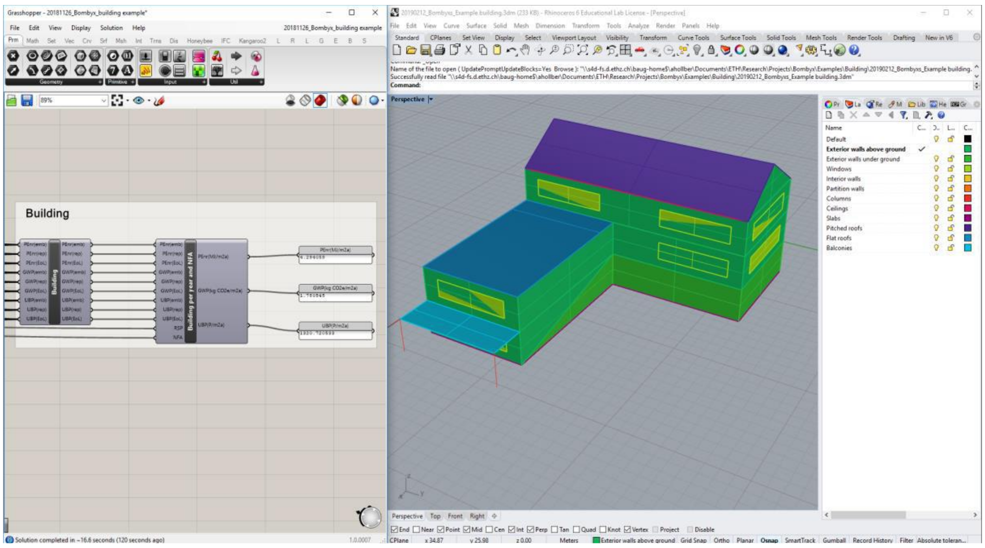


Figure 52: Bombyx plug-in in GH (left) and geometry with pre-defined layers (right).

Case Study 23

BIM-based Life cycle Assessment and Life Cycle Costing of an Office Building in Western Europe

Corresponding case study author: Rúben Santos, CERIS, Instituto Superior Técnico, University of Lisbon, Portugal (ruben.e.c.santos@tecnico.ulisboa.pt)
Original publication: Santos, R., Costa, A. A., Silvestre, J. D., Vandenbergh, T., & Pyl, L. (2020). BIM-based life cycle assessment and life cycle costing of an office building in Western Europe. Building and Environment, 169, 106568. https://doi.org/10.1016/j.buildenv.2019.106568

Abstract

Purpose/aim

The main aim of this research is to enhance the integration of LCA and LCC methodologies with BIM, as existing approaches still have limitations (e.g., interoperability issues, non-editable databases). For that purpose, an automatic LCA/LCC analysis within a BIM-based environment is proposed.

Method

An office building under construction in the Netherlands is used as a pilot case study. Moreover, a prototype tool developed by the authors is used to support the study and validation of the framework. The BIM-LCA/LCC approach is compared with two other tools, Tally and ATHENA Impact Estimator.

Results

A Streamlined analysis was conducted, demonstrating that an automatic LCA and LCC analysis is possible if the correct information is contained within the model. However, the user (e.g., designer, LCA/LCC expert) must provide project-specific information to perform a Complete analysis.

Discussion

The selected approach must allow users to select materials manufactured in the same geographic region of the project. Secondly, the flexibility of the external LCA/LCC databases, how they are integrated with the BIM tools, and how the information within the BIM model can be reused are the aspects that influence the BIM-LCA/LCC integration the most.

Conclusion

This study unveiled the potential of BIM-based simulations for the assessment of the environmental and economic impacts of buildings by integrating semantic information in the model. The work presented in this research is expected to contribute to the development of automatic sustainability simulations, creation of tailor-made BIM objects' libraries, and use of historical data contained within data-rich models for predictive analyses.

Explanation of Figure 53

Figure 53 illustrates the qualitative impacts per element for the LCC, and global warming potential (GWP) and the cumulative non-renewable energy demand (PE-NRe) environmental categories. For each category, the prototype tool identifies the elements with maximum and minimum contributions (disregarding the elements with empty indicators) and assign the red, orange, purple, blue, and green colour to the elements that have impacts higher than 80% of the maximum contribution, 80-60%, 60-40%, 40-20%, and lower than 20%, respectively. Therefore, the element with the highest contribution will always be highlighted in red and the one with the lowest in green.

