BUILDING DATA MODELS FOR SCALABLE HIGH-DEFINITION LIFE CYCLE ASSESSMENT

METRICS, METHODS, AND MODELS TO SUPPORT A REGENERATIVE BUILT ENVIRONMENT

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„We need to learn, but we need to waste
no time with our learning.“

Donella Meadows

~

To

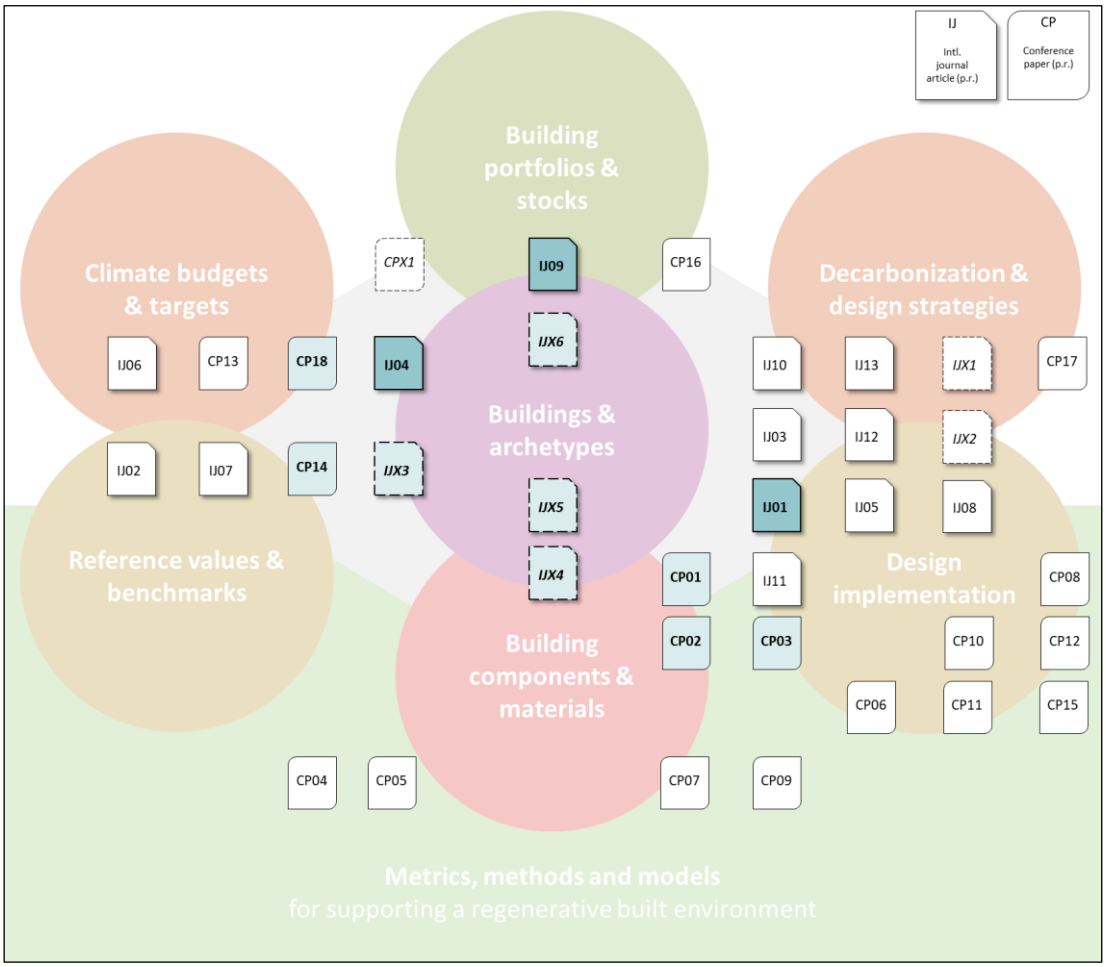
Zora

~

PREFACE

The present document is a cumulative, paper-based dissertation prepared by the author, Martin Röck, in partial fulfilment of the requirements for a dual PhD conducted at KU Leuven and TU Graz, supported by a DOC research fellowship awarded to the author by the Austrian Academy of Sciences. The doctoral research was informed by diverse collaborations undertaken in various international research projects, as indicated in the respective chapters and articles. The research has particularly benefited from collaborations within the IEA EBC Annex 72 on environmental assessment of buildings across their full life cycle; the PEF4Buildings study on the implementation of the Product Environmental Footprint to buildings, contracted by the European Commission DG ENV; contributions to the Level(s) Sustainability Report Framework pilot phase; leading collaborations within a project towards embodied carbon benchmarks for European buildings, funded by the Laudes Foundation; as well as model research and development within the supporting study informing the development of a roadmap for the decarbonization of EU buildings, contracted by the European Commission DG ENV.

The thesis is based on a selection of six peer-reviewed journal articles, or drafts thereof, that represent the foundation of the doctoral research. The below figure offers an illustrative overview of the author's research outputs mapped onto relevant topics, ranging from climate budgets and benchmarks over decarbonization strategies to methods for design implementation, and from building component and material level over building level up to building portfolio and building stock macro-level. The core of the doctoral research are contributions focusing on challenges related to provision and handling of building level data for analysis of reference values and benchmarks, for systematic environmental hotspot analysis, as well as for high-definition life cycle modelling of building stocks up to macro-scale.



#	Title / Journal / Reference
IJ01	LCA and BIM: Visualization of Environmental Potentials in Building Construction at Early Design Stages. *Building and Environment* (Röck et al., 2018a)
IJ02	Environmental benchmarks for buildings: needs, challenges and solutions. *International Journal of Life Cycle Assessment* (Frischknecht et al., 2019)
IJ03	Strategies to Improve the Energy Performance of Buildings: A Review of Their Life Cycle Impact. *Buildings* (Mirabella et al., 2018)
IJ04	Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation. *Applied Energy* (Röck et al., 2020c)
IJ05	BIM and LCA integration: A systematic literature review. *Sustainability* (Obrecht et al., 2020a)
IJ06	Carbon budgets for buildings: Harmonizing temporal, spatial and sectoral dimensions. *Buildings & Cities* (Habert et al., 2020a)
IJ07	Life cycle GHG emissions of residential buildings in humid subtropical and tropical climates: Systematic review and analysis. *Buildings* (Satola et al., 2021)
IJ08	Review of visualising LCA results in the design process of buildings. *Building and Environment* (Hollberg et al., 2021)
IJ09	Environmental modelling of building stocks – An integrated review of life cycle-based assessment models to support EU policy making. *Renewable and Sustainable Energy Reviews* (Röck et al., 2021)
IJ10	Critical life cycle assessment of the innovative passive nZEB building concept 'be 2226' in view of net-zero carbon targets. *Building and Environment* (Maierhofer et al., 2022)
IJ11	Using Systematic Building Decomposition for Implementing LCA: The Results of a Comparative Analysis as Part of IEA EBC Annex 72. *Journal of Cleaner Production* (Soust-Verdaguer et al., 2023)
IJ12	Environmental Potentials of Bio-based Construction Materials - Life Cycle Assessment of Regenerative Design Strategies (1/2). *Energy and Buildings* (Mouton et al., 2023a)
IJ13	Low-Tech Passive Building Concepts to meet Climate Targets - Life Cycle Assessment of Regenerative Design Strategies (2/2). *Energy and Buildings* (Mouton et al., 2023b)
IJX1	Carbon footprint assessment of a wood multi-residential building considering biogenic carbon. *Journal of Cleaner Production* (Ouellet-Plamondon et al., 2023)
IJX2	Social innovation for regenerative buildings: Insights from Austria. *(Forthcoming)* (Hirschberg et al., 2022)
IJX3	Benchmarking Whole Life Embodied Carbon of Buildings at Scale: Data-Driven Baseline Analysis for Buildings across Europe. *(Forthcoming)* (Röck et al., 2023b)
IJX4	CarbEnMats: An Open Database on Whole Life Carbon, Energy and Material Intensity of Buildings (CarbEnMats-Buildings-DB) *(Forthcoming)* (Röck and Sørensen, 2023)
IJX5	SLiCE – An Open Building Data Model for Scaling High-Definition Life Cycle Engineering and Environmental Hotspot Analysis *(Forthcoming)* (Röck et al., 2023a)
IJX6	SLiCE Building LCA Model - Implementation for High-Definition Life Cycle Assessment of Buildings across Spatiotemporal Scales *(Forthcoming)* (Röck and Allacker, 2023)

#	Title / Journal / Reference
CP01	Visualising Embodied Impacts Using Building Information Modelling (BIM). World Sustainable Built Environment Conference WSBE2017 Hong Kong (Röck et al., 2017)
CP02	The coupling of BIM and LCA—challenges identified through case study implementation. *Proceedings of the Sixth International Symposium on Life-Cycle Civil Engineering (IALCCE 2018),* Gent (BE) (Röck et al., 2018c)
CP03	LCA and BIM: Integrated assessment and visualization of building elements' embodied impacts for design guidance in early stages. *Procedia CIRP 69*, 25th CIRP Life Cycle Engineering (LCE) Conference, Copenhagen (DK) (Röck et al., 2018b)
CP04	Comparison of the environmental assessment of an identical office building with national methods. *IOP Conf. Ser.: Earth Environ. Sci. 323*, Sustainable Built Environment Conference SBE19 Graz (AT) (Frischknecht et al., 2019b)
CP05	A cross-platform modular framework for building Life Cycle Assessment. *IOP Conf. Ser.: Earth Environ. Sci. 323*, Sustainable Built Environment Conference SBE19 Graz (AT) (Kiss et al., 2019)
CP06	BIM for public authorities: Basic research for the standardised implementation of BIM in the building permit process. *IOP Conf. Ser.: Earth Environ. Sci. 323*, Sustainable Built Environment Conference SBE19 Graz (AT) (Plazza et al., 2019)
CP07	Testing of PEF method to assess the environmental footprint of buildings – results of PEF4Buildings project. *IOP Conf. Ser.: Earth Environ. Sci. 297*, Sustainable Built Environment SBE19 Helsinki (FI) (Spirinckx et al., 2019a)
CP08	Embodied GHG emissions of buildings - Critical reflection of benchmark comparison and in-depth analysis of drivers. *IOP Conf. Ser. Earth Environ. Sci. 588*, World Sustainable Built Environment Conference WSBE2020 Gothenburg (SE) (Röck et al., 2020a)
CP09	Austrian GHG emission targets for new buildings and major renovations: An exploratory study. *IOP Conf. Ser. Earth Environ. Sci. 588*, World Sustainable Built Environment Conference WSBE2020 Gothenburg (SE) (Hoxha et al., 2020)
CP10	Survey results on acceptance and use of Life Cycle Assessment among designers in world regions: IEA EBC Annex 72. *IOP Conf. Ser. Earth Environ. Sci. 588*, World Sustainable Built Environment Conference WSBE2020 Gothenburg (SE) (Balouktsi et al., 2020)
CP11	The challenge of integrating Life Cycle Assessment in the building design process - A systematic literature review of BIM-LCA workflows. *IOP Conf. Ser. Earth Environ. Sci. 588*, World Sustainable Built Environment Conference WSBE2020 Gothenburg (SE) (Obrecht et al., 2020b)
CP12	Combining LCA and LCC in the early-design stage: A preliminary study for residential buildings technologies. *IOP Conf. Ser. Earth Environ. Sci. 588*, World Sustainable Built Environment Conference WSBE2020 Gothenburg (SE) (Dejaco et al., 2020)
CP13	Implications of using systematic decomposition structures to organize building LCA information: A comparative analysis of national standards and guidelines- IEA EBC ANNEX 72. *IOP Conf. Ser. Earth Environ. Sci. 588*, World Sustainable Built Environment Conference WSBE2020 Gothenburg (SE) (Soust-Verdaguer et al., 2020)
CP14	Comparison of the greenhouse gas emissions of a high-rise residential building assessed with different national LCA approaches - IEA EBC Annex 72. *IOP Conf. Ser. Earth Environ. Sci. 588*, World Sustainable Built Environment Conference WSBE2020 Gothenburg (SE) (Frischknecht et al., 2020)
CP15	Towards indicative baseline and decarbonization pathways for embodied life cycle GHG emissions of buildings across Europe. *IOP Conf. Ser.: Earth Environ. Sci. 1078*, Sustainable Built Environment Conference SBE22 Berlin (DE) (Röck et al., 2022a)
CP16	Social innovations for supporting regenerative lifestyles: Exploration of three pioneering co-housing projects in Austria. *IOP Conf. Ser.: Earth Environ. Sci. 1078*, Sustainable Built Environment Conference SBE22 Berlin (DE) (Hirschberg et al., 2022)
CP17	Life cycle GHG emissions of the Austrian building stock: a combined bottom-up and top-down approach. *IOP Conf. Ser.: Earth Environ. Sci. 1078*, Sustainable Built Environment Conference SBE22 Berlin (DE) (Truger et al., 2022)
CP18	ROTUNDORO: A web-based decision support prototype for housing refurbishments considering consumer preferences. *IOP Conf. Ser.: Earth Environ. Sci. 1085*, Sustainable Built Environment Conference SBE22 Delft (NL) (Kaltenegger et al., 2022)
CPX1	Archetype selection process for the development of a building stock model. Sustainable Built Environment Conference SBE23 Thessaloniki (GR) (Pristera et al., 2023)

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And finally, to my beloved daughter, Zora, a source of endless joy in my life. Thank you for bringing new light and laughter into my world. I cherish your presence, and I eagerly look forward to continuing exploring this world alongside you.

To all the friends and colleagues I have encountered along the way, and to those I have yet to meet but already feel connected to in our shared pursuit of a better future: See you out there!

ABSTRACT

The built environment is a major contributor to the climate and ecosystem emergency with building construction and operation responsible for almost 40% of energy-related greenhouse gas (GHG) emissions globally. Increasing energy efficiency of buildings and adopting sustainable construction practices are crucial for achieving decarbonization goals. Furthermore, addressing the entire life cycle of buildings, including operational and embodied GHG emissions, has been identified as a key area for action by scientific bodies such as the Intergovernmental Panel on Climate Change (IPCC) and is at the heart of a new wave of climate policies within the European Union.

This thesis aims to overcome prevailing limitations in building life cycle assessment (LCA) to inform policy making and regulation for reducing the climate impacts of individual buildings and building stocks. The lack of understanding regarding the significance of GHG emissions at different stages of a building life cycle remains a challenge. Additionally, standardized documentation requirements, data collection protocols, and data processing tools need further development. The availability of open and accessible data for benchmarking the environmental impact of buildings and setting decarbonization targets is thus far limited. At the macro scale, modelling building stocks faces challenges due to limited information on impacts related to the full building life cycle and a narrow representation of building types. Existing approaches tend to focus on energy and GHG emissions associated with building operation, overlooking other life cycle stages and lacking a comprehensive LCA indicator perspective. This thesis addresses these gaps through research questions related to embodied carbon in building life cycles, metrics and methods supporting European climate policy, and the integration of comprehensive LCA for building and building stock analysis.

The research utilizes evidence synthesis, environmental LCA, building information modelling (BIM), and building stock modelling. The thesis is comprised of eight chapters: Chapter 1, the introduction, provides an overview of the relevance and urgency of reducing whole life GHG emissions in buildings, highlighting the limitations in current approaches and the research objectives; Chapter 2 presents a systematic review and global meta-analysis which unravel the role of embodied GHG emissions in the life cycle of new buildings, emphasizing the importance of mitigating these emissions to address the climate crisis; Chapter 3 offers an analysis of embodied carbon data from new buildings across Europe and investigates benchmarking whole life embodied carbon, considering different building typologies, construction types, and carbon intensities. It includes and examination of the contribution of various life cycle stages and building parts and addresses methodological inconsistencies and data limitations; The dataset established thus far is presented in chapter 4 via a detailed data descriptor for an open database on whole life carbon of buildings. It describes the collection, processing, and harmonization of data underlying the previous chapters, providing an overview of the resulting database and attribute distributions; In chapter 5 the step towards building stock level is made via an integrated review of assessment models for environmental analysis of building stocks mapped with the objectives of specific EU policy initiatives related to the Green Transformation of the Built Environment. The chapter identifies strengths and weaknesses of existing models, providing insights for robust decision making; Chapter 6 introduces the Scalable Life Cycle Engineering (SLiCE) data model. It also proposes the space-time-indicator (STI) framework to conceptualize data requirements for comprehensive LCA for building and building stock analysis. The SLiCE building data model is presented as an open data logic designed to handle large amounts of high granularity building life cycle information. The chapter also showcases the implementation of SLiCE within a prototypical hotspot analysis tool as well as for dynamic climate impact assessment; Chapter 7 presents an implementation of the SLiCE logic to address the trade-off between model resolution and scale of assessment. SLiCE is implemented with

KU Leuven's building LCA model, establishing a novel building LCA ecosystem. The chapter demonstrates the application of SLiCE in various research contexts, from micro-scale to macro-scale analysis and elaborates on the use of SLiCE for prospective analysis of the European building stock; Finally, chapter 8 synthesizes the findings from the previous chapters, discusses insights from applying the SLiCE model, and offers an outlook for the use of SLiCE in supporting decision making, policy development, and real estate management.

By addressing these research questions and providing the insights and novel methods outlined above, this thesis contributes to advancing environmental engineering research with a particular focus on sustainable construction and the reduction of whole life carbon in buildings. The metrics, methods and models presented support sustainable building practices and policies at the European level and beyond.

SAMMENVATTING

De gebouwde omgeving levert een belangrijke bijdrage aan de noodsituatie van het klimaat en het ecosysteem, waarbij de bouw en exploitatie van gebouwen wereldwijd verantwoordelijk zijn voor bijna 40% van de energiegerelateerde uitstoot van broeikasgassen. Het is van cruciaal belang om de energie-efficiëntie van gebouwen te verhogen en duurzame bouwpraktijken toe te passen om de doelstellingen voor het koolstofarm maken van gebouwen te behalen. Het aanpakken van de gehele levenscyclus van gebouwen, inclusief operationele en materiaalgebonden broeikasgasemissies, is door wetenschappelijke instanties zoals het Intergovernmental Panel on Climate Change (IPCC) aangewezen als een belangrijk actiegebied en staat centraal in een nieuwe golf van klimaatbeleid binnen de Europese Unie.

Deze dissertatie heeft als doel om de heersende beperkingen in de levenscyclusanalyse (LCA) van gebouwen te overwinnen om beleidsvorming en regelgeving te informeren over het verminderen van de klimaateffecten van individuele gebouwen en gebouwenparken. Het gebrek aan inzicht in de betekenis van broeikasgasemissies in verschillende stadia van de levenscyclus van een gebouw blijft een uitdaging. Daarnaast moeten gestandaardiseerde documentatie-eisen, protocollen voor gegevensverzameling en hulpmiddelen voor gegevensverwerking verder worden ontwikkeld. De beschikbaarheid van open en toegankelijke gegevens voor het benchmarken van de milieu-impact van gebouwen en het bepalen van doelstellingen voor het koolstofarm maken van gebouwen is tot nu toe beperkt. Op macroniveau wordt het modelleren van gebouwenbestanden bemoeilijkt door beperkte informatie over de effecten van de volledige levenscyclus van gebouwen en een beperkte vertegenwoordiging van gebouwtypes. Bestaande benaderingen richten zich meestal op energie en broeikasgasemissies die verband houden met de exploitatie van gebouwen, waarbij andere fasen van de levenscyclus over het hoofd worden gezien en een alomvattend LCA-indicatorperspectief ontbreekt. Deze dissertatie richt zich op deze hiaten door middel van onderzoeksvragen met betrekking tot materiaalgebonden (grijze) broeikasgassen in de levenscyclus van gebouwen, meetsystemen en methoden ter ondersteuning van het Europese klimaatbeleid en de integratie van een uitgebreide LCA voor gebouwen en gebouwenbestanden.

Het onderzoek maakt gebruik van een synthese van bewijsmateriaal, milieugerichte LCA, building information modelling (BIM) en modellering van gebouwbestanden. Het proefschrift bestaat uit acht hoofdstukken: Hoofdstuk 1, de inleiding, geeft een overzicht van de relevantie en urgentie van het terugdringen van broeikasgassen tijdens de gehele levensduur van gebouwen, met aandacht voor de beperkingen in de huidige benaderingen en de onderzoeksdoelstellingen; Hoofdstuk 2 presenteert een systematisch overzicht en een globale meta-analyse die de rol van de materiaalgebonden broeikasgasemissies in de levenscyclus van nieuwe gebouwen ontrafelen, met nadruk op het belang van het verminderen van deze emissies om de klimaatcrisis aan te pakken; Hoofdstuk 3 biedt een analyse van materiaalgebonden broeikasgasemissies van nieuwe gebouwen over hun hele levenscyclus in heel Europa en onderzoekt benchmarking ervan, rekening houdend met verschillende gebouwtypologieën, constructie types en koolstofintensiteiten. Het bevat een onderzoek naar de bijdrage van verschillende levenscyclusfasen en gebouwonderdelen en gaat in op methodologische inconsistenties en gegevensbeperkingen; De opgestelde datasets uit hoofdstuk 3 worden in hoofdstuk 4 gepresenteerd via een gedetailleerde gegevensbeschrijving voor een open databank met gegevens over de totale broeikasgasemissies van gebouwen. Het beschrijft het verzamelen, verwerken, en harmoniseren van de data en geeft een overzicht van de resulterende databank met de noodzakelijke gebouwgegevens. In hoofdstuk 5 wordt de stap gezet naar het niveau van een gebouwenbestand via een geïntegreerd overzicht van beoordelingsmodellen voor milieuanalyses van gebouwbestanden die in overeenstemming zijn met de doelstellingen van specifieke EU-beleidsinitiatieven met betrekking tot

de groene transformatie van de gebouwde omgeving. Het hoofdstuk identificeert sterke en zwakke punten van bestaande modellen en biedt inzichten voor robuuste besluitvorming; Hoofdstuk 6 introduceert het gegevensmodel Scalable Life Cycle Engineering (SLiCE). Het stelt ook het ruimte-tijd-indicator (space-time-indicator - STI) raamwerk voor om de gegevensvereisten voor een uitgebreide LCA voor gebouwen en gebouwenbestanden te conceptualiseren. Het SLiCE-gegevensmodel voor gebouwen wordt gepresenteerd als een open gegevenslogica die is ontworpen om grote hoeveelheden informatie met een hoge granulariteit over de levenscyclus van gebouwen te verwerken. Het hoofdstuk toont ook de implementatie van SLiCE in een prototypisch hotspot analyse-instrument en voor dynamische klimaateffectbeoordeling; Hoofdstuk 7 presenteert een implementatie van de SLiCE-logica om de afweging tussen modelresolutie en beoordelingsschaal te maken. SLiCE wordt geïmplementeerd met het LCA-model van KU Leuven, waardoor een nieuw LCA-ecosysteem voor gebouwen ontstaat. Het hoofdstuk demonstreert de toepassing van SLiCE in verschillende onderzoekscontexten, van microschaal- tot macroschaalanalyse en gaat dieper in op het gebruik van SLiCE voor prospectieve analyse van het Europese gebouwenbestand; Hoofdstuk 8 tenslotte synthetiseert de bevindingen uit de vorige hoofdstukken, bespreekt inzichten uit de toepassing van het SLiCE-model en biedt een vooruitblik op het gebruik van SLiCE ter ondersteuning van besluitvorming, beleidsontwikkeling en vastgoedbeheer.

Door deze onderzoeksvragen aan de orde te stellen en de hierboven beschreven inzichten en nieuwe methoden te verschaffen, draagt dit proefschrift bij aan het bevorderen van milieutechnisch onderzoek met een bijzondere focus op duurzaam bouwen en de reductie van broeikasgasemissies gedurende de gehele levensduur van gebouwen. De gepresenteerde meetsystemen, methoden en modellen ondersteunen duurzame bouwpraktijken en een duurzaam bouwbeleid op Europees niveau en daarbuiten.

ZUSAMMENFASSUNG

Die bebaute Umwelt trägt wesentlich zum Klima- und Ökosystemkrise bei, denn Bau und Betrieb von Gebäuden sind weltweit für fast 40 % der energiebedingten Treibhausgas (THG) Emissionen verantwortlich. Die Steigerung der Energieeffizienz von Gebäuden und die Einführung nachhaltiger Baupraktiken sind daher für die Erreichung der Dekarbonisierungsziele von entscheidender Bedeutung. Die Dekarbonisierung des gesamten Lebenszyklus von Gebäuden, also sowohl der betriebsbedingten als auch der konstruktionsspezifischen Emissionen (engl. Embodied Emissions), wurde von wissenschaftlichen Gremien wie dem Intergovernmental Panel on Climate Change (IPCC) als Schlüsselbereich für Maßnahmen zur Emissionsreduktion identifiziert und steht im Mittelpunkt einer neuen Welle von regulatorischen Initiativen innerhalb der Europäischen Union (EU).

Die vorliegende Arbeit zielt darauf ab, die vorherrschenden Beschränkungen bei der Ökobilanzierung (engl. Life Cycle Assessment (LCA)) von Gebäuden zu überwinden, um politische Entscheidungen und Vorschriften zur Verringerung der Klimaauswirkungen von einzelnen Gebäuden und Gebäudebeständen zu unterstützen. Das mangelnde Verständnis für die Bedeutung der Treibhausgasemissionen in den verschiedenen Phasen des Lebenszyklus eines Gebäudes ist eine aktuelle Herausforderung. Um sie zu bewältigen, braucht es neue und weiterentwickelte standardisierte Dokumentationsanforderungen, Datenerfassungsprotokolle und Werkzeuge zur Datenverarbeitung. Die begrenzte Verfügbarkeit offener und zugänglicher Daten für das Benchmarking der Emissionen und Umweltwirkungen, schränkt derzeit vielerorts die Festlegung und rechtliche Verankerung von Dekarbonisierungszielen ein. Auf der Makroebene ist zudem die Modellierung von Gebäudebeständen aufgrund begrenzter Informationen über die Auswirkungen auf den gesamten Lebenszyklus von Gebäuden erforderlich, jedoch aufgrund eingeschränkter Repräsentation von Gebäudetypen und mangelnder Datengrundlage mit Herausforderungen verbunden. Bestehende Ansätze konzentrieren sich in der Regel auf Energiebedarf und Emissionen im Zusammenhang mit dem Gebäudebetrieb, wobei andere Lebenszyklusphasen unberücksichtigt bleiben und eine umfassende LCA-Indikatorperspektive weitestgehend fehlt. Die vorliegende Arbeit befasst sich mit diesen Lücken durch Forschungsfragen im Zusammenhang mit den konstruktionsspezifischen THG-Emissionen im Lebenszyklus von Gebäuden, sowie mit Metriken und Methoden zur Unterstützung der europäischen Klimapolitik und mit der Integration einer umfassenden Lebenszyklusanalyse für Gebäude und Gebäudebestände.

Die Forschung nutzt die systematische Synthese von Erkenntnissen (bspw. Meta-Analysen), umfassende Methoden der Ökobilanzierung (engl. Life Cycle Assessment (LCA)), Gebäude-Daten-Modellierung (engl. Building Information Modelling (BIM)) sowie Gebäudebestands-Modellierung (engl. Building Stock Modelling). Die Arbeit besteht aus acht Kapiteln: Kapitel 1, die Einleitung, gibt einen Überblick über die Relevanz und Dringlichkeit der Reduzierung des THG Emissionen entlang des gesamten Lebenszyklus von Gebäuden, wobei die Grenzen der bisherigen Ansätze und die Forschungsziele hervorgehoben werden; Kapitel 2 stellt eine systematische Übersicht und eine globale Metaanalyse vor, die die Rolle der konstruktionsspezifischen THG Emissionen im Lebenszyklus neuer Gebäude bewertet und die Bedeutung der Verringerung dieser Emissionen für die Bewältigung der Klimakrise hervorhebt; Kapitel 3 bietet eine detaillierte Analyse der konstruktionsspezifischen Emissionen von neuen Gebäuden in ganz Europa und entwickelt Richtwerte für konstruktionsspezifische Emissionen über die gesamte Lebensdauer unter Berücksichtigung verschiedener Gebäudetypologien, Bauarten und Emissionsintensitäten. Das Kapitel umfasst eine Untersuchung des Beitrags verschiedener Lebenszyklusphasen und Gebäudeteile und befasst sich mit methodischen Unstimmigkeiten und Schwächen einer derartigen datenbasierten Analyse. Kapitel 4 präsemtiert den bis dahin entwickelten Datensatz anhand einer detaillierten Datenbeschreibung für eine

offene Datenbank zu den THG-Emissionen im gesamten Lebenszyklus von mehr als 1200 Gebäuden. Das Kapitel beschreibt die Sammlung, Verarbeitung und Harmonisierung der Daten, die den vorangegangenen Kapiteln zugrunde liegen, und gibt einen Überblick über die resultierende Datenbank und die Verteilung der Attribute. In Kapitel 5 erfolgt der Schritt zur Ebene des Gebäudebestands durch eine integrierte Überprüfung von Bewertungsmodellen für die Umweltanalyse von Gebäudebeständen, im Kontext spezifischer politischer Initiativen der EU im Zusammenhang mit der grünen Transformation der bebauten Umwelt. In diesem Kapitel werden die Stärken und Schwächen bestehender Modelle aufgezeigt, die Erkenntnisse für eine solide Entscheidungsfindung liefern sollen. In Kapitel 6 wird das SLiCE-Datenmodell (engl. Scalable Life Cycle Engineering (SLiCE)) für eine skalierbare, hochauflösende Lebenszyklusanalyse vorgestellt. Außerdem wird das Raum-Zeit-Indikator-Rahmenwerk (engl. Space-Time-Indicator (STI) Framework) vorgeschlagen, um die Datenanforderungen für eine umfassende Lebenszyklusanalyse für Gebäude und Gebäudebestände konzeptuell zu erfassen. Das SLiCE-Gebäudedatenmodell wird als eine offene Datenlogik vorgestellt, die für die Verarbeitung großer Mengen von hochgranularen Informationen über den Lebenszyklus von Gebäuden konzipiert ist. Das Kapitel zeigt auch die Implementierung von SLiCE in einem prototypischen Hotspot-Analysetool sowie die Anwendung von SLiCE Daten für eine dynamische Klimafolgenabschätzung; Kapitel 7 stellt eine Implementierung der SLiCE-Logik vor, die den Kompromiss zwischen Modellauflösung und Bewertungsmaßstab adressiert. SLiCE wird mit dem Gebäude-LCA-Modell der KU Leuven implementiert, wodurch ein neuartiges, hochauflösendes und skalierbares Gebäude-LCA-Ökosystem entsteht. Das Kapitel demonstriert die Anwendung von SLiCE in verschiedenen Forschungskontexten, von der Analyse auf der Mikro- bis zur Makroebene, und geht näher auf die Verwendung von SLiCE für die prospektive Analyse des europäischen Gebäudebestands ein. Kapitel 8 schließlich fasst die Ergebnisse der vorangegangenen Kapitel zusammen, erörtert die Erkenntnisse aus der Anwendung des SLiCE-Modells und gibt einen Ausblick auf die Verwendung von SLiCE zur Unterstützung der Entscheidungsfindung im Kontext einer lebenszyklus-orientierten Gebäudeoptimierung, sowie zur Unterstützung von Politikentwicklung und einer nachhaltigen Immobilienwirtschaft.

Durch die Beantwortung der relevanten Forschungsfragen und die Bereitstellung der oben beschriebenen Erkenntnisse und neuartigen Methoden trägt diese Arbeit dazu bei, die Forschung im Bereich Umwelttechnik und Ökobilanzierung voranzutreiben, wobei der Schwerpunkt auf nachhaltigem Bauen und der Verringerung der THG-Emissionen in Gebäuden über deren gesamte Lebensdauer liegt. Die vorgestellten Metriken, Methoden und Modelle unterstützen nachhaltige Baupraktiken und Klimapolitik auf europäischer Ebene und darüber hinaus.

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1. INTRODUCTION

1.1. Motivation

The climate and environmental emergency

Climate change is real and the fight to limit global warming and avoid ecosystem collapse are considered the major challenges of our time (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services and Intergovernmental Panel on Climate Change, 2019; Ripple et al., 2019; Rockström et al., 2017, 2009; Steffen et al., 2018; Wiedmann et al., 2020). The potential consequences of the climate crisis and the effects it has already triggered are prompting an intensive examination of the necessity of and possibilities for reducing anthropogenic greenhouse gas (GHG) emissions (Andersen et al., 2019; European Academies Science Advisory Council (EASAC), 2021; Grubler et al., 2018; Rockström et al., 2017). The importance of the topic is highlighted by the integration of climate change mitigation measures into the Sustainable Development Goals (SDGs) (IPCC (Intergovernmental Panel on Climate Change), 2018a; United Nations (UN), 2019), the alarming reports of the Intergovernmental Panel on Climate Change (IPCC) (Intergovernmental Panel on Climate Change (IPCC), 2022a; Intergovernmental Panel on Climate Change (IPCC) et al., 2021; IPCC (Intergovernmental Panel on Climate Change), 2018b) and the commitments to national GHG emission reduction measures within the framework of the United Nations Climate Change Conference of the Parties (COP) (Bjørn et al., 2021; Savaresi, 2016). In face of this evidence, also the understanding of 'sustainability' is evolving, from a concept of three equally important 'pillars of sustainability' – society, economy, and environment – towards an integrated vision of sustainable development for society and economy depending on a life within planetary boundaries (Rockström et al., 2009; Sala et al., 2016a). A new consciousness is emerging based on the understanding that the 'safe and just operating space for humanity' (Leach et al., 2013; Raworth, 2017) can only be found when respecting both the ecological ceiling (the planetary boundaries) as well as the social foundation, the struggle to secure well-being and prosperity for all. Beyond sustainability, resilient and regenerative development furthermore aims at restoring and repairing the damage done to enable long-term flourishing on Earth (Attia, 2016; Pedersen Zari et al., 2022; Sonetti et al., 2019).

Systems thinking: Places to intervene for a shift towards regenerative spatial systems

A famous quote of Donella Meadows, one of the modern pioneers of environmental analysis and system thinking, postulates that *"Indicators arise from values (we measure what we care about), and they create values (we care about what we measure)"* (Meadows, 1998). Beyond this well-known snippet, Meadow's work, and in particularly her theory of places to intervene in systems – as illustrated in Figure 1 - shaped my own view as to where to focus my own work. Coming from an engineering and architecture background, and with a strong prior interest and some expertise in parametric design and building information modelling, I relate to the importance of understanding the *Parameters* of a system, in our case the built environment – building construction and operation, more specifically – and how aspects such as the structure of material stocks and flows in building and building stocks relate to the environmental impacts we observe – the classic steps of inventory analysis and impact assessment. Moving from mere problem analysis into actionability, requires better understanding of *Feedbacks*, particularly with regards to the strength of negative feedbacks, such as unintended environmental impacts, or the gains around positive feedback loops, such as the wellbeing gain related to the provision of decent housing. In this context, the length of delays relative to the rate of system change certainly represents a particular problem for climate change mitigation in the built environment and elsewhere, due to the immense timescales at which today's GHG emission will continue to influence the Earth

ecosystem. (Note: The notion of delay between action and consequence also hints at the revelation hidden behind understanding building's upfront embodied carbon as the main source dominating new building emissions – more on that in chapter 2). Beyond the conventional scope of research, I am increasingly interested in how scientific insights can inform and influence a system's *Design*. As convinced European citizen, I am certain that this means using scientific inquiry to understand the structure of information flows as well as influence the rules of the system, meaning rules for building construction and operation within the European Union. I thus decided in the early years of my doctoral research that I want to investigate my research questions, as much as possible, in the context of real-world scientific studies with immediate relevance, such as for informing ongoing policy making processes. While this might imply certain trade-offs with regards to the need for being 'pragmatic' at times, I believe that we live in a period of fundamental change at unprecedented pace, where scientific 'novelty' becomes increasingly temporary, and the real value is in ensuring immediate scientific 'relevance' to the immense task of addressing the climate and environmental emergency in the early years of this *decade of action*. It is an important next step, to collaboratively understand, question, and change where needed, the *Intent* of our prevailing system. As becomes increasingly evident, the goals of the system are not fit for purpose, if the purpose is sustainable development. Hence also the mindsets and paradigms our current system logic is built upon will have to change from profiting at the expense of others, towards an inclusive vision of thriving for all within planetary boundaries.