As visualized in Figure 53, most of the elements exhibit a green colour in the LCC category. In contrast, the glazed curtain walls (red), ground floor slab (orange), the roofing and EPS 140 mm (purple), and the partition walls (blue) were the elements that had a different colour range, indicating that these were the elements that contributed the most to this category (in absolute terms).

For environmental categories, the canopy (i.e., the rectangular steel frame around the ground and first floor's slabs) is the element that contributes the most to both categories because of the amount of steel (a high energy intensive material) used in its manufacturing.

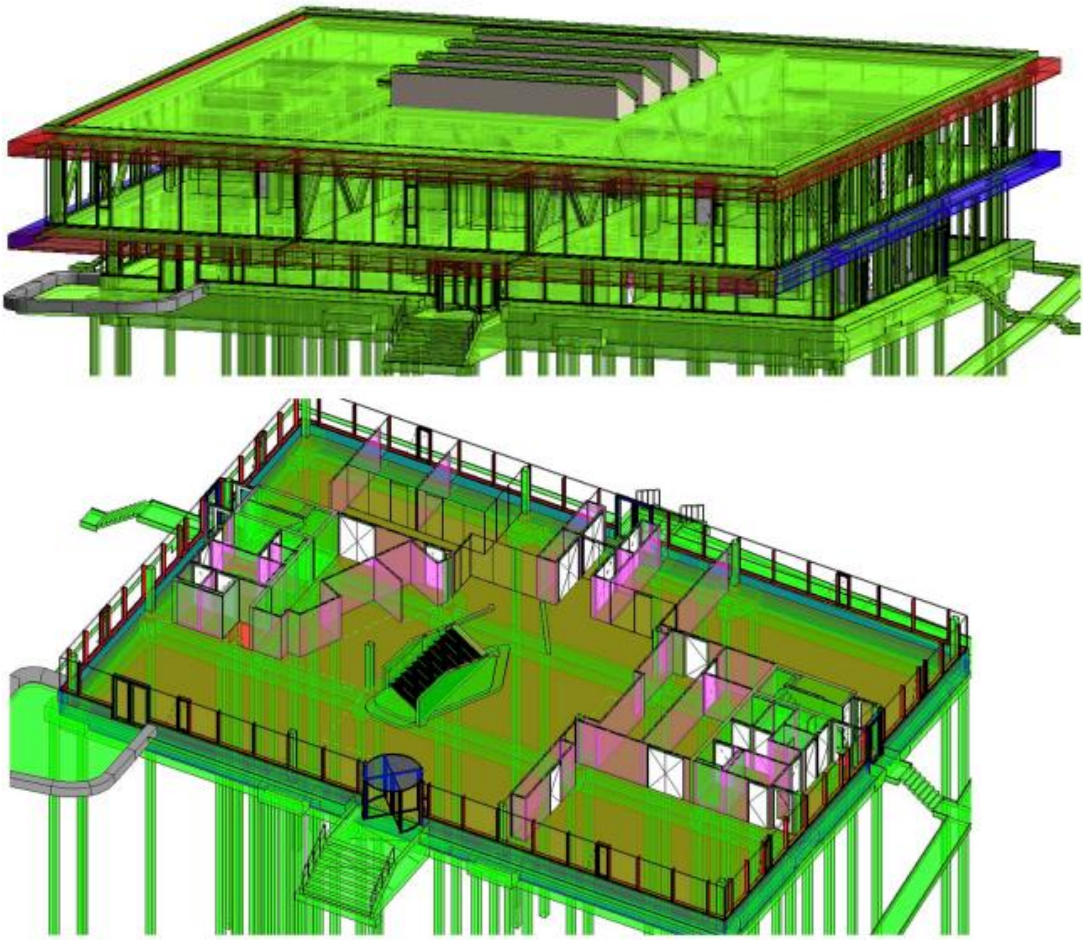


Figure 53: Visualisation of a BIM-based LCA (GWP and PE-NRe) and LCC analyses.

Case Study 24

Development of a BIM-based Environmental and Economic Life Cycle Assessment tool

Corresponding case study author: Rúben Santos, CERIS, Instituto Superior Técnico, University of Lisbon, Portugal (ruben.e.c.santos@tecnico.ulisboa.pt)
Original publication: Santos, R., Aguiar Costa, A., Silvestre, J. D., & Pyl, L. (2020). Development of a BIM-based Environmental and Economic Life Cycle Assessment tool. Journal of Cleaner Production, 265, 121705. https://doi.org/10.1016/j.jclepro.2020.121705

Abstract

Purpose/aim

The main aim of this research is to enhance the integration of LCA and LCC methodologies with BIM, as existing approaches still have limitations (e.g., interoperability issues, non-editable databases). For that purpose, an automatic LCA/LCC analysis within a BIM-based environment is proposed.