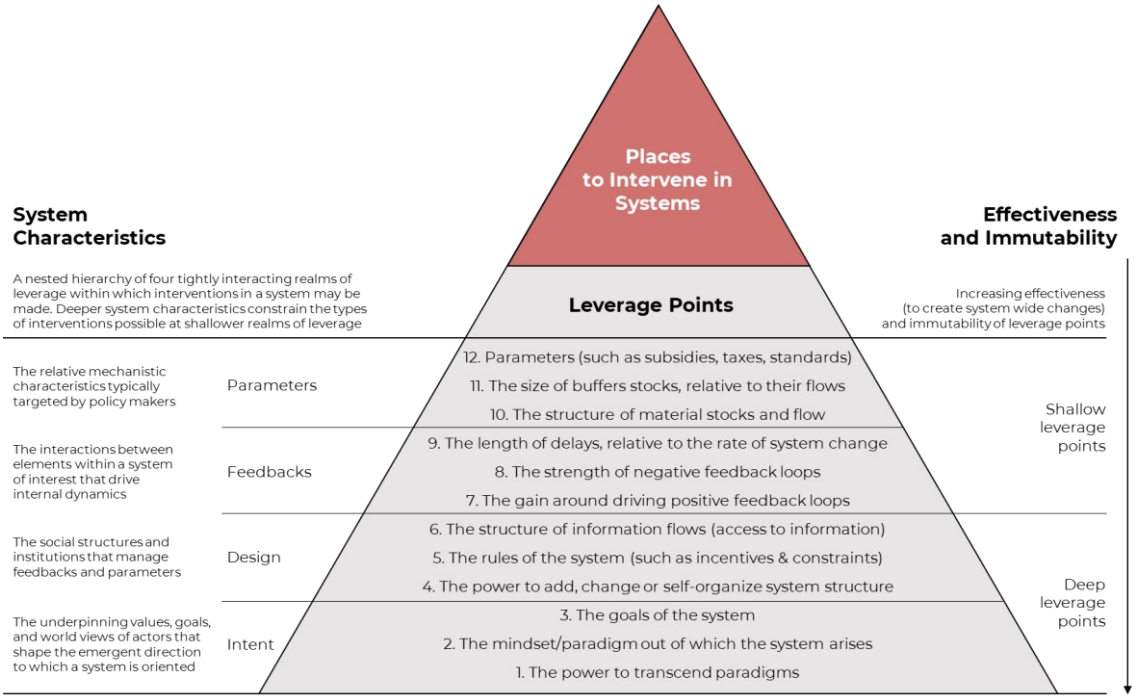

Figure 1: Places to intervene in systems, showing twelve leverage points for intervening in systems (center), ordered in increasing effectiveness and immutability (right), and four interacting realms of systems (parameters, feedbacks, design, intent) and their characteristics within which the leverage points can be understood (left). Own figure after (Meadows, 2009).

Considerations on the role of science, industry and policy making

As scientists we must not sit and wait until our ideas and proposals are taken up by industry or policy makers. The times for a 'neutral position' (if there ever was one) and comments from the ivory tower is over. While not every scientist might be willing or able to participate in civil disobedience (the effectiveness of which is becoming increasingly evident (Capstick et al., 2022)), I am convinced that it is our moral duty to use our privilege and relative influence to actively coordinate and engage with decision makers in order to inform and enable necessary changes towards regenerative spatial systems.

My own journey into this PhD started on the building level, with the research conducted in my master's thesis, which combined the interest in participatory building design process, with the use of building information modelling (BIM) tools and life cycle assessment (LCA) methods for analysing and understanding the life cycle climate impacts of building designs in early design phases – some of the results on the integration of BIM and LCA are published in first journal publication (Röck et al., 2018a).

I then got the chance to shape and work on international research projects such as the IEA EBC Annex 72 (R. Frischknecht et al., 2019a), where my contribution focused on the joint development and dissemination of best practices for building assessment workflows and tools suitable to support researchers as well as industry pioneers to understand *parameters* and *feedbacks.* Within 'the Annex' we furthermore worked on international harmonization of assessment methods to ensure comparability, feasibility, and upgradability of building life cycle related indicators. I increasingly understood that the conventions and standards, shaping the *design* of the built environment system, must be changed to consider climate performance assessment and evaluation of climate target compliance as an integral part of the building design task. And while standardisation and the work of crafting international standards is important, it is also highly technical and can take a (very) long time. Standardization procedures, despite efforts to enable broad participation, are in part due to their highly technical nature also rather opaque and hardly accessible for active participation of building design professionals, not to mention the wider public. Furthermore, I realized that the problem is not so much solving the technical integration of LCA in the design process, or the standardization therefor, but rather the lack of clear incentives and requirements for building design professionals to conduct building LCA in their process and use the findings for improving building design choices. The problem was – and still is – a lack of regulatory guidance for effective decarbonization of the built environment.

I therefore shifted my attention towards working on the science needed to accelerate the legislative and regulatory requirements for LCA of buildings. I actively looked for opportunities to develop and acquire projects that would enable interdisciplinary research contributions to inform the public discourses around the role of embodied and whole life carbon emissions of buildings. The results are several projects and collaborations involving partners from consultancy, non-governmental, and academia for both philanthropic funders as well as contract research for public bodies. In particular, I got to work on studies on the benchmarking of embodied carbon across Europe, or the wider implications of taking a whole life carbon of buildings perspective for informing the decarbonization of the European building stock, in ongoing studies for the European Commission. My research at the science-to-policy interface is shaped by an awareness of the need to bridge the gap between building level LCA and macro-scale level analysis of building-related environmental impacts. The metrics, methods and models presented in this PhD thesis therefor aim to do just that, to leverage the building-level LCA logic, information and results accessible to building design professionals, and use it to enable the provision of detailed building life cycle data in studies at the macro-scale for information policy making with the science needed to move forward on legislating whole life carbon reduction on both building and building stock level.

Moving forward, I am convinced that aspects such as sufficiency require considerations of the role of different building categories in the allocation of carbon budgets, require debate and decisions on the *intent* and goal of built environment systems that should be negotiated and decided in a collaborative and participatory manner. The participatory aspect is crucial to distribute environmental responsibility democratically and address and implement climate mitigation needs in a transparent way. In hindsight, the participatory aspects in this PhD are limited to engaging stakeholders from the research community (such as in the Annex 72), as well as from the construction industry, including front-running building design professionals (in the various projects on embodied and whole life carbon in the EU context).

1.2. Background

Reducing whole life carbon of buildings

The relevance of 'buildings' and the 'construction industry' in addressing the climate and environmental emergency is highlighted by yearly status reports published by UN Environment, the International Energy Agency (IEA) and the Global Alliance for Buildings and Construction (GABC)(United Nations Environment Programme (UNEP) and Global Alliance for Buildings and Construction (GABC), 2022). These reports emphasize that building construction and operations account for more than 1/3 of global final energy use and approximately 40% of energy-related carbon dioxide (CO_2) emissions. The numbers highlight that increasing the energy efficiency of both existing and new buildings, as well as shifting to sustainable construction practices, are major opportunities for decarbonising the economy in the coming decades. In recent reports, the IPCC identified the decarbonisations of the full life cycle of buildings – meaning carbon emissions related to both building operation as well as those embodied in construction products and material-related processes (cf. EN 15978 (European Committee for Standardization (CEN), 2011)) – as an essential field of action (Intergovernmental Panel on Climate Change (IPCC), 2022b). The European Union (EU), within its framework for the European Green Deal (European Commission, 2019), is advancing on the topic of whole life carbon regulation via initiatives such as the Energy Performance of Buildings Directive, the Taxonomy for Sustainable Activities and the EU Climate Transition Benchmark Regulation (Official Journal of the European Union, 2020a, 2020b, 2020c). The effective implementation of these initiatives depends on the deployment of suitable methods and tools to support environmental modelling, monitoring and management of both individual buildings as well as the EU building stock at large (European Commission (EC), 2020a; Röck et al., 2021).

Decarbonization and carbon targets for buildings

To guide development of buildings and building stocks along a just and fair global decarbonization pathway, it is useful to establish carbon budgets (Friedlingstein et al., 2022; Rogelj et al., 2019) and related budget-based targets for buildings and infrastructure (Habert et al., 2020a; Horup et al., 2022). In doing so, it is important to consider not only historical responsibilities and current levels of prosperity, but also the different sectors and activities associated with the life cycle of buildings and building stock in general (Habert et al., 2020a; Röck et al., 2021; Williges et al., 2022). Besides being important contributors to current carbon emissions, the 'carbon investment' for both building construction and operation represents a particular challenge as well as potential lock-in and inherent time conflict due to building's long-lasting nature. *"Buildings are long-lasting artefacts. The buildings created today are expected to operate far beyond 2050 when buildings will need to be net-zero emissions."* (Habert et al., 2020a). However, to inform official target setting and provide guidance on life cycle related building decarbonization policy in the EU, there is a need to first establish evidence on the whole life carbon emissions of buildings to inform both the understanding of current emission levels as well as strategies and measures for whole life carbon reduction. Existing reduction pathways for different sectors can provide indicative relative reduction targets relevant for building construction and operation (European Commission (EC), 2020b, 2020c, 2018a).

Informing policy action towards regenerative building stock development

To create and identify effective strategies to minimize building-related GHG emissions and other environmental consequences, both individual building modelling and optimization (Hollberg and Ruth, 2016; Röck et al., 2018a) as well as system-level analysis of building stocks at scale are needed (Allacker et al., 2019; Röck et al., 2021; Sala et al., 2021). Various research projects have centered on methodological issues surrounding building stock modelling (Göswein et al., 2019; Hobday et al., 2005;

Mastrucci et al., 2017a; Moffatt, 2004a), which is primarily used to model building-related energy use and its environmental implications, but is increasingly used to model material and life cycle related environmental impacts, such as the whole life carbon emissions of new and existing buildings (Buffat et al., 2017; Heeren and Hellweg, 2019a; Mastrucci et al., 2017c; Röck et al., 2021). The European Union, but really the Global North as a whole, has a special role and historical responsibility (Buch-Hansen and Nesterova, 2023; Dorninger et al., 2021; Klinsky and Mavrogianni, 2020; Rubiano Rivadeneira and Carton, 2022) with regards to the need for policy action that enables rapid decarbonization and a regenerative development of the building going forward. The EU aims to be climate-neutral by 2050, requiring a fundamental transformation of the construction and building sectors. The present decade is hence critical as building related carbon emissions need to be reduced by more than half until 2030 to get on track for a net-zero carbon building stock by 2050. Emissions must be drastically cut throughout the whole lifecycle of buildings, encompassing all operational and embodied emissions. However, while a small set of EU Member States have set out national strategies, targets and regulations, an EU-wide roadmap for the reduction of whole lifecycle carbon (WLC) emissions in buildings has not yet been developed. To address this need, the European Commission's Directorate-General for Environment (DG ENV) has initiated an ongoing study aimed at supporting the development of an EU roadmap (Le Den et al., 2023), outlining how all building-related emissions (both operational and embodied) can be mitigated by 2050. Many open questions remain to be tackled regarding both the assessment of building level whole life carbon and related benchmarking and carbon reduction target setting, as well as methodological challenges of modelling building related whole life carbon emissions at the macro scale to inform decarbonization policy in Europe and beyond.

Life cycle assessment of buildings and building stocks: Potentials and challenges

To be able to provide the robust science needed for informed policymaking, a thorough understanding of the state-of-the-art as well as limitations and next steps required in developing methods and models for life cycle assessment (LCA) of buildings. Life Cycle Assessment (LCA) has emerged as a widely recognized methodology to comprehensively evaluate the environmental impacts associated with buildings (Hauschild and Huijbregts, 2015; Klöpffer and Grahl, 2014; Sala et al., 2015).

LCA is a systematic approach that quantifies the environmental burdens associated with a product, process, or system throughout its life cycle stages, from raw material extraction to end-of-life disposal (Hauschild and Huijbregts, 2015). LCA evaluates multiple environmental impact categories, including carbon emissions, energy consumption, resource depletion, and waste generation (Hauschild and Huijbregts, 2015; JRC European commission, 2011). By considering the entire life cycle, LCA provides a holistic perspective, enabling decision-makers to identify opportunities for improvement at various stages of a building's life (European Committee for Standardization (CEN), 2011).

Understanding the spatial scales at which buildings operate is crucial for accurate carbon footprint analysis (Heeren and Hellweg, 2019a; Mastrucci et al., 2020a, 2017a). Buildings can range from individual structures to entire urban areas, and their impacts vary accordingly (Göswein et al., 2019; Mastrucci et al., 2017a). In context of building stock modelling, spatial scales and the level of aggregation particularly influence data availability, representativeness, and the level of modelling detail required for accurate assessments (Allacker et al., 2019; Heeren and Hellweg, 2019a; Röck et al., 2021). Additionally, different building archetypes (e.g., residential, commercial, industrial) exhibit distinct energy consumption patterns, specific material characteristics and element build-ups, and hence distinct life cycle emission profiles (Baldassarri et al., 2017; Levasseur et al., 2010a; Röck et al., 2020c; Verellen and Allacker, 2022). Therefore, it is essential to consider spatial scales and implications for definition and modelling of representative building archetypes when conducting building LCA studies to capture the diversity and heterogeneity of the built environment. While traditional LCA focuses on

assessing the current and historical environmental performance of buildings, there is a growing interest in prospective LCA (Drouilles et al., 2019a; Heeren and Hellweg, 2019a; Mastrucci et al., 2017c; Peñaloza et al., 2018a). Prospective LCA explores the potential environmental impacts of different future scenarios, enabling the identification of sustainable strategies and guiding decision-making processes. By integrating prospective analysis, LCA can assist in the design and planning of low-carbon buildings and infrastructure (European Commission (EC), 2020c; Röck et al., 2021).

Despite its strengths, LCA is not without limitations. The accuracy of LCA results heavily relies on data quality, completeness, and reliability. Gathering comprehensive and representative inventory data for every stage of a building's life cycle can be challenging and time-consuming (Hollberg et al., 2021; Hollberg and Ruth, 2016; Röck et al., 2018a; Soust-Verdaguer et al., 2017). Moreover, LCA has predominantly focused on individual buildings, often neglecting the broader context of building stocks and their interrelationships - a limitation becomes particularly evident when attempting to upscale bottom-up building stock LCA results to macro scales, as it may magnify errors and uncertainties associated with data aggregation and extrapolation (Mastrucci et al., 2017a; Röck et al., 2021; Truger et al., 2022). To address the risk of magnifying errors in upscaling bottom-up building stock LCA, hybrid approaches for establishing LCA inventory data have emerged (Crawford et al., 2018; Helal et al., 2020; Mutel and Hellweg, 2009). Also for the building stock modelling context, novel approaches suggest combining detailed bottom-up data collection for representative building types with macro-level modelling techniques that account for the variability and diversity of building stock characteristics (Gulotta et al., 2020; Heeren and Hellweg, 2019a; Röck et al., 2021; Andre Stephan and Athanassiadis, 2017). Despite the advancements in LCA methodologies, several research gaps remain. Further exploration is needed to refine and standardize LCA methodologies for building carbon footprint analysis, particularly regarding the integration of prospective analysis and the consideration of spatial scales and use of detailed archetypes for building stock analysis at macro-scale. Additionally, research efforts should focus on enhancing data quality, completeness, and accessibility, as well as developing robust approaches that effectively tackle the challenge related to upscaling of building level data for modelling of building stocks at the macro-scale.

1.3. Problem statement and research questions

Problem statement

The author of this thesis acknowledges the need for reducing whole life carbon of buildings and the importance of clear decarbonization action and carbon targets required to achieve this. At the same time, it is also acknowledged, that policy action requires robust evidence to inform the necessary regulation towards a climate neutral and regenerative building stock across Europe. This thesis aims to address prevailing limitations of building LCA and its use for informing policy making and regulation for reducing the climate impacts of individual buildings as well as understanding and managing the climate impacts of building stocks at the macro-scale. This thesis addresses the problem that:

At the building level, there remains a lack of comprehension regarding the significance of greenhouse gas (GHG) emissions occurring at different stages throughout the life cycle of buildings. However, recent advancements, including contributions made by the author of this thesis, have brought about substantial improvements, and shifts in perspectives. Nonetheless, significant gaps persist concerning the standardized definition of documentation requirements, protocols for data collection, and tools for data processing and analysis. Furthermore, in the context of benchmarking current building performance to establish future decarbonization targets, there is a scarcity of openly accessible data on life cycle carbon emissions, as well as material and energy usage, for buildings.

Moreover, when conducting life cycle-oriented modelling of building stocks at the macro scale, beyond the scope of cities or local regions, several research gaps emerge. These gaps include limited information on stock activities such as new construction and retrofitting, as well as a restricted representation of building types, predominantly focusing on residential structures. Initially, building stock modelling primarily emphasized the energy perspective and GHG emissions associated with building operation. Consequently, prevalent approaches for life cycle assessment of building stocks have been confined to a limited set of materials, or have solely focused on selected life cycle stages, such as end-of-life or new construction. No models have been proposed that offer a comprehensive and full life cycle perspective for modelling building stocks at the macro scale.

Research questions

This thesis addresses three main research questions and related sub questions – illustrated in Table 1.

Table 1: Research questions addressed in different chapters of this doctoral thesis.

Research questions	**Chapter**					
	2	**3**	**4**	**5**	**6**	**7**
RQ 1: What is the role of embodied carbon in the life cycle of buildings in context of the need for rapid decarbonization by 2050?						
A. What is the historical trend and current state-of-the-art regarding the contribution of embodied versus operational GHG emissions in the life cycle of buildings?						
B. Is there a clear and causal trade-off between operational and embodied GHG emissions, or can buildings have both below-average operational and below-average embodied GHG emissions?	X	X				
C. How does temporal distribution, i.e., time of occurrence of GHG emissions in the life cycle of buildings, influence conclusions in the context of the climate crisis?						
D. What is the whole life carbon baseline for new buildings across Europe?						
E. How are embodied carbon emissions distributed across space and time?						
RQ 2: What metrics and methods are required to support the next wave of European climate policy for building construction and operation?						
A. What is the state of data availability of whole life carbon data across Europe and which data needs should be addressed in future?						
B. What is the current state of methods for modelling and assessing environmental impacts of building stocks and related spatial and temporal dynamics?		X	X	X		
C. What are the EU policy objectives related to building stock development and to what degree are existing modelling approaches suitable for supporting the assessment and implementation of these objectives?						
RQ 3: How can comprehensive life cycle assessment be integrated for both building and building stock analysis to inform EU climate policy?						
A. What are the relevant information points and attributes to inform a comprehensive analysis of environmental hotspots for buildings?						
B. Which scalable and accessible data model can be conceived to enable advanced analysis of environmental hotspots across spatial and temporal dimensions?			X	X	X	X
C. How can such a data model be implemented at scale to enable high-resolution life cycle analysis across spatial and temporal dimensions?						

1.4. Methodological approach

Table 2 offers an overview of the methods applied in this thesis including an indication of the respective chapters. An introduction to the different methods is provided in the following chapters.

Table 2: Overview of methods in different chapters of the thesis.