Method

The methodology used in this study followed a quantitative approach based on computer simulation and case study method. Furthermore, this study does not focus on the critical analysis of the LCA and LCC results of a project but rather on how to insert and handle sustainable-related information within BIM models.

Results

Unlike existing tools in the market, the BIMEELCA tool (Figure 54) allows users to insert the required information within the BIM model for the LCA and LCC analyses. This is done by importing the data contained in spreadsheets into the model and by the automatic quantity take-off generated by the BIM tool, resulting in an automatic Streamlined LCA/LCC analysis.

Discussion

The proposed approach and tool not only benefit the decision-making process at an early stage of the project development but also the decisions made at later stages of the projects. Facilities managers or designers that work with refurbishment or renovation projects can also benefit from the use of semantic-rich BIM models. In this sense, if materials and/or elements are added to or removed from the model, the facility managers only need to update the corresponding information, and a new LCA/LCC analysis can be automatically/semi-automatically performed.

Conclusion

It is possible to perform LCA and LCC analyses at early design stages within a BIM-based environment if the necessary information is contained in the model. The tool also identifies the elements that contribute the most to the impact categories.

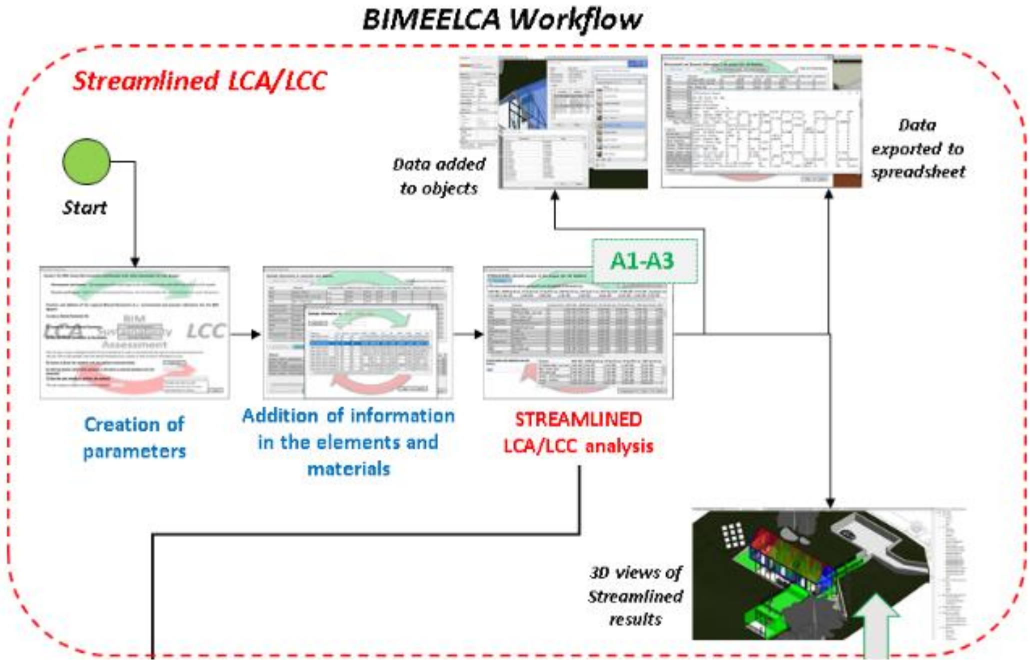


Figure 54: BIM-based Environmental and Economic Life Cycle Assessment (BIMEELCA) tool. Better illustrations of the individual steps of the workflow can be found in the full paper by Santos et al. (2020) (see the link to the paper given on the previous page).

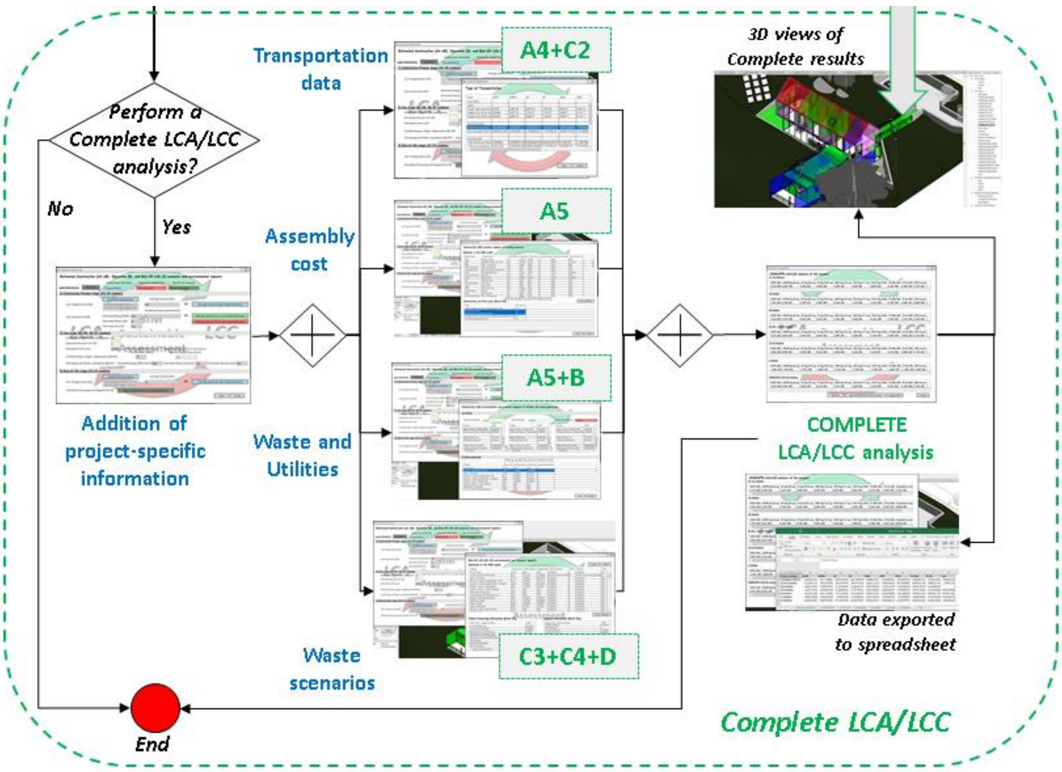


Figure 55: BIMEELCA tool (cont.). Better illustrations of the individual steps of the workflow can be found in the full paper by Santos et al. (2020) (see the link to the paper given on the previous page).

Case Study 25

Design Aid Using Optimisation, Building Energy Simulation and Life Cycle Assessment

Corresponding case study author: Bruno Peuportier, MINES ParisTech, France (bruno.peuportier@mines-paristech.fr)
Original publication: Recht T., Schalbart P., and Peuportier B., Ecodesign of a "plus energy" house using stochastic occupancy model, life cycle assessment and multi-objective optimisation, Hamza N and Underwood C. (Ed), Building Simulation & Optimization 2016, Newcastle, September 2016: Ecodesign of a 'plus-energy' house using stochastic occupancy model, life-cycle assessment and multi-objective optimisation (archives-ouvertes.fr).

Abstract

Purpose/aim

This case study illustrates an optimization process based upon building energy simulation [1] and life cycle assessment [2] in order to reduce both cost and environmental impacts of a construction project.

Method

Eleven design variables have been optimised using the NSGA-II (Non-Dominated Sorting Genetic Algorithm) multi-objective genetic algorithm.

Results

An example Pareto front and statistical analysis on 90 optimal solutions are presented in Figures 56 and 57.

Discussion

In order to evaluate the robustness [3] of the obtained solutions, the optimisation process was repeated with various occupancy scenarios (family, retired couple and single person).

Conclusion

Optimisation based upon LCA can be used as a building design tool [4] to reduce environmental impacts and cost.

Figure 56: Example of a Pareto front.

Explanation of Figure 56 and 57

A single-family house to accommodate three people for 100 years is studied, considering an average statistical occupancy scenario. Design parameters include thickness of insulation, glazing type and area, number of PV modules etc. An initial population if formed by random draw, then parents are selected according to their performance and children are obtained by via crossover and mutation operators.

The process is stopped after 20 generations, leading to a Pareto front including non-dominated solutions (lowest cost or lowest impact). A constraint corresponding to a positive energy balance is considered, leading to the green points in Figure 56. The initial design proposed by the architect (red point) was not energy positive. Figure 57 shows that nearly all solutions of the Pareto front include triple glazing and dual flow ventilation (with heat recovery).