	Chapters					
Methods	**2**	**3**	**4**	**5**	**6**	**7**
Evidence synthesis	X	X	X	X		
Life cycle assessment	X	X	X	X	X	X
Building information modelling	X	X	X	X	X	X
Building stock modelling				X		X

1.4.1. Evidence synthesis

Evidence synthesis describes a set of methods for gathering and analysing research from a range of sources to inform debates and decisions on specific issues (Gough et al., 2020; Haddaway et al., 2020; Jordan, 2020; Nakagawa et al., 2020; "The value of evidence synthesis," 2021). Various online resources provide good introduction to the topic, such as Cornell University Library (Kibbee, 2023), which also provide overviews of evidence synthesis methods and types of reviews illustrated in Figure 2. Evidence synthesis can involve a methodical, systematic literature synthesis focused on a well-formulated research question, including the synthesis of both published and unpublished studies. Evidence syntheses may also include a meta-analysis to provide quantitative evidence for practice and policy making, as well as to identify gaps in the research. Evidence syntheses are more resource-intensive than traditional literature reviews (often called 'narrative reviews') and, depending on the scope and chosen methods, the process of evidence synthesis can require multi-person research teams and can take several months. It is important to clearly identify the reasons for conducting evidence synthesis before embarking on this process.

Systematic reviews are rigorous and comprehensive research approaches used to synthesise evidence from multiple studies (Gough, 2017; Higgins and Green, 2008; Wohlin, 2014). Systematic reviews rely on evidence-based methods to maximise rigor and minimise bias. Systematic reviews are commonly used in the medical field, where they are crucial to provide reliable and up-to-date information to practitioners. Increasingly, systematic reviews are also used in other fields, such as in the environmental sciences, to identify gaps in knowledge and areas where further study is needed. The methodological basis for systematic reviews is under active development, with various contributions on both the critical appraisal and application of the methodological frameworks (Haddaway et al., 2022, 2020; Page et al., 2021) as well as on the efficient planning and implementation of systematic reviews (Haddaway and Westgate, 2019; Page et al., 2021; van de Schoot et al., 2021).

Systematic mapping is a method for collating and cataloguing evidence relating to a topic or question of interest (James et al., 2016). The method was developed in social sciences due to a lack of empirical data when answering questions using systematic review methods and is now being translated for use in environmental sciences. The method involves establishing a review team and engaging stakeholders, setting the scope and question, setting inclusion criteria for studies, searching for and screening evidence, coding, producing a database, and describing and visualizing the findings.

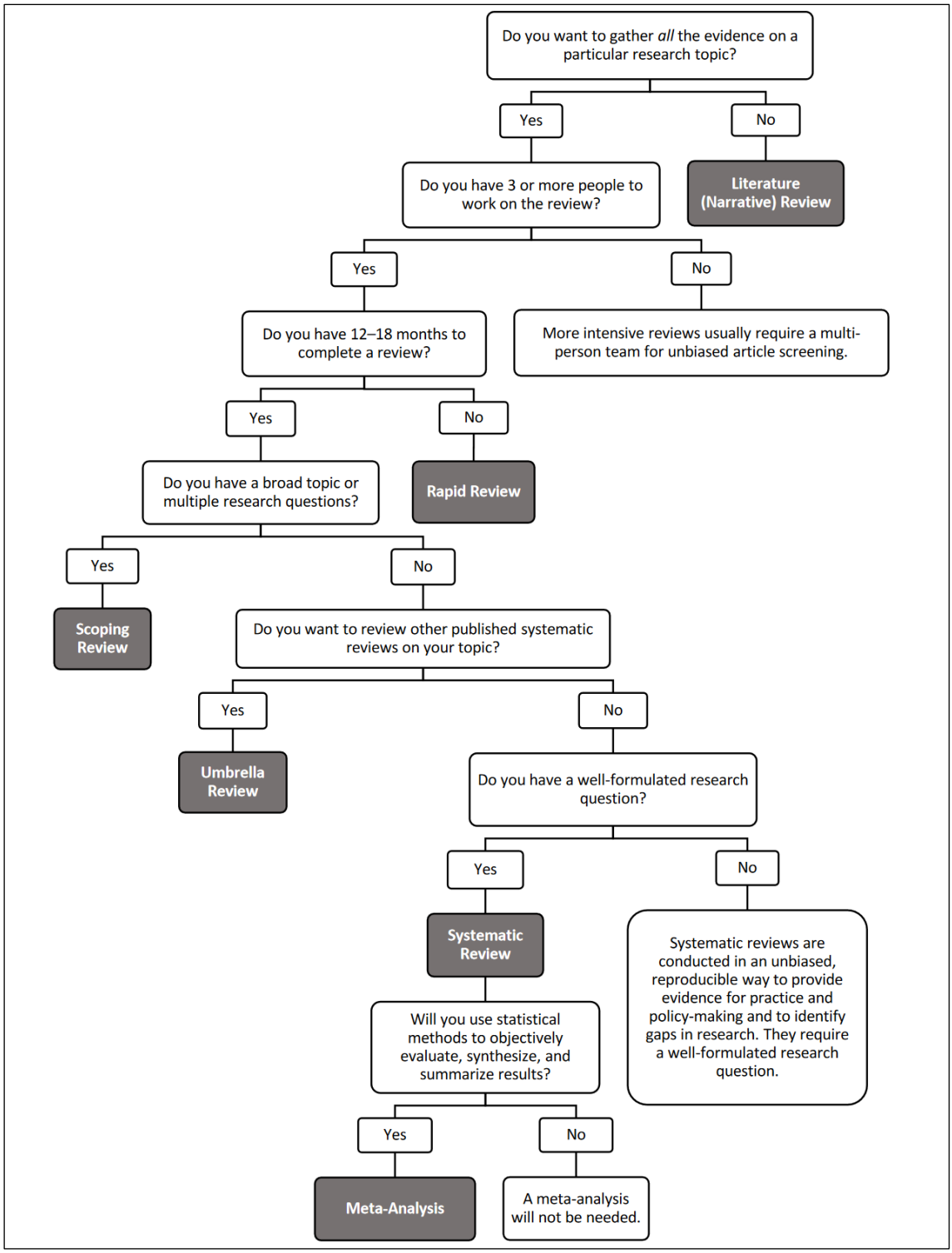

Figure 2: Decision tree for identifying evidence synthesis methods and review type (Cornell University Library, 2023).

Both systematic review and systematic mapping are commonly deployed along eight consecutive stages: 1) Objective definition; 2) Question formulation; 3) Search strategy definition; 4) Study screening and exclusion; 5) Data extraction; 6) Critical appraisal; 7) Synthesis; and 8) Reporting.

Meta-analysis extends the above with additional stages for synthesizing data from multiple studies to draw conclusions about a particular research question, by combining the statistical results from two or more existing studies (Barani et al., 2018; Mengist et al., 2020; Oxman and Guyatt, 1993). Meta-

analysis is an important research method within evidence synthesis as it helps to improve precision about evidence where individual studies are too small to provide convincing data and can help to settle divergences between conflicting studies. As meta-analysis requires data transformation and classification, harmonization and dis-/aggregation, it usually involves the application of processes and tools for data processing and engineering (McKinney, 2017; Paffenroth and Kong, 2015; Perez and Granger, 2007; Stepanek, 2020), as well as analysis and visualization (Hunter, 2007; Lemenkova, 2020; Waskom, 2021; Yang et al., 2022). Meta-analyses can inform answers to questions with a broader scope than captured by individual studies, for example by exploring the distribution of a metric (e.g., whole life carbon) or the effect of a measure (e.g., carbon reduction strategies) across multiple contexts.

1.4.2. Life cycle assessment

The following introduction to life cycle assessment (LCA) is based on excerpts of and further elaborated in chapter 2 (The relevance of embodied carbon in the life cycle of new buildings), based on (Röck et al., 2020c), and chapter 5 (Policy objectives and the state of building stock models), based on (Röck et al., 2021), respectively.

To inform policy makers and other decision makers on the environmental implications of decisions, the life cycle assessment method is increasingly applied. Recent studies have highlighted the role and increasing importance of LCA in EU policymaking (Sala et al., 2021). Furthermore, LCA is listed as a tool for policy support in the Better Regulation Toolbox, an EU initiative aiming at improving the policy process. LCA use cases range from supporting the policy anticipation and problem definition (identification of issues for which a policy intervention is needed), up to policy impact assessment (comparing different policy options) as well as policy implementation and assessment of policy effectiveness – as illustrated in Figure 3.

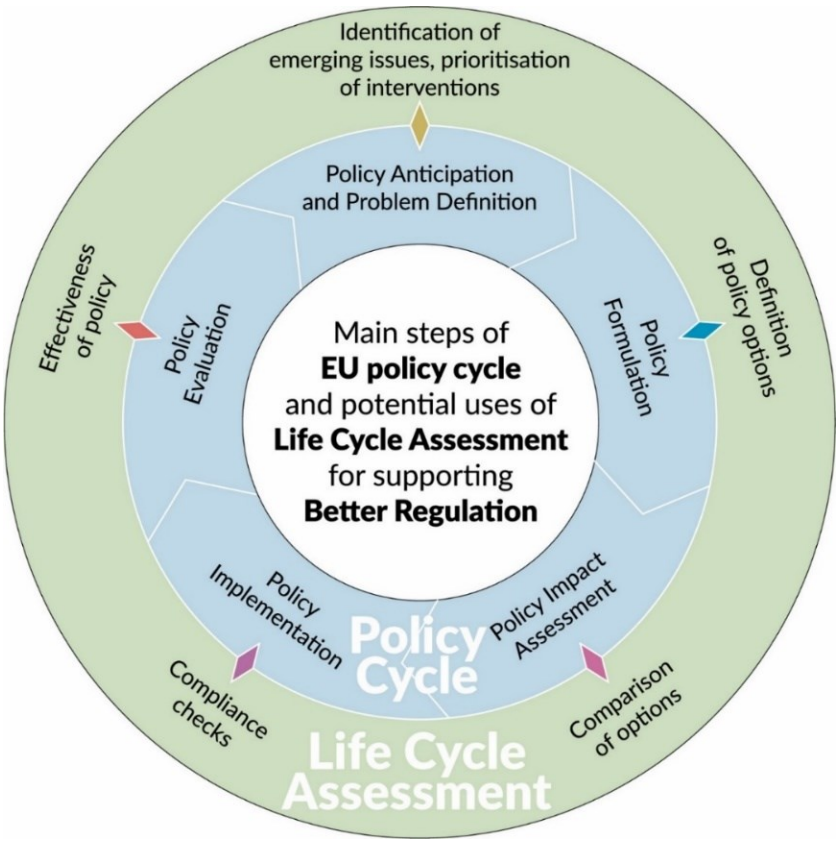

Figure 3: Main steps of the EU policy cycle and the potential uses of Life Cycle Assessment to support Better Regulation ((Röck et al., 2021) adopted from (Sala et al., 2021)).

The LCA methodology, internationally standardised in the 1990s, aims at quantifying the environmental impacts of products and processes throughout their entire life cycle, i.e., from 'cradle-to-grave' (European Commission. Joint Research Centre., 2019; Hauschild and Huijbregts, 2015; Hellweg and Milà i Canals, 2014). This approach provides a sound methodological basis for calculating energy use and assessing resource depletion, GHG emissions and other environmental indicators over the full life cycle of buildings (Basbagill et al., 2013; Buyle et al., 2013; JRC European commission, 2011; Lasvaux et al., 2016; VITO et al., 2018). Due to methodological developments in recent years, the application of LCA has been successfully facilitated in the construction industry. Increasingly, manufacturers of construction products publish LCA data for their products using Environmental Product Declarations (EPD) (Hunsager et al., 2014; Modahl et al., 2013; Passer et al., 2015) and other formats, the establishment of which follows international standards such as ISO 14040/14044 (Klöpffer, 2012). In a European context, the related standards for the sustainability of construction works are EN 15978 ('Assessment of environmental performance of buildings') and EN 15804 (stating the core rules of establishing EPDs). Figure 4 presents the general structure and definition of stages in the life cycle of buildings according to the European standard for the sustainability of construction works, assessment of the environmental performance of buildings (EN 15978). These standards are providing guidance on how to analyse and quantify the impacts of building products and buildings over their entire life cycle, they enable decision makers to make more informed decisions about the sustainability of their projects. Furthermore, the standards also provide a framework for evaluating the environmental performance of existing buildings, allowing for comparison between different projects and potential strategies for the development of building portfolios and stocks.

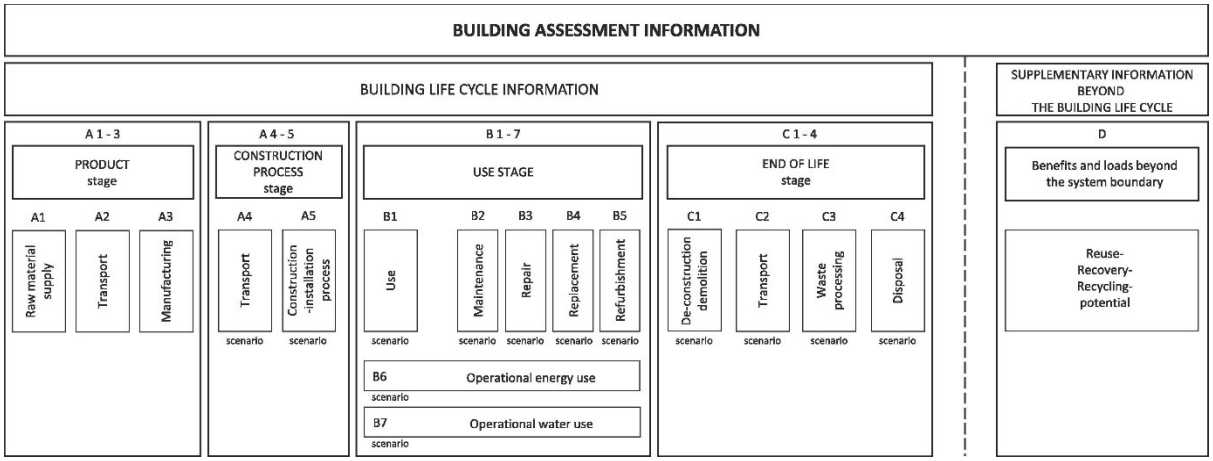

Figure 4: Modular approach to temporal building assessment information ((Röck et al., 2020c) acc. EN 15978).

The objective of LCA is to evaluate the environmental impacts of a product, service, or process throughout its life cycle, from resource extraction and production to use and disposal. LCA commonly involves four iterative steps: Goal and scope definition; inventory analysis; impact assessment; and interpretation. Goal and scope definition involves setting the boundaries and objectives of the LCA; inventory analysis involves collecting data on the resources used, energy consumed, and waste produced throughout the life cycle; impact assessment involves evaluating the potential environmental impacts of the life cycle; and interpretation involves communicating the results of the LCA to stakeholders.

The conventional approach in life cycle inventory (LCI) analysis involves aggregating exchanges from each emission throughout the life cycle into a single value, followed by characterizing the potential impacts in life cycle impact assessment (LCIA). However, this traditional approach lacks or obstructs temporal information and relies on limited steady-state models in LCIA, which compromises the

accuracy of life cycle assessment (LCA). To overcome this limitation, methods for a dynamic LCA have been proposed (Beloin-Saint-Pierre et al., 2017; Levasseur et al., 2010a; Mutel and Hellweg, 2009), which incorporates temporally or regionally differentiated profiles of emissions. Dynamic LCA can consider the LCI result for each emission as a function of time, aiming to enhance the methodology's temporal aspects, or specifically locate the space of emissions within the supply chain (Heeren and Hellweg, 2019a; Mutel and Hellweg, 2009). In this thesis, the building LCA approach is further developed through the introduction of the SLiCE data model. This model enables the utilization of high-resolution, temporally, and spatially explicit life cycle inventory foreground data, facilitating advanced analysis of environmental hotspots and dynamic assessment of the environmental impacts throughout the life cycle. environmental impacts and potential benefits across the building life cycle.

1.4.3. Building information modelling

The following introduction to building information modelling is based on excerpts of the journal articles published by the author and colleagues, namely (Röck et al., 2018a, 2018c).

In the context of integrating LCA in the design process, the use of Building Information Modelling (BIM) has gained attention as it promises to support complex decision making by providing opportunities to link numerous aspects and large amounts of information in a common data environment. As various disciplines involved in building construction are moving towards BIM application, it is also desirable to develop BIM-integrated LCA workflows in order to take the aspect of environmental impact into account in complex decision making throughout the building life cycle (Chong et al., 2017; Eleftheriadis et al., 2018; Kreiner et al., 2015; Zanni et al., 2017). As BIM implementation increases, efforts are made to advance the common understanding and definition of the at times vaguely used term “BIM”. BIM in its wider sense can be understood as a ‘building information model’ encompassing every analogue or digital information on a building, both structured and unstructured, stored in a common data environment (CDE) or spread out across one or more offices and stakeholders. In practice, BIM leverages digital processes to increase efficiency and commonly builds on a 2D or 3D representation of a building’s geometry, linked with information on its physical and functional characteristics. BIM software solutions aim at offering tools for supporting collaborative processes for building design and operation and aim to enable architects, engineers, and construction professionals as well as facility managers and real estate professionals to create and manage building information throughout the entire life cycle, from design and construction to operation and maintenance as well as, eventually, deconstruction and end-of-life.

To enable the use of BIM models for the various potential applications (e.g., documentation, estimation, simulation, tendering, fabrication, etc.) it is generally agreed that the quality of a BIM model regarding its Level of Development (LOD) is a crucial factor. Following the generally accepted LOD approach, such a level is comprised of various definitions to describe e.g., the Level of Geometry (LOG) and Level of Information (LOI) of a BIM element’s quality and reliability regarding geometric representation (LOG) and information specified (LOI). A common practice in BIM-based building representation in building data in BIM is the use of hierarchical modelling of building geometry, following the so-called element-method. While different software solutions and use cases apply different hierarchical levels, the concept can be explained as illustrated in Figure 5, where construction materials are composing sub-elements (or work sections), which are composing building elements, which are composing buildings. The parametric logic builds on a modular approach, i.e., the same construction materials can be used by different sub-elements, which can use different materials. The logic can further be extended to higher and lower-level entities.

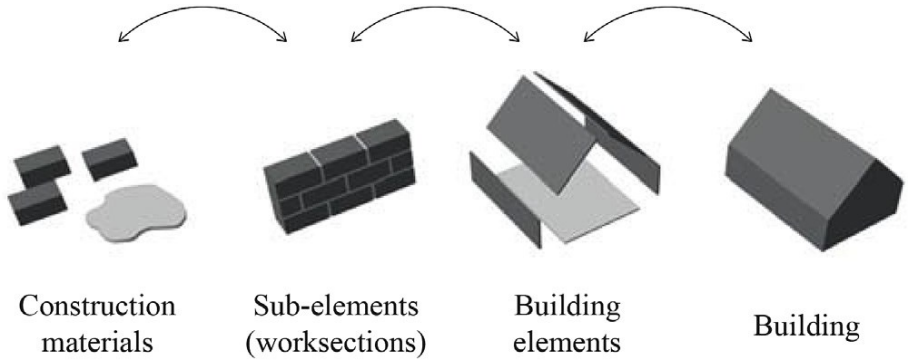

Figure 5: Illustration of hierarchical building information modelling of spatial information ((Röck et al., 2018a) adapted from (Trigaux et al., 2017)).

Another important concept is the notion of "dimensions of information" in the context of multi-dimensional life cycle information on buildings. Dimensions therein refer to the different types of information that can be included in a BIM model. These dimensions are commonly broken down into:

- 3D: Includes information on the physical geometry of a building and its components (such as walls, floors, and roofs) and enables quantification of spatial elements (e.g., materials, elements) as well as the linking of other properties related to those items (see other dimensions).
- 4D: Adds the element of time to the model, in practice often utilised to implement information on the construction process and scheduling of different phases of the project.
- 5D: Often interpreted for incorporating financial information into the model, allowing for cost estimation and analysis throughout the project's life cycle.
- 6D: Often refers to information on sustainability and environmental performance, such as data on energy use and emissions, relevant for the assessment of a building's life cycle impacts.

While definitions of the above dimensions beyond ‘3D’ are just more or less useful conventions, BIM experts move beyond this illustrative classification and rather consider BIM as a set of methods and tools that enable authoring, managing, and analysis of multi-dimensional, or n-dimensional, information of buildings (Balouktsi et al., 2020; Chong et al., 2017; Obrecht et al., 2020a; Röck et al., 2018a, 2018c). Multi-dimensional data is also common in other domains such as geospatial research and modelling, where various layers or ‘bands’ of information are superimposed to form n-dimensional, high-definition datasets (Breunig et al., 2020; Coetzee et al., 2020; Cortés, 2023; Gorelick et al., 2017; Keith et al., 2022). By incorporating all relevant dimensions into a BIM model, it is possible to create a multi-dimensional representation of the building and its life cycle, enabling more informed decision-making by architects, engineers, construction professionals, and policy makers. This approach allows for the optimization of the building's design, construction, and operation to reduce its environmental impact, improve its energy efficiency, and ultimately contribute to the mitigation of the climate crisis.

In the context of this thesis, building information modelling is indeed understood as the creation and processing of building related information for the purpose of generating valuable insights into the life cycle performance of buildings.

1.4.4. Building stock modelling

The following introduction to building stock modelling is based on excerpts of and further elaborated in chapter 5 (Policy objectives and the state of building stock models), based on (Röck et al., 2021).

To develop and identify effective policies to reduce building related GHG emissions and other environmental impacts, not only the modelling and assessment of individual buildings but also a move to the system level is required, considering the characteristics and dynamics of building stocks at scale.

Several research projects have focused on methodological questions surrounding building stock modelling – primarily utilised for modelling building-related energy use – and its practical implications. In the review presented in chapter 5 (Policy objectives and the state of building stock models), (Röck et al., 2021) elaborate on previous proposals (Göswein et al., 2019; Mastrucci et al., 2017a; Moffatt, 2004a) and suggest six basic modules common in contemporary building stock modelling studies, as presented in Figure 6: i) building stock characterization; ii) material modelling; iii) energy modelling; iv) life cycle impact assessment; v) building stock aggregation; and vi) visualization and reporting. These represent the basic blocks of models for the environmental assessment of building stocks, as identified in our review. Some models make use of a central database or a common data environment to manage the large variety and quantity of data to be processed in complex building stock models. Furthermore, the data processed in the respective modules may follow one definition or contain multiple alternative solutions, as is the case in investigations of different scenarios, e.g., for different retrofit strategies in material modelling or climate change scenarios in energy modelling.

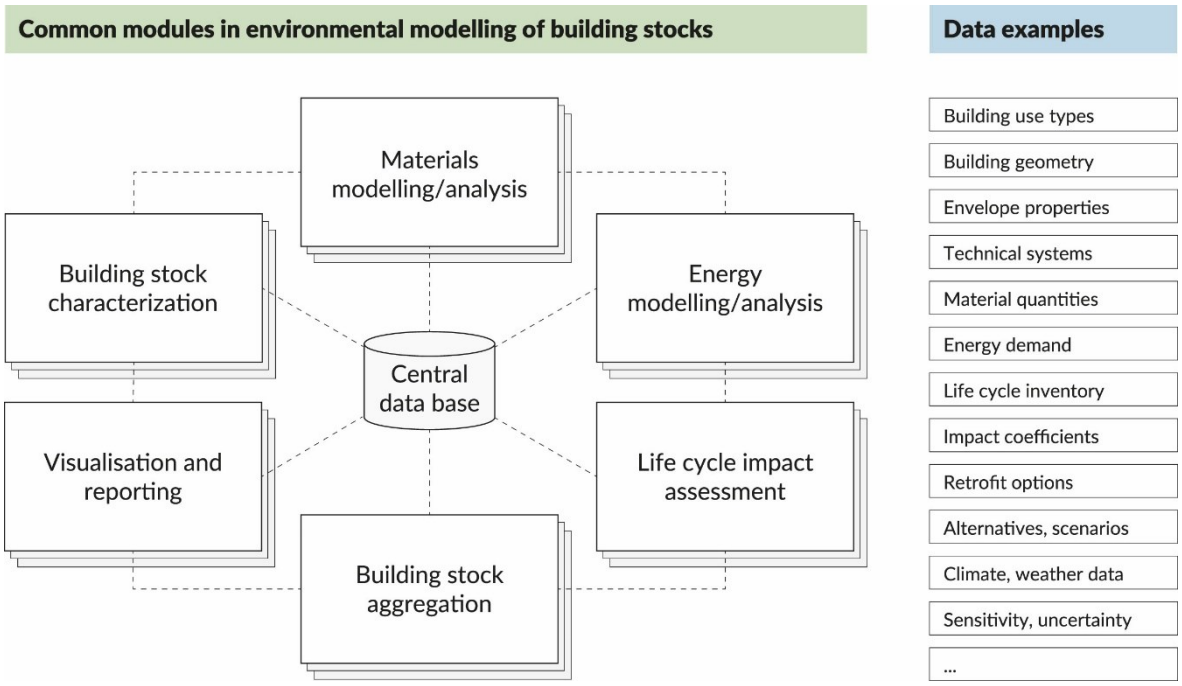

Figure 6: Common modules and data in environmental modelling of building stocks (Röck et al., 2021)

While relying on many static parameters, building stock modelling commonly considers various dynamics of building stock development. Dynamic aspects can cover both the inventory and the impact assessment side and chapter 5 (Policy objectives and the state of building stock models) shows examples of different dynamic aspects and where these occur in. Commonly considered dynamics are, e.g., spatial differentiation of buildings in the stock, temporal evolution of future energy mixes, or spatial-temporal changes to buildings due to renovation activities. Some studies even anticipate the effects of climate- or weather-related changes or consider the influence of dynamic impact characterization. Other dynamic aspects considered include exogenous factors driving stock development, such as projected population development, occupational density (i.e., floor area per capita), material efficiency or the influence of financial aspects on the feasibility of certain renovation measures and related changes in the renovation rate.

In this thesis the terms granularity, resolution, and (high-)definition refer to similar but different aspects: i) High or low granularity refers to data and model inputs and their level of information; ii) High or low resolution refers to models and processes, which require high-granularity data inputs to enable high-

resolution in modelling; iii) High-definition (or HD) is used as an umbrella term to capture the benefits of high levels of information density (definition) obtainable when combining both, high-granularity data and high-resolution modelling.

1.5. Organization of the Thesis

This thesis is structured around six paper-based chapters which represent the core of the doctoral research contribution, flanked by this general introduction and a discussion and outlook – see Figure 7.

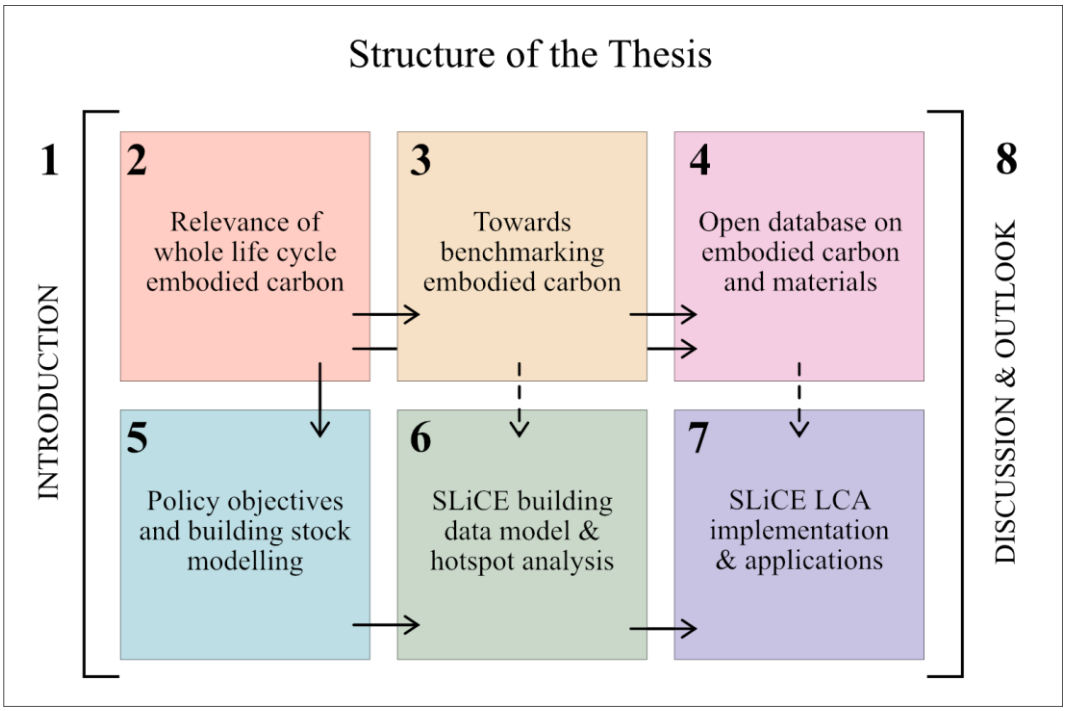

Figure 7: Thesis structure and logic of the different chapters. Starting from a general introduction to the topic and the research questions (1), the core chapters start off with an investigation of the relevance of whole life embodied carbon globally (2) and a study towards benchmarking embodied carbon in Europe (3). The learnings from data collection and analysis as well as the data itself are presented in a data descriptor chapter (3). A review of EU policy objectives and methods for building stock modelling (5) provides the transfer to the core proposal of the SLiCE building data model for hotspot analysis and dynamic impact assessment (6) as well as the implementation of SLiCE in a building LCA model and further application examples (7), including for SLiCE-based building stock and scenario modelling. The thesis concludes with discussion and outlook (8).

The thesis is framed by the introduction (**chapter 1**) and the concluding discussion and outlook (**chapter 7**). The six paper-based core chapters present the evolution of the research from a systematic literature review-based meta-analysis on the role of embodied carbon emissions in the life cycle of new buildings, and particularly their importance in enabling effective mitigation of new building's contribution to the climate crisis (**chapter 2**); to a comprehensive analysis of the data available for benchmarking whole life embodied carbon from new buildings across Europe, considering different building typologies, construction types and carbon intensities per-m² as well as per-capita (**chapter 3**). The chapter includes the investigation of the contribution of different life cycle stages and building parts as well as the influence on the results obtained from methodological inconsistencies and limitations in data availability. Consecutively, the data descriptor for an open database on whole life carbon of buildings is presented **(chapter 4)**, describing the database established through structured collection and processing of data underlying chapters 2 and 3, including the detailed description of attributes contained in the database, information on procedures applied for data processing and harmonization, as well as an overview of the resulting database and value distribution for main attributes. The following chapter (**chapter 5**) makes the step to the macro-level and the analysis of building stocks based on

representative archetypes. The foundation is again laid with a systematic review of published assessment models for the environmental assessment of building stocks and a mapping of the objectives from specific EU policy initiatives related to the Green Transformation of the Built Environment This integrated review synthesises the needs for policy-informing and informed decision makers and reveals strengths and weaknesses of existing models to provide the necessary insights for guiding robust decision making in the years ahead. In response to the identified needs of policy makers and to advance on shortcoming of existing building models, the next chapter (**chapter 6**) builds on the initial embodied carbon meta-analyses, the EU benchmarking data study, and the review of integrated building stock models and EU policy and presents the space-time-indicator (STI) framework as a means of conceptualizing the problem to aid a solution: An open building data model for scalable life cycle analysis (SLiCE). SLiCE is designed to enable the handling of large amounts of high granularity building life cycle information and is intended to support detailed environmental hotspot analysis across spatiotemporal dimensions. The proof-of-concept is delivered with an implementation of the SLiCE data model within a prototypical hotspot analysis tool. The final content chapter (**chapter 7**) elaborates the SLiCE proposal by presenting an implementation of the data model that addresses a second major drawback of existing models currently faced by decision makers: The prevailing trade-off between model resolution and scale of the assessment. In this implementation, SLiCE is applied with KU Leuven's building LCA model and a novel building LCA ecosystem is established, utilizing state-of-the-art methods and tools for data handling, computation and visualization. The chapter is concluded by the presentation of several applications of SLiCE in research practice, ranging from micro-scale (e.g., building elements), over meso-scale (e.g., building level), up until macro-scale (as a basis for prospective modelling of the European building stock). The concluding chapter (**chapter 8**) offers a synthesis of the previous chapters, discusses relevant insights from applying the SLiCE model and offers an outlook into future use for supporting decision makers in policy making, local governance as well as procurement, design and management of public and commercial real estate.



2. THE RELEVANCE OF EMBODIED CARBON IN THE LIFE CYCLE OF NEW BUILDINGS

Bibliographic data

Title	Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation
Authors	Martin Röck, TU Graz (AT) Marcella Ruschi Mendes Saade, LIRIDE (CA) Maria Balouktsi, KIT (DE) Freja Nygaard Rasmussen, AAU BUILD (DK) Harpa Birgisdottir, AAU BUILD (DK) Rolf Frischknecht, Treeze Ltd (CH) Guillaume Habert, ETH Zurich (CH) Thomas Lützkendorf, KIT (DE) Alexander Passer, TU Graz (AT)
Journal	Applied Energy
Date(s)	Submitted 30 June 2019; Accepted 8 November 2019
DOI	https://doi.org/10.1016/j.apenergy.2019.114107

Highlights

- Systematic literature study covering 650+ building LCA cases on life cycle greenhouse gas emissions.
- Buildings life cycle GHG emissions are reducing due to energy efficiency improvements.
- Embodied GHG emissions are increasing and on track to become the largest part of life cycle emissions.
- Upfront GHG emissions of new buildings dominate the timeframe for climate change mitigation.
- Decarbonization measures are needed to meet net-zero life cycle targets and avoid lock-in effects.

Author contributions

Martin Röck: Conceptualization, Methodology, Software, Formal Analysis, Investigation, Data Curation, Visualization, Writing (Original draft, review and editing), Project administration.

Marcella Ruschi Mendes Saade: Methodology; Formal analysis; Data curation; Writing (Original draft, review and editing); Visualization.

Maria Balouktsi: Methodology; Formal analysis; Data curation; Writing (Original draft, review and editing).

Freja Nygaard Rasmussen: Formal analysis; Data curation; Writing (Original draft); Visualization.

Harpa Birgisdottir: Conceptualization; Data curation; Writing (Review and editing); Supervision.

Rolf Frischknecht: Conceptualization; Data curation; Writing (Review and editing); Supervision.

Guillaume Habert: Conceptualization; Writing (Review and editing); Supervision.

Thomas Lützkendorf: Conceptualization; Methodology; Data curation; Writing (Original draft, review and editing); Supervision; Project administration.

Alexander Passer: Conceptualization; Methodology; Data curation; Writing (Original draft, review and editing); Supervision; Project administration.

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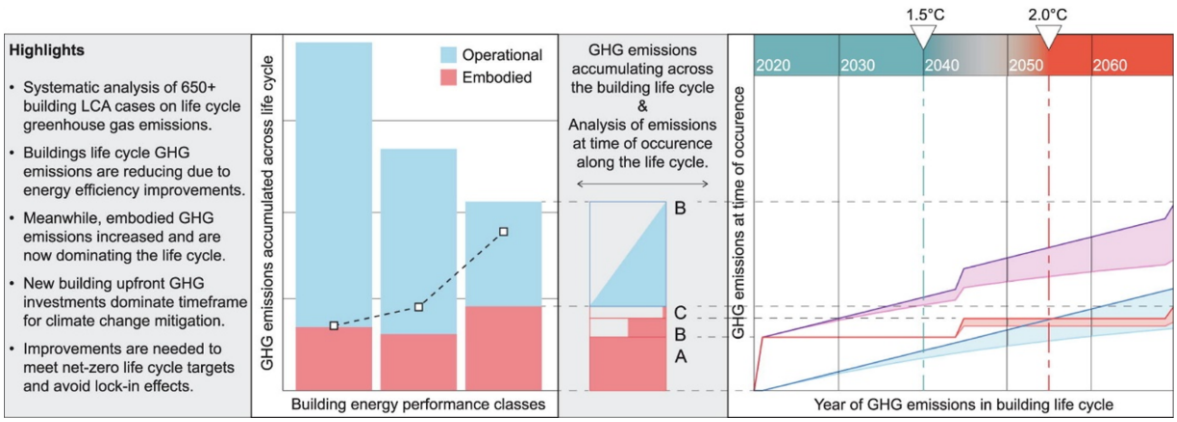
Abstract

Buildings are major sources of greenhouse gas (GHG) emissions and contributors to the climate crisis. To meet climate-change mitigation needs, one must go beyond operational energy consumption and related GHG emissions of buildings and address their full life cycle. This study investigates the global trends of GHG emissions arising across the life cycle of buildings by systematically compiling and analysing more than 650 life cycle assessment (LCA) case studies. The results, presented for different energy performance classes based on a final sample of 238 cases, show a clear reduction trend in life cycle GHG emissions due to improved operational energy performance. However, the analysis reveals an increase in relative and absolute contributions of so-called 'embodied' GHG emissions, i.e., emissions arising from manufacturing and processing of building materials. While the average share of embodied GHG emissions from buildings following current energy performance regulations is approximately 20–25% of life cycle GHG emissions, this figure escalates to 45–50% for highly energy-efficient buildings and surpasses 90% in extreme cases. Furthermore, this study analyses GHG emissions at time of occurrence, highlighting the 'carbon spike' from building production. Relating the results to existing benchmarks for buildings' GHG emissions in the Swiss SIA energy efficiency path shows that most cases exceed the target of 11.0 $kgCO_2eq/m2a$. Considering global GHG reduction targets, these results emphasise the urgent need to reduce GHG emissions of buildings by optimizing both operational and embodied impacts. The analysis further confirmed a need for improving transparency and comparability of LCA studies.

Keywords

Life cycle assessment (LCA) Construction Buildings Embodied carbon Greenhouse gas (GHG) emissions Environmental impacts.

Graphical abstract



2.1. Introduction

2.1.1. The role of buildings in responding to the climate crisis

The potential consequences of the climate crisis and the effects it has already triggered are prompting an intensive examination of the necessity of and possibilities for reducing anthropogenic greenhouse gas (GHG) emissions. The relevance and pressing nature of this topic is highlighted by the integration of climate change mitigation measures into the globally recognised Sustainable Development Goals (SDGs), the alarming reports of the Intergovernmental Panel on Climate Change (IPCC) (IPCC (Intergovernmental Panel on Climate Change), 2018b) and the commitments to national GHG emission reduction measures within the framework of the United Nations Climate Change Conference of the Parties (COP). The relevance of 'buildings' and the 'construction industry' in this context is highlighted, for example, in the yearly status reports published by UN Environment, the International Energy Agency (IEA) and the Global Alliance for Buildings and Construction (GABC). These reports make it clear that "building construction and operations [account for] 36% of global final energy use and 39% of energy-related carbon dioxide (CO_2) [emissions]" (Abergel et al., 2018). In recent reports (de Coninck et al., 2018; IPCC (Intergovernmental Panel on Climate Change), 2018b), the IPCC identified 'buildings' as an essential field of action for a number of reasons. First, building operations worldwide account for 28% of energy-related GHG emissions (Abergel et al., 2018). These emissions from building operation arise from the energy used for heating and/or cooling, hot water supply, ventilation and air conditioning, lighting, and process-related climate-relevant GHG emissions, i.e., the release of refrigerants and blowing agents (HFC- and PFC-gases). Second, because 'buildings' are responsible for a massive amount of current GHG emissions, they also have significant potential to reduce GHG emissions through improved operational energy efficiency. In this context, the IPCC states that "1.5 °C-consistent pathways require building [GHG] emissions to be reduced by 80–90% by 2050, new construction to be fossil-free and near-zero energy by 2020", and the need for "an increased rate of energy refurbishment of existing buildings to 5% per annum in OECD countries"(de Coninck et al., 2018). Thus far, efforts to improve building related GHG emissions focus mainly on increasing energy efficiency to reduce operational energy demand and on increasing the use of renewable energy carriers. Eventually, the aim is a net-zero energy and emissions balance in the use phase of buildings. In addition to conserving non-renewable energy sources, pursuing these goals should support the reduction of GHG emissions across the life cycle of buildings. The tightening of legal requirements regarding energy efficiency in building operation has led to, e.g., growing awareness among actors in the construction and real estate industry, increased development of related construction products and systems, and the establishment and improvement of various information and design support tools. Altogether, these measures have successfully contributed to a decline in the energy demands of building operation, thus shifting the environmental hotspots to other stages in the life cycle of buildings (Mirabella et al., 2018).

2.1.2. Shifting focus from efficiency in operation towards a full life cycle perspective

Currently, a large part of the scientific community in the field of buildings and energy research focuses on optimizing the so-called 'operational' energy use of buildings and, more recently, on the associated GHG emissions. However, given the full life cycle of buildings, energy use and GHG emissions occur for reasons that extend beyond building operation. Energy is required for the manufacturing of construction products; it is 'invested' in the construction of new buildings and in modernization and replacement measures; and it is consumed by transport and construction processes as well as during the dismantling and disposal of buildings and materials. The field of buildings and energy research can build on previous work on embodied energy from the twenties and eighties of the last century (Bekker,

1982; Friedrich et al., 1922; Gartner and Smith, 1976; Stein et al., 1980). In particular, the publicly available results of IEA ECBCS Annex 31 Energy-related environmental impacts of buildings (Hobday et al., 2005) and IEA EBC Annex 57 Evaluation of Embodied Energy and CO_2eq for Building Construction (IEA EBC, 2016) are highly relevant. The life cycle assessment (LCA) methodology, internationally standardised in the 1990s, aims at quantifying the environmental impacts of products and processes throughout their entire life cycle, i.e., from 'cradle-to-grave' (European Commission. Joint Research Centre., 2019; Hauschild and Huijbregts, 2015; Hellweg and Milà i Canals, 2014). This approach provides a sound methodological basis for calculating energy consumption and assessing resource depletion, GHG emissions and other environmental indicators over the full life cycle of buildings (Basbagill et al., 2013; Buyle et al., 2013; JRC European commission, 2011; Lasvaux et al., 2016; VITO et al., 2018). Due to methodological developments in recent years, the application of LCA has been successfully facilitated in the construction industry. Increasingly, manufacturers of construction products publish LCA data for their products using Environmental Product Declarations (EPD) (Hunsager et al., 2014; Modahl et al., 2013; Passer et al., 2015) and other formats, the establishment of which follows international standards such as ISO 14040/14044 (Klöpffer, 2012). In a European context, the related standards for the sustainability of construction works are EN 15978 ('Assessment of environmental performance of buildings') and EN 15804 (stating the core rules of establishing EPDs). Figure 8 presents the general structure and definition of stages in the life cycle of buildings according to the European standard for the sustainability of construction works, assessment of the environmental performance of buildings (EN 15978).

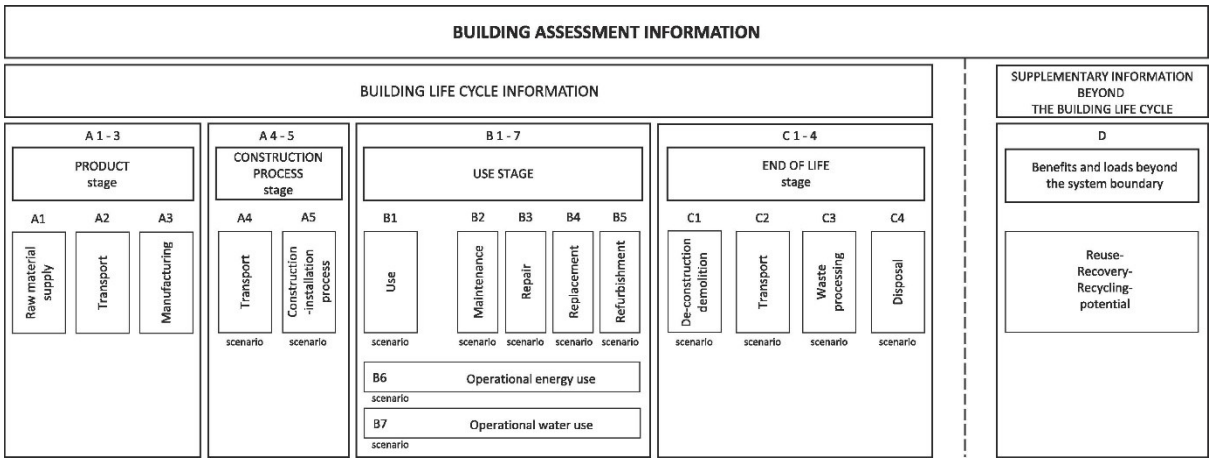


Figure 8: Display of modular information for the different stages of building assessment (acc. EN 15978)

2.1.3. Challenges and misconceptions regarding life cycle related GHG emissions

There are systemic reasons for the lack of attention paid to embodied impacts in building-related energy research thus far. The energy consumption and GHG emissions that arise in the life cycle of buildings are cross-sectoral issues. Top-down statistics and environmental considerations are typically broken down by economic sectors. The 'buildings' sector includes all activities related to the operation of buildings, whereas the construction of these very same buildings is attributed to the 'industry' sector. Today, the production of construction products used for new buildings and for the refurbishment of existing ones represents 11% of global overall energy- and process-related GHG emissions, with more than half of these emissions related to the manufacturing of steel and cement (International Energy Agency, 2019). The most recent IPCC report aimed to overcome this division by including a short

discussion of embodied energy in buildings (de Coninck et al., 2018). One of the reasons embodied impacts have seldom been considered in policy making is the misconception that factors other than operational energy demands and GHG emissions are negligible aspects of a building's environmental performance. Now considered outdated, earlier studies showed that for typical buildings, the ratio of embodied to operational impacts was approximately 1:10. Therefore, the embodied contribution to life cycle energy was within the uncertainty range of the energy demand forecast for building use and thus not considered relevant (Ramesh et al., 2010). However, this situation has changed dramatically. In recent years, several studies have demonstrated the growing importance of embodied impacts, both relative to their contribution to life cycle-based performance and in absolute terms (De Wolf et al., 2017; Dixit, 2017; Häkkinen et al., 2015; Ibn-Mohammed et al., 2013). Among the topics investigated and discussed are the relative and absolute values of the embodied impacts as well as how to identify related benchmarks (Kathrina Simonen et al., 2017; K. Simonen et al., 2017; Stewart et al., 1999). In some countries, there are initial standards that identify benchmarks for embodied and operational GHG emissions, e.g., the Swiss SIA (SIA, 2010, 2017). Studies often use only one or a few buildings to examine how individual building and site characteristics affect the magnitude of the embodied GHG emissions or their contribution to life cycle GHG emissions; few studies have investigated a larger number of buildings (Kathrina Simonen et al., 2017). Examples of the parameters commonly analysed are (i) the type of building and its use (Hossain and Ng, 2018; Säynäjoki et al., 2017a); (ii) site-specific properties (e.g., country, climatic zone, seismic zone) (Cobîrzan et al., 2017; Ng et al., 2016); (iii) the energy performance standard (Chastas et al., 2016; Koezjakov et al., 2018); (iv) construction method (choice of main building materials (e.g., for structural system, envelope, internal walls) (De Wolf et al., 2016, 2014; Passer et al., 2012; Säynäjoki et al., 2017a); and (v) the size and shape of the building (e.g., floor area, number of stories, general shape) (Säynäjoki et al., 2017a; Kathrina Simonen et al., 2017). However, as shown in Table 1, studies investigating the matter have thus far been limited regarding the number and variety of studies compared; they are often limited to one building type and are limited in scope with regard to temporal and spatial representativeness. To date, no studies have systematically investigated recent trends in the contribution of embodied and operational impacts across the life cycle of buildings. The present paper aims to analyse the relative and absolute relevance of operational and embodied GHG emissions across different geographical locations, building types and energy performance standards.

Table 3: Overview of previous studies documenting embodied GHG emissions and the parameters that affect them.

Paper(s)	**Number of buildings**	**Analysed parameter(s) affecting embodied GHG**
De Wolf, Iuorio and Ochsendorf, 2014	3	Construction method (choice of main building materials)
De Wolf et al., 2015	200	Construction method (choice of main building materials)
Chastas, Theodosiou and Bikas, 2016	90	Energy performance standard
Cobîrzan et al., 2017	2	Site-specific properties
Hossain and Ng, 2018	37	Type of building and use
Koezjakov et al., 2018	25	Energy performance standard
Ng et al., 2016	1	Site-specific properties
Passer, Kreiner and Maydl, 2012	5	Construction method (choice of main building materials)
Säynäjoki, Heinonen, Junnila, et al., 2017	116	Construction method (choice of main building materials); Size and shape of building
Simonen, X Rodriguez and De Wolf, 2017	1007	Size and shape of building

2.1.4. Research questions

Building on the state of the art as described above, the following research questions are investigated:

I. What is the historical trend and current state-of-the-art with regard to the contribution of embodied versus operational GHG emissions in the life cycle of buildings?
II. Is there a clear and causal trade-off between operational and embodied GHG emissions, or can buildings have both below-average operational and below-average embodied GHG emissions?
III. How does a consideration of the temporal distribution, i.e., time of occurrence of GHG emissions in the life cycle of buildings, influence conclusions in the context of the climate crisis?

2.2. Material and methods

2.2.1. Systematic compilation of scientific literature

The collection of published information and subsequent analysis of the documents were performed following the structured protocol for Systematic Literature Review (SLR) and the 'snowball' approach (Higgins and Green, 2008; Wohlin, 2014), a complementary strategy to assure relevant sources are not left out which consists of checking the reference lists of papers and reports collected via the initial protocol. Based on the previously defined research questions, the authors systematically searched the publicly available literature using the following keyword string: [(LCA OR life cycle assessment) AND buil* AND embodied]. The search was performed on 'Scopus', checking for the presence of selected terms in the paper's abstract, title or keywords, limiting results to English written papers only. The search criteria further predicted the exclusion of grey literature (e.g., conference proceedings, master's and/or doctoral theses, books/chapters), and no time boundaries were set. In addition, the authors used the snowball approach to identify publications that are relevant but may have not shown up in the systematic search. This approach was executed by (i) checking the reference list of each sampled paper, (ii) assessing case studies listed in European technical reports, and (iii) consulting experts in the field for additional input regarding relevant LCA studies. The database search was finalised in July 2018, but additions via the snowball method continued through March 2019. The scientific papers that matched the initial search criteria were then transferred to a reference management software, where, following the SLR method, they went through three filtering phases: (i) a title analysis, (ii) an abstract analysis and (iii) a full paper in-depth analysis and data extraction. Filtering was carried out conservatively, i.e., by retaining – up until the final screening phase – papers for which it was uncertain whether they could contribute to answering the research questions (iii). Figure 9 illustrates the phases of database search and filtering, showing the number of studies remaining after each phase. A total of 369 papers matched the initial search. After the first filtering round (title-based), 20 papers were excluded. The abstract analysis led to the elimination of 168 papers. Finally, after a full paper investigation, the final paper sample was composed of 94 files, encompassing 325 case studies. The snowball approach added 331 case studies to the review, documented in 43 scientific papers, 9 reports, 2 master theses and one book. An overview of all studies compiled for this analysis, and the studies contained in the final sample, can be found in the supplementary information. To extract information from the studies in the final sample, a data extraction table was established to systematically collect relevant metadata, building-related and method-related information, as well as energy and GHG emissions from sampled papers and technical reports (Figure 9). The information collected in the data extraction table fed the meta-analysis, which allowed for a joint discussion of the findings, as well as an in-depth analysis of GHG emissions across buildings' life cycles as reported in the identified studies.

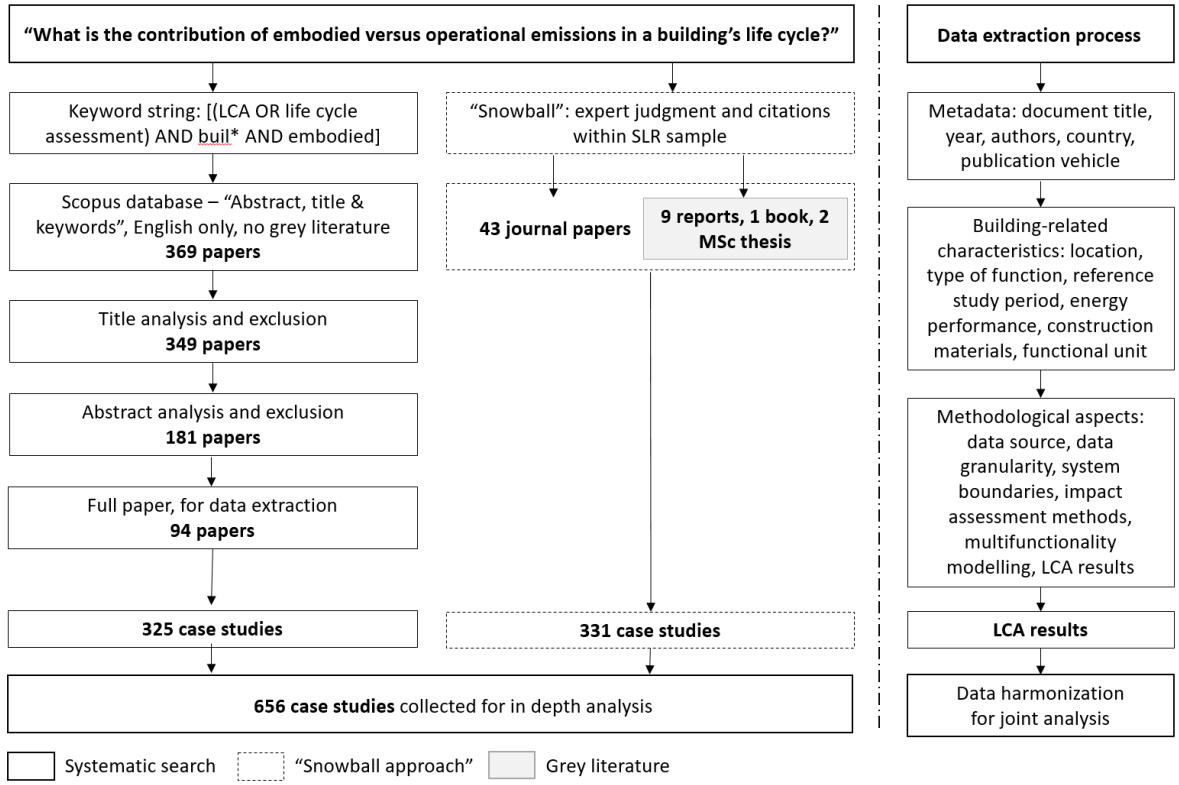


Figure 9: Overview of systematic search and data analysis

2.2.2. Data transformation and classification

Harmonization procedure

For the analysis of absolute embodied GHG emission (EGHG) values, all results collected in this study have been harmonised to the common reference unit $kgCO_2e/m2a$, which expresses GHG emissions in $kgCO_2$ equivalent per square metre (m2) of gross floor area (GFA) normalised across a 50-year Reference Study Period (RSP).

Due to the aim of applying a harmonization procedure towards a common floor-area-based reference unit, the sample of LCA results was limited to studies reporting the GHG emissions either per m2 GFA or m2 NFA (net floor area) or, at least, providing the information necessary to calculate any of these two areas (e.g., building plans). In other words, studies that only vaguely defined the functional equivalent were excluded from the final sample. In the case of the studies that only reported the m2 NFA, the results were converted to m2 GFA using a net-to-gross adjustment factor, as described in the following. The definitions 'usable floor area' and 'gross internal floor area' were considered to be equivalent to the NFA definition. As a general rule, GFA indicates the total constructed area, while NFA refers to the area inside the building and excludes the area covered by the outer walls of a building (ISO 6707-1). All values of the sample were transformed to the common reference unit $kgCO_2eq/m2a$ by dividing, where necessary, with the reference study period and square metres stated in each study. As previous studies have showed, differences in the building life span as well as in the reference study period could lead to significant variations in the results (Pannier et al., 2018; Rauf and Crawford, 2015). Hence, following this initial harmonization, a two-step procedure was employed.

First, the total sample of annualised EGHG values was normalised for a 50-year reference study period using Formula (1).

(1) $$EGHG_{norm1} = EGHG\left(\frac{RSP}{50}\right)$$

where,

- $EGHG_{norm1}$ = Annualised EGHG value after the 50-year normalization ($kgCO_2eq/m^2a_{50}$)
- RSP = Reference study period considered in the investigated study

Second, using Formula 2 for building cases where only the NFA was known, the $EGHG_{norm1}$ values were converted into GFAs by applying a constant of 0.8 m^2 NFA per m^2 GFA (in line with (European Commission (EC), 2015)). However, the specific net-to-gross floor-area conversion factor may differ across countries and building types due to differences in building codes and architectural practices (Säynäjoki et al., 2017a).

(2) $$EGHG_{norm2} = 0.8\, EGHG_{norm1}$$

The relative figures (i.e., share of embodied GHG emissions) were obtained by converting EGHGnorm1 values from step 1 into percentages.

Data classification

The final sample dataset was analysed with regard to the building type, energy performance standard and location. For building types, a two-category division into residential and office buildings was employed. For the energy performance classification, the building cases were categorised into three different types of energy performance:

a) "New advanced" buildings (i.e., studies assessing passive houses, low-energy buildings or near/net zero energy or emission (NZEB) buildings).
b) "New standard" practices (i.e., buildings following current standards regarding operational energy performance, which are in place as legal requirements in most of the countries investigated), or
c) "Existing standard," buildings constructed before the tightening of legal requirements for building operation (these "existing standard" buildings make up the majority of the building stock).

For the latter two types, a point in time was defined before which buildings were considered to have a different level of energy performance. This time point was defined following a "rule of thumb" regional approach and giving the label "existing standard" to the following:

- All existing building cases built prior to 2005 for Europe and Australia. This date was chosen as critical for these two regions because a few years earlier, stricter energy standards began to be introduced, i.e., the first version of the Energy Performance of Buildings Directive (EPBD) in Europe in 2002 (updated in 2010) (EU, 2010) and a '4-star' requirement in the Building Code of Australia in 2003 (McLeod and Fay, 2010)
- All office buildings built prior to 2007 and residential buildings built prior to 2009 for the USA. The selection of these two dates is also based on the introduction of tighter energy standards in the US around that period of time, i.e., ASHRAE 90.1:2007 (ASHRAE Standing Standard Project Committee, 2009) and the 2009 International Energy Conservation Code (IECC)

Although each country has a different history with respect to enforcing stricter energy efficiency regulations and standards, defining a different point in time for each country included in the review was not feasible. For the classification of location-based climate zones, the widely applied Köppen-Geiger climate classification (1980-2016) (Beck et al., 2018) was applied, focusing on its five main zones: A) Tropical; B) Arid; C) Temperate; D) Continental; E) Polar.

Exclusion criteria and data quality requirements

One challenge identified in the screened literature was that a significant share of the published papers, surprisingly, either do not report their datasets in sufficient detail to allow an analysis of their scope or, in some cases, report implausible results. This limitation reduced the number of eligible results that could be included in the analysis to 583 cases. The systematic analysis focuses on studies investigating 'New buildings' (calculated GHG emissions of new building models and archetypes) and 'Existing buildings' (impacts of buildings already in operation) and was limited to residential and office buildings. All papers dealing with 'refurbishment' cases were excluded because, from a methodological point of view, they do not allow comparison with the results of new construction cases. This restriction reduced the dataset to 401 cases. Therein, studies reporting only embodied energy (EE), but no embodied GHG emissions (EGHG) were excluded because a 'general' conversion factor from primary energy to GHG emissions does not exist and a regional conversion based on the various differences in construction material use, fuel type or year was not feasible. The final dataset for the analysis of global trends was composed of 269 building cases based on 54 studies. It is important to note that in many papers, the results were not provided in numerical terms but only given in graphs and charts. Although the extracted values from these papers are thus only visual approximations, they are accurate enough for the purposes of the present study and therefore were considered in the analysis if all other inclusion criteria were met. Although the harmonization of the reference unit and reference study period of the results analysed in this study enables general comparison, the results are still influenced by the studies' diversity regarding building type, climate, scope in relation to the included life cycle stages, type of LCI data, etc. As these parameters could not be fully harmonised, they indicate a source of systematic uncertainty.

2.2.3. Final sample meta-analysis

The meta-data analysis of the studies contained in the final sample, as presented in Table 4, shows that the majority of case studies within the final sample come from European countries (74%), followed distantly by Asian countries (14%) and Oceania (7%). Cases from North America, South America and other regions make up only a minor fraction in this sample (sum of 4%). This distribution explains why the majority of case studies were located in either a Temperate (C) (64%) or Continental (D) climate (26%). The analysis thus revealed a clear research gap regarding studies from the Americas as well as from tropical countries more generally. This gap in the analysis is notable considering how outside temperature can affect heating and cooling energy demand during a building's use phase. In terms of building type and energy performance, the final sample is hence composed of office (65) and residential buildings (204), mostly adopting current standards in energy performance, i.e., 'New standard' and 'New advanced' buildings.

Table 4: Number of cases in the final sample (and total of initially eligible but excluded cases) sub-divided based on, e.g., building's type of function, energy performance class, world region and climate zones (acc. Köppen-Geiger definition).

Type of function		**Energy performance**		**World region**		**Climate zone**	
Residential	204 (416)	Existing Standard	67 (89)	Europe	200 (388)	Tropical (A)	10 (27)
Office	65 (83)	New standard	111 (274)	Asia	38 (77)	Arid (B)	12 (18)
other	- (84)	New advanced	60 (159)	Oceania	18 (60)	Temperate (C)	172 (393)
		n/a	31 (61)	North America	4 (21)	Continental (D)	71 (138)
				South America	7 (24)	Polar (E)	1 (1)
				other	2 (13)	n/a	1 (6)

For the reference study period (RSP) applied throughout the different studies, an RSP of 50 years was the predominant choice (approximately 60% of the sample). The preference for this specific estimation is consistent with the depreciation principles for construction investments (Marsh, 2017).

2.3. Results and discussion

2.3.1. The increasing importance of embodied GHG emissions

The analysis of life cycle GHG emissions in the collected building cases makes clear that with increasing energy efficiency in buildings, the relevance of embodied GHG emissions is increasing in both relative and absolute terms as shown in Figure 10.

Figure 10a presents the outcome of the analysis of the average of GHG emissions across the life cycle of the buildings investigated in absolute terms (i.e., $kgCO_2eq/m^2a$), distinguishing between embodied and operational GHG emissions (stacked bar graph). Furthermore, Figure 10a shows the relative contribution (percentage) of embodied GHG emissions in buildings' life cycle GHG emissions (line graph). The figure presents these values for both residential and office buildings combined as well as separately for each of these building types. The results are further distinguished into three 'energy performance classes', ranging from 'existing standard' buildings to 'new standard' and 'new advanced' buildings', as defined in chapter 2.2.2 (Data transformation and classification). Focusing on this embodied GHG emissions share, there has been a global escalation of the contribution of embodied GHG emissions in both residential and office buildings – from ~20% to ~50% in new advanced buildings, surpassing 90% in extreme cases. This relative increase in embodied GHG emissions is mainly because operational GHG emissions have dropped in the transition from existing buildings to buildings with new and advanced standards. These trends can be observed for both building types, i.e., in office and residential buildings. These results are consistent across different locations, i.e., there are similar trends in studies from Europe or Asia as well as in the full set of globally distributed LCA studies. At the same time, embodied GHG emissions have, in absolute terms, either not declined or have even increased. Our analysis shows that this increase in embodied GHG emissions in absolute terms can be observed as an overall trend for residential buildings, where embodied GHG emissions have been reduced on average, from approximately 6.7 $kgCO_2eq/m^2a$ for existing buildings to 6.7 and 11.2 $kgCO_2eq/m^2a$ in new and advanced residential buildings. The same trend is not found for the investigated office buildings, where in absolute terms, a decrease and levelling of embodied GHG emissions can be observed, from approximately 17.3 $kgCO_2eq/m^2a$ for existing buildings to 11.6 or 12.0 $kgCO_2eq/m^2a$ for new or advanced office buildings.

Investigating the distribution of data in more detail, as shown in Figure 10b, values of both operational and embodied emissions are found to vary widely even for buildings of the same type and energy performance class. The absolute values for GHG emissions embodied in new buildings with standard and advanced energy performance, ranges from approximately 3.3 to 13.3 $kgCO_2eq/m^2a$ for residential buildings and 7.1 to 11.6 $kgCO_2eq/m^2a$ for office buildings (1st to 3rd quartile).

Complete descriptive statistics and related values can be found in Table S2 of the supplementary information. Furthermore, the distribution of embodied and operational GHG emissions is presented for cases from Europe and Asia in Figures S1 and S2, respectively. Potential aspects driving these differences are discussed in the "Limitations and methodological considerations" chapter.

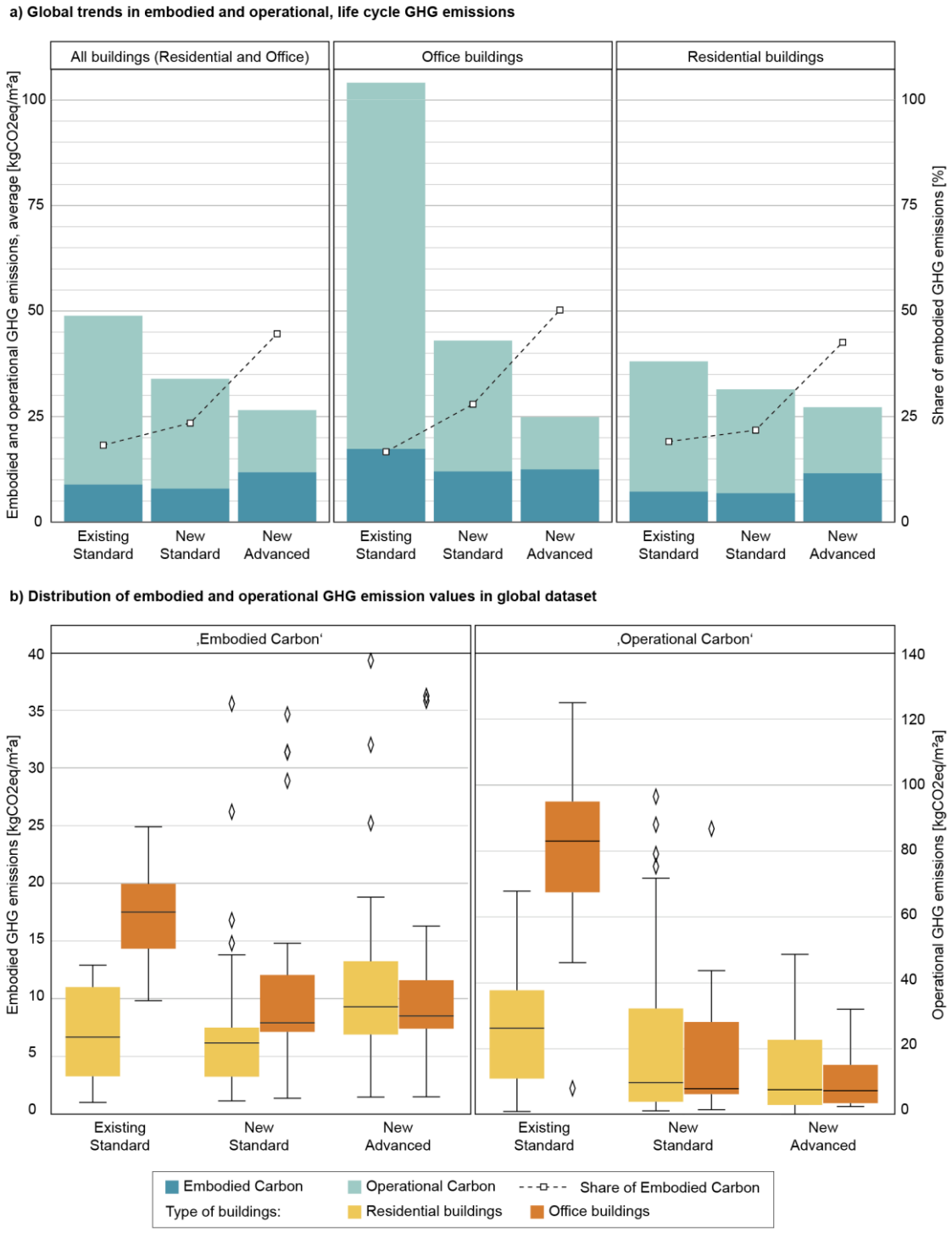


Figure 10: Global trends in buildings' life cycle GHG emissions (a), and distribution of GHG emission values (b) for residential and office buildings by energy performance class.

A critical investigation of these results reveals that the GHG emission peak for existing office buildings globally is mainly driven by results obtained from Input-Output (IO)-based LCA studies of office buildings in Japan (Suzuki and Oka, 1998) and the United States (Junnila et al., 2006). These two studies provide more than ninety percent of the 'existing' office building cases in the sample, while most of the other building cases use the Ecoinvent database (i.e., a generic database containing average environmental datasets about construction materials) either exclusively or in combination with regional data sources. An overview of the wide variety of data sources used by the studies contained in the final

sample is provided in the supplementary information (Table S3). IO-based LCA studies, in general, are known to yield impact results at a higher level than process-based studies (Säynäjoki et al., 2017b, 2017a), which could explain why these studies report higher GHG emissions. The methodological differences between following a bottom-up (process-based) or a top-down (IO-based) approach arise at the very beginning of an LCA study, defining early modelling choices and paths to be taken by the LCA practitioner.

2.3.2. Life cycle GHG emission metrics of individual building cases

The life cycle performance of a building in terms of its environmental impact depends on various factors, as laid out earlier. Furthermore, the building function, related requirements for thermal comfort, and its occupational patterns during use, including user behaviour, influence life cycle impacts and, for that matter, GHG emissions.

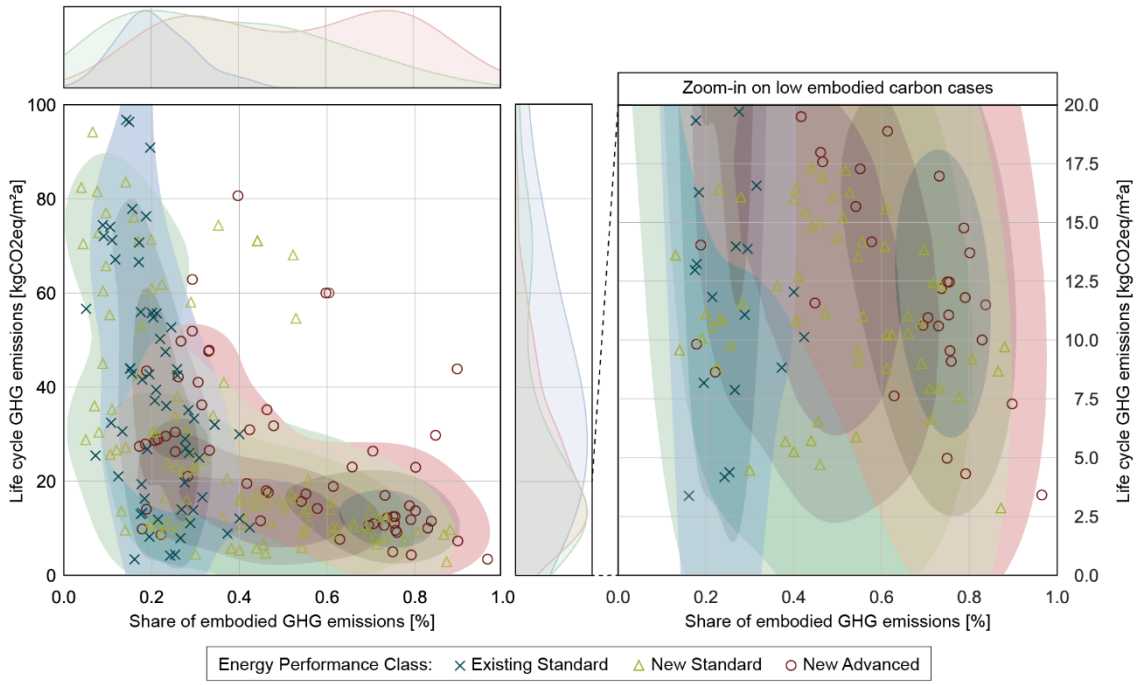


Figure 11: Overview of individual results regarding GHG emissions across the life cycle and share of embodied impacts, incl. zooming in on the low life-cycle-emissions examples

Figure 11 gives an overview of the individual results from the investigated studies by showing the total life cycle GHG emissions over the share of embodied GHG emissions. Coloured areas provide an approximation of clusters representing the energy performance classes. Note that to provide a clearer picture of the situation, we have limited the y-axis to 100 $kgCO_2eq/m^2a$, hence omitting a small number of extreme results (occurring for reasons discussed in the methodology chapter). We observe a spread of GHG emissions ranging from below 10 $kgCO_2eq/m^2a$ up to more than 90 $kgCO_2eq/m^2a$. However, we can also clearly see a trend in which the energy efficient buildings, where operational energy consumption has been reduced (indicated by a higher share of embodied GHG emissions), have overall lower emissions across the life cycle. This result confirms the previous observation arguing that the improvement of energy efficiency in buildings did reduce overall GHG emissions (Figure 10). Moreover, when zooming in on buildings with low total GHG emissions in the reference study period (lower than 20 $kgCO_2eq/m^2a$), it becomes evident that the share of embodied GHG emissions tends to increase from existing standard buildings to new standard and new advanced buildings.

This result is striking because it shows that it was and is possible to design low life-cycle-emissions buildings with all types of standards. However, buildings built with existing standards relied on smaller embodied GHG emissions and a higher contribution of operational energy and related GHG emissions. In contrast, for similar total GHG emissions, the buildings with newly advanced standards show a substantially higher share of embodied GHG emissions, which means that most of the GHG emissions saved through energy efficiency measures have been lost or even outweighed through extra emissions from building materials and technical systems.

Figure 11 clearly shows a shift in the origin and therefore the timing of occurrence of GHG emissions from existing to advanced buildings. The results confirm that there is a general tendency towards a higher share of embodied GHG emissions, which, in the current analysis, correlate with lower total GHG emissions in the building life cycle. At the same time, the results show that it is possible to achieve low total emissions without necessarily increasing the share of embodied GHG emissions.

As will be discussed in more detail, the results of LCA studies of individual building cases are influenced by a variety of parameters and methodological choices. However, across all these varieties, which are in part due to the large number of studies analysed, we see clear trends and consistent results in the average values shown in Figure 10 and when investigating the clusters of individual studies' results as shown in Figure 11. The results are therefore considered robust because they show consistent trends across studies from different geographical contexts, climate zones and building types.

2.3.3. European residential buildings and benchmark comparison

To improve the understanding of individual buildings performance, we investigate the relation of the best-practice examples in this analysis and existing benchmarks for buildings GHG emissions.

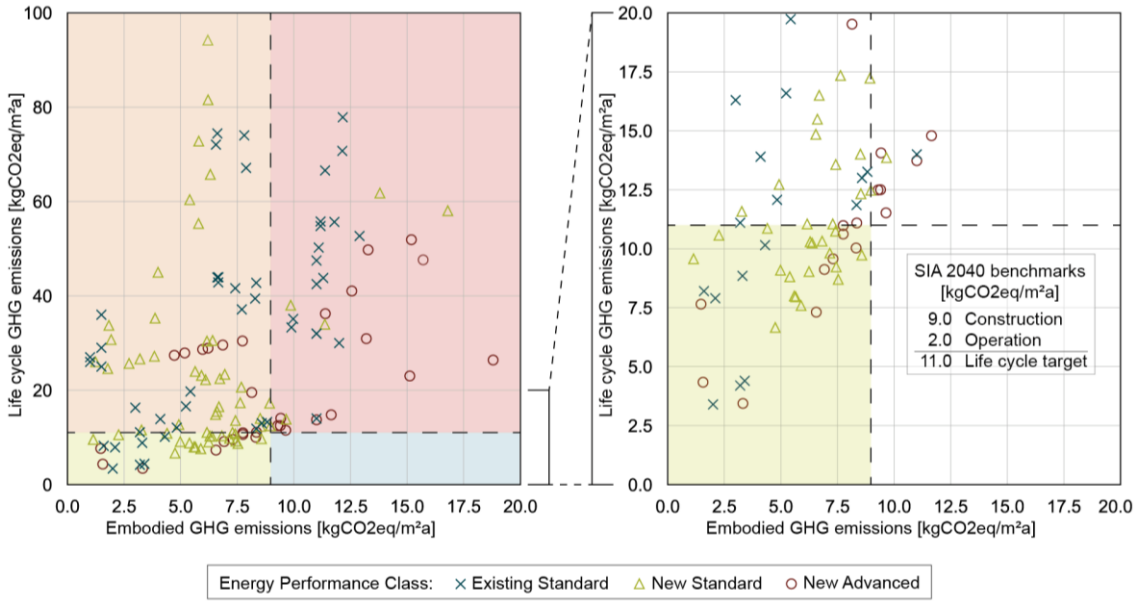


Figure 12: European residential buildings GHG emissions across the life cycle and absolute embodied GHG in relation to Swiss SIA 2040 benchmarks.

As described in the meta-analysis, most of the data collected in the systematic review are from buildings in Europe. Within this dataset, we observe a more homogenous situation regarding differences in geographical aspects as well as overall technical building standards. In this sense, an analysis is presented below focusing on how the residential buildings in Europe contained in the dataset perform in relation to existing benchmarks for buildings life cycle performance as well as benchmarks for embodied GHG emissions. The benchmark used for comparison is the Swiss SIA 2040 (SIA, 2017).

The SIA 2040 provides well-established benchmarks for buildings based on the '2000 Watt society' concept. The benchmark provides a life cycle-based target value for buildings, including embodied impacts, operational impacts, and impacts due to so-called building-related mobility. These benchmarks were established following a top-down approach based on a global GHG budget, which was transferred to a budget per capita. According to the Swiss 2000 Watt society principles (Zimmermann et al., 2005), and according to the German Environment Agency (Benndorf et al., 2013), reaching a goal of reducing GHG emissions to 1 t CO_2eq per capita and year by the year 2050 puts us on track to achieve "climate neutrality"[1]. SIA 2040 further splits this per capita budget into different sectors, such as housing, mobility or private and public consumption. Thirty-six percent of GHG emissions are attributed to housing. Other countries currently have, or are planning to introduce, benchmarks for the GHG emissions of buildings (see (Rolf Frischknecht et al., 2019a)), but the 2000 W society benchmark is at this point considered one of the clearer approaches and has already been used by many studies investigating the environmental impacts of buildings (Hoxha E et al., 2016; Wyss et al., 2014).

Figure 12 shows the total life cycle GHG emissions of European residential buildings over the amount of embodied GHG emissions and the related benchmarks according to SIA 2040. The figure clearly shows that most of the buildings do not meet the target values. For the vast majority of cases, total life cycle GHG emissions are higher than 11.0 kgCO_2eq/m^2a. This is the case independent of the building energy standard. For all energy performance categories, i.e., existing standards for new standard and new advanced buildings, only a few cases meet the benchmark. Considering the buildings that do meet the target, it can be observed that it is not necessarily the buildings with new standards that have a better chance of meeting the targets. This raises the question of the adequacy of building standards, focusing on operational energy efficiency, compared to the targets that need to be achieved to stay at a global temperature increase of 'well below 2°C'. If new building standards do not necessarily meet the targets, which kind of building requirements, policies and directives have to be implemented to bend the GHG emission curve of buildings? The analysis shows that target values related exclusively to the operational phase are not sufficient for reducing life cycle GHG emissions. It is therefore necessary to develop and implement benchmarks addressing embodied GHG emissions and overall environmental life cycle performance to put buildings on track for ambitious and effective climate mitigation scenarios.

2.3.4. Temporal distribution: The 'carbon spike' from initial GHG 'investments'

The importance of addressing embodied GHG emissions is further emphasised when considering the temporal distribution of life cycle GHG emissions due to the 'carbon spike' resulting from building production. In the context of the Paris climate goals and limited GHG emission budgets for achieving net zero GHG emissions globally, as emphasised in the IPCC 1.5°C Special reports (IPCC (Intergovernmental Panel on Climate Change), 2018b), emissions across the life cycle of buildings have to be lowered to 'net zero' eventually. Hence, the GHG emissions invested in erecting and modernizing buildings and other infrastructure must be 'cost-effective', i.e., their GHG 'investment' has to contribute to eventually reducing the level of GHG emissions from a whole life cycle perspective. The previous chapters showed that investing more in embodied GHG emissions does not necessarily reduce life cycle GHG emissions and that 'advanced' building concepts are not necessarily the most effective way to achieve low life cycle GHG emissions.

[1] At the time of writing this article, the 2000 Watt society benchmarks are under revision. Most likely, the benchmarks will be substantially lowered to comply with the scientific findings of the IPCC 1.5°C special reports (Rogelj et al., 2018).

To further explore the issue of GHG investment, Figure 13 illustrates the temporal occurrence of GHG emissions across the building life cycle. The figure draws on the average values for embodied and operational GHG emissions as shown in Figure 10, partly reversing the normalization and transforming the values to the accumulated sum of embodied and operational GHG emissions across the life cycle. Embodied GHG emissions therein are distributed by allocating GHG emissions across different life cycle stages based on shares from the literature (Rasmussen et al., 2018), i.e. the production and construction process stage (64%); the use stage (maintenance and replacement) (22%); and the end-of-life stage (14%).

Figure 13 conceptually shows the accumulation of GHG emissions plotted at the time of occurrence on a year-by-year basis for 'New Standard' and 'New Advanced' buildings. In this exercise, all GHG emissions associated with the replacement of construction elements during the use stage are modelled as taking place in one single year, i.e., in year 25 after construction. In reality, both replacement activities and the related GHG emissions would occur at different discrete points in time during the use stage.

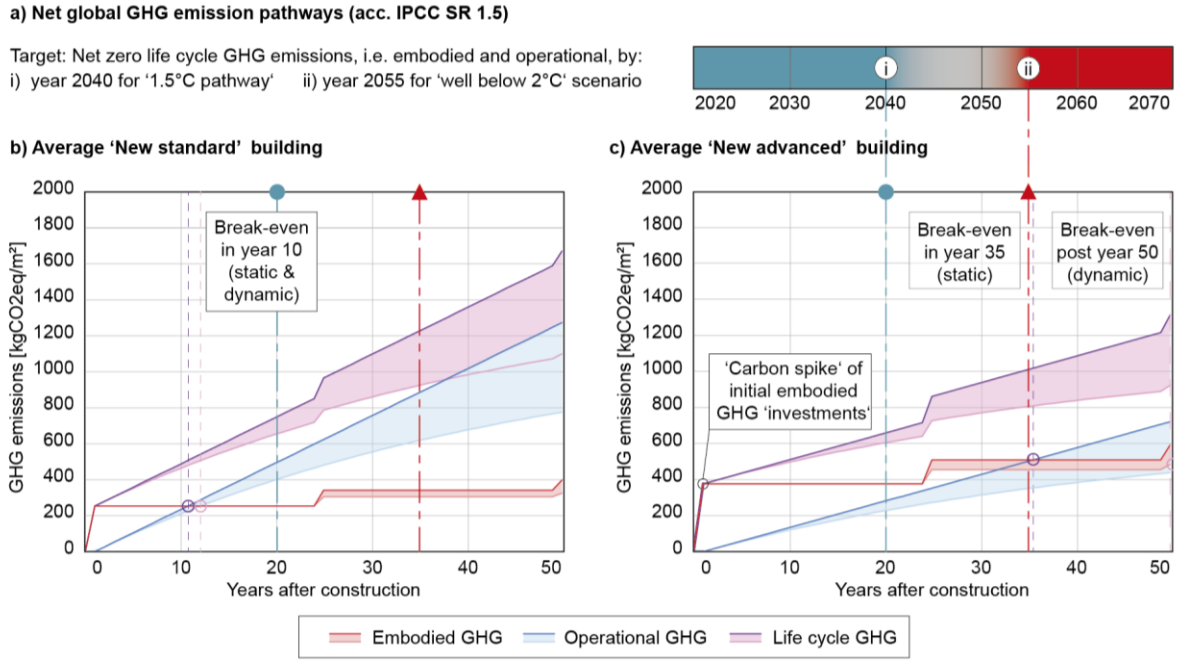


Figure 13: Temporal distribution of GHG emissions: (a) IPCC GHG emission reduction pathways (acc. (IPCC (Intergovernmental Panel on Climate Change), 2018b)) in relation to the (embodied and operational) GHG emissions across the life cycle of (b) 'New Standard' buildings and (c) 'New Advanced' buildings. Projections for future reduction of emission intensity (hatched areas) are based on a yearly improvement of 2% (acc. IEA (Abergel et al., 2018)).

The embodied 'carbon spike' occurring in the year of construction (plotted in year 1) relates to emissions from the production of building materials and the construction of the building. Following the findings presented in Figure 10, on average, this initial GHG investment for 'New Standard' buildings is 253 $kgCO_2eq/m^2$. For 'New Advanced' buildings, the initial investment is 377 $kgCO_2eq/m^2$ on average. Investigating the dataset in detail, the variety of this initial GHG investment for new standard or advanced buildings ranges from 103 to 423 $kgCO_2eq/m^2$ (1st to 3rd quartile) and surpasses 1250 $kgCO_2eq/m^2$ in extreme cases. The replacement of materials, when summed as one occurrence, generates an additional spike of GHG emissions during the use stage, in the magnitude of on average 87 $kgCO_2eq/m^2$ for 'New Standard' buildings and 132 $kgCO_2eq/m^2$ for 'New Advanced' buildings (based on today's GHG emissions of materials manufacture).

Operational GHG emissions occur on an annual basis, with amounts of 26 kg $kgCO_2eq/m^2a$ for 'New Standard' buildings and 15 $kgCO_2eq/m^2a$ for 'New Advanced' buildings. Assuming constant GHG emission values and plotting over the reference study period (50 years), the accumulating operational GHG emissions exceed the amount of embodied GHG emissions of 'New Standard' buildings after approximately 10 years of operation. For 'New Advanced' buildings, this break-even occurs only in year 35, i.e., after all GHG emissions from replacements have been taken into account. This 'static' approach towards modelling operational impacts can be considered the default procedure in building LCA. However, due to ambitions to increase renewable energy production, the annual change in energy intensity and related GHG emissions from the energy demand of buildings are expected to decrease. According to the International Energy Agency (IEA), global GHG intensity of energy production fell an average of 2.0% in the period 2014-2018 (International Energy Agency, 2019). Projecting that trend of intensity reduction, the actual relevance of GHG emissions from operational energy use will further decrease with time. This trend towards increased GHG emissions efficiency in production is expected to also lower the embodied impacts associated with the future replacement of building materials and the end-of-life treatment of construction materials. However, the figure shows that improvements to material production and end-of-life treatment are less relevant to the accumulated GHG emissions than is the reduction in operational GHG emissions.

When considering the expected GHG emission reduction of the energy mix in the future, the 'investment' of embodied GHG emissions due to building production is becoming the single most influential source of GHG emissions in the life cycle of buildings (as shown in Figure 13). In this case, the comparison of embodied versus operational GHG emissions in the life cycle of 'New Advanced' buildings reveals a ratio of approximately 1:1 on average, with embodied GHG emissions dominating the life cycle.

Furthermore, this analysis also showed that a 2% annual decrease in the GHG emissions intensity of grid energy (Abergel et al., 2018) will only bring about half the emission reductions needed for the net-zero target of 2050. Hence, this demands that the energy sector further accelerates the decarbonisation of energy provision to reach that target. Simultaneously, decarbonisation efforts related to building operation need to further reduce energy demand and GHG emissions from building operation in the future, down to 'near-zero'. The potential strategies for improving energy systems on different scales and through different technologies (e.g., district heating or combined heat and power (CHP) vs. electrification and use of heat pumps on a building level) have to be assessed on a case-by-case basis with regard to their economic and technical feasibility as well as their effectiveness in reducing GHG emissions and other environmental impacts (Eyre and Baruah, 2015; Quiggin and Buswell, 2016; Victor et al., 2018). In line with IPCC recommendations, this requires "*new construction to be fossil-free and near-zero energy by 2020"*, and *"an increased rate of energy refurbishment of existing buildings to 5% per annum in OECD countries"*(de Coninck et al., 2018). To achieve the required 'near-zero' energy performance for both new and existing buildings, additional embodied GHG investments in building materials and systems are necessary.

As these embodied GHG emissions are occurring at (or prior to) the time of construction, they are exceptionally relevant considering the need to decarbonise the global economy while respecting limited GHG emissions budgets. This situation emphasises the urgent need to assess and optimise the effectiveness of embodied GHG emissions invested in buildings.

In this paper, the term 'decarbonisation' is used to describe the process of reducing emissions of CO_2 and other GHGs, which is consistent with the wording used by, e.g., the IPCC. Because the GHG emissions reduction is achieved mainly through reduction of fossil fuel-based energy provision, the term 'defossilisation' is found more and more in contemporary discourse.

2.3.5. Limitations and methodological considerations

LCA results are heavily dependent on the methodological choices made by practitioners. Moreover, when applying the method to a complex and long-living system, i.e., an entire building, the number of crucial aspects and scenarios to be considered increases. In these cases, practitioners' preferences and idiosyncrasies, coupled with the peculiarities of the systems that compose a building and their interactions, play a significant role in the LCA's modelling design.

To collectively assess the findings of whole-building LCAs, one must identify certain archetypes that allow the case studies to be compartmentalised into groups. Here, as previously mentioned, the results were divided among others based on the type of function (office or residential), energy efficiency performance, building location and climate zone. Nevertheless, harmonizing the results within those groups was sometimes challenging. The obstacles faced were twofold, related either to varying building and use characteristics or to how the LCA was modelled. The former involves various specificities within a case study, including certain outstanding aspects: (i) the size of the building (number of stories and built area), (ii) the construction materials used (mainly those in the building's structure and envelope), (iv) the location of the building (due to related differences in, e.g., building requirements, climatic context, cultural norms), (v) the various technical systems used to provide cooling or heating, as well as (vi) socio-economic aspects and their influence on, e.g., operational energy use, as shown by (Besagni and Borgarello, 2018; Brounen et al., 2012; Filippini and Pachauri, 2004; Longhi, 2015). Even within one category, these factors affect life cycle impacts and can lead to divergent results.

Regarding methodological choices in LCA, a number of differences can arise and affect comparability. First, the scope of the assessment in terms of the life cycle stages considered greatly affects the outcome regarding environmental impacts. Although all the assessed papers covered (at least) the product stage (A1-A3 according to EN 15978) and the operational energy use (B6), papers that included additional stages were kept in the sample, and the level of data granularity within similar stages might have differed. Furthermore, the differences in the scope of the assessment (i.e., including building components and life cycle stages covered) are critical for comparison. Hence, the extracted LCA results could have been influenced by the varying scopes of the LCA studies performed, which are seldom reported in detail (e.g., by publishing the Life Cycle Inventory (LCI)). Even in cases of similar assessment scopes, it is still likely to have variations in LCA results due to the application of different data sources (Lasvaux et al., 2015; Takano et al., 2014a). There is a diverse range of sources (and providers) of LCI data for common building products and processes, and these sources might not always use the same cut-off rules, allocation principles and other underlying assumptions. This diversity results in different emission factors for the same category of building material, product and component. As some authors suggest, data quality indicators can be helpful in this case (Anand and Amor, 2017). In any case, these differences were documented, and the related results went through the same harmonization process as explained in the methodology chapter.

Another limitation and important aspect of the analysis of published LCA studies is their general lack of transparency. In many cases, basic methodological assumptions were omitted and at times impossible to trace within the publications. The obscurity of key aspects of the LCA leads to superficial results, preventing aggregated analyses that can eventually feed decision making (Ruschi Mendes Saade et al., 2018). Thus, comparability was hindered, and for that reason, some papers had to be excluded from the review. LCA studies, even while allowing diverging scopes and some freedom for interpretation, are robust enough to set benchmarks and scientifically grounded public policies regarding the required performance of the built environment if certain key requirements are followed. To properly implement this approach, however, the global scientific community needs harmonised and clear guidelines on how to perform and document whole-building LCAs; such guidelines are long overdue. Proposals for

harmonizing the LCA of buildings on an international level can be based on existing standards, e.g., the ISO 14000 series or European EN 15978, and are also being developed, for example, within