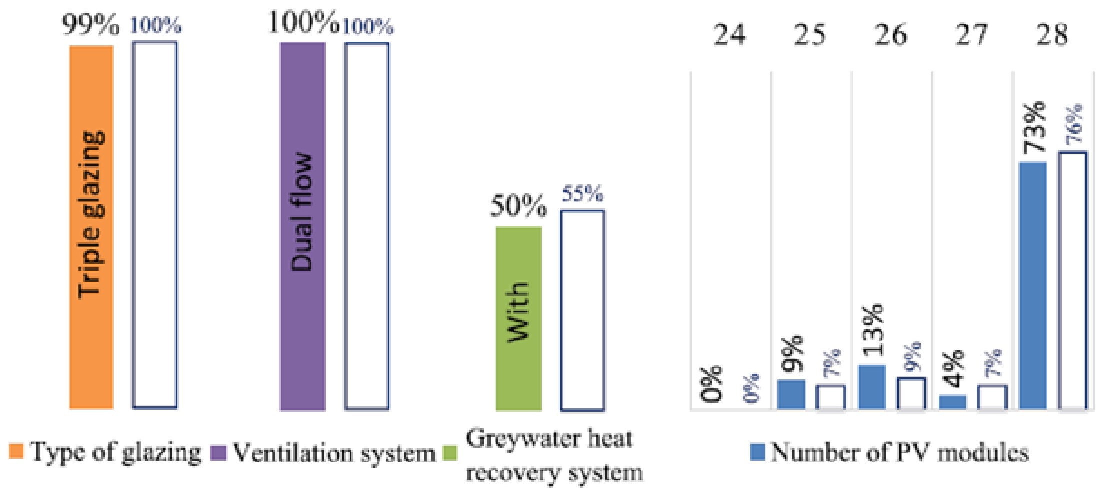


Figure 57: Examples of statistical analysis on optimal solutions. Note: The white bars correspond to a calculation of all possible parameters combinations (over 4 millions) and the coloured bars to the results of the genetic algorithm (8,000 calculations). Both Pareto fronts provide similar trends.

Additional references:
[1] Peuportier B. and Blanc Sommereux I., Simulation tool with its expert interface for the thermal design of multizone buildings, International Journal of Solar Energy, vol. 8 pp 109-120, august 1990
[2] Polster, B., Peuportier, B., Blanc Sommereux, I., Diaz Pedregal, P., Gobin C. and Durand, E. Evaluation of the environmental quality of buildings - a step towards a more environmentally conscious design, Solar Energy vol. 57 n°3, pp 219-230, 1996
[3] Frossard M., Schalbart P., Peuportier B., Dynamic and consequential LCA aspects in multi-objective optimisation for NZEB design, Beyond 2020 World Sustainable Built environment online Conference, Gothenburg/virtual, November 2020
[4] Peuportier, B. Eco-design for buildings and neighbourhoods, Taylor & Francis Group, London, 286p, 2015

5. Summary of Findings

This report includes case studies from A72 experts covering four important topics: LCA-related methodological aspects, benchmarking-related aspects parametric-related aspects, and BIM-related aspects. Selected findings are presented below.

LCA-related studies

In general, the contribution of the choice of the electricity mix to the overall LCA results for buildings is important. That is why there are several case studies in literature examining this effect. In this report, Case Study 01 showed that the national electricity mix based on production and commercial trade is very similar to a building specific electricity mix. Thus, there is no need for building specific electricity mixes. It was also shown that the environmental impacts of operation are significantly lower when applying GO mixes and the expected future mix. However, GO are often used to convert nuclear electricity into renewable electricity. Therefore, care should be taken when applying GO mixes as they are prone to double counting.

With the increasing integration of renewable energy technologies into buildings, another important methodological question often raised is how to model such technologies from an LCA perspective especially when they provide two functions: building skin and electricity production. Case Study 02 assessed the environmental impacts of BIPV systems integrated in 6 buildings to determine the share of impacts at-attributable to the building and the electricity produced. The total emissions vary significantly of the different PV systems. Major contributors are the PV panel, the inverters and power optimisers and the mounting structure. For example, electricity produced with BIPV systems tends to cause higher specific GHG emissions and environmental impacts than optimally oriented building attached PV systems. Main reasons are their application on all façades (including north oriented façade) and their colouring.

Future electricity mix does not only influence building operation but also future embodied impacts of construction products. Along with a decarbonised electricity mix, other processes will also advance in future such as transport, manufacturing and recycling processes, which all have a significant effect on future embodied impacts of construction products. Case study 05 showed that with future construction materials manufacture, GHG emissions are reduced on average by 65 %, non-renewable primary energy demand by 48% and the total environmental impact by 38%. At building level, GHG emissions of construction (including building technology) and dismantling can be reduced by 50-60%. However, although with today's expected changes in production processes, substantial GHG reductions are within reach, this is not sufficient. Construction material industries need to achieve close to zero GHG emissions (including supply chain), which makes binding commitments to the 1.5°C target and substantial changes in the production processes a necessity.

Another important LCA-related aspect currently often discussed is whether a dynamic approach shall be used to account for biogenic carbon uptake. Case Study 06 showed the resulting gap when different accounting approaches are considered, which at a building level, is close to 30%. However, the dynamic approach considers time aspects and rotation times and thus involves more subjective choices than the more simplified approaches (0/0 and -1/+1) currently recommended in different standards and national methods.

These aspects, among others, are addressed in the A72 report *“Context-specific Assessment Methods for Life Cycle-related Environmental Impacts Caused by Buildings”*.

Benchmarking-related studies

In relation to environmental benchmarking, it is often discussed whether useful information can be derived from using single-score benchmarks which represent an aggregate of several environmental indicators in comparison to only consider GHG emissions benchmarks. Case study 07 addressed this question using the Swiss eco-factors 2013 according to the ecological scarcity method to assess energy efficient new and retrofit office buildings. It was concluded that the single score points to potential environmental trade-offs when used together with the climate change indicator “greenhouse gas emissions”.

The emerging scientific discourse on planetary boundaries and the need to define a global SOS within which social and economic development should be coordinated there is have triggered an interest in supplementing bottom-up approaches with science-based top-down approaches as part of governments' responsibility to protect the ecosystem. Responding to this need, Case Study 08 illustrates different approaches to allocating the share of safe operating space (SoSOS) for evaluations concerning the absolute sustainability of a single-family stand-alone dwelling in Denmark. Particularly, six combinations of allocation principles were determined based on approaches reflecting egalitarian, utilitarian and acquired rights principles of distribution. A similar exploration is also realised in Case Study 9 which applies a combination of sharing principles to allocate the global carbon budget to three New Zealand (NZ) residential dwelling typologies. Both case studies show the substantial efforts required to align with the global carbon budgets, among others.
Case Study 10 and Case Study 11 deal with the question of how to combine bottom-up with top-down benchmarking approaches to support design decisions. The proposed concept consists in first calculating the target value based on the top-down benchmarks. If the environmental impact of the building is higher than the target value, the impact of each building element is compared to the bottom-up benchmarks to analyse the material-related improvement potential. If this potential is not sufficient to reach the target, a change to the design (shape, floorplan, etc) is proposed.
These aspects, among others, are addressed in the A72 report *"Benchmarking and Target-setting for the Life Cycle-based Environmental Performance of Buildings"*.

Parametric-related studies

The assessment of many variables and their interdependency in the optimization of buildings' performance is a challenging task and a different level of detail is required for the different objective functions. A parametric analysis can be applied to solve the complexity of the computation. For example, Case Study 13 applied the parametric LCA tool Bombyx and showed how it is possible to get a complete estimation of the life cycle impact of a building based on very few inputs, such as building type, intended use and structural system. The proposed approach allows for quick feedback regarding environmental impacts over the whole life cycle in every design phase. From just defining four input parameters in the first building level, to finally defining each material, the approach makes sure that the LCA is calculated as accurately as possible in each stage. More case studies dealing with the topic of optimisation can be found in the A72 report "*Life-cycle optimization of building performance: a collection of case studies*"

BIM-related studies

Since the use of BIM among designers is increasing, it is important to investigate its potential and challenges in relation to using for tasks associated with LCA. For example, Case Study 16 used a detailed BIM model to assess the contribution of HVAC systems to LCA results for buildings and showed that it lies in the range of 15–36% of the total embodied impact of office buildings. This leads to an embodied impact of the HVAC systems 3 times higher than the targets provided by SIA 2040. Another study, Case Study 21 showed that by using the current BIM design workflow as it is, embodied GHG emissions in early design stages is highly overestimated – emissions can be twice as high compared to the final building – and discusses three alternatives to established automatic quantity take-off. Case Study 23 and Case Study 24 propose an approach and tool that proves that it is possible to perform LCA and LCC analyses at early design stages within a BIM-based environment if the necessary information is contained in the model. The tool also identifies the elements that contribute the most to the impact categories.
These aspects, among others, are addressed in the A72 report *"Guidelines for design decision makers"*.

ANNEX 72

EBC

Energy in Building and Communities Programme

www.iea-ebc.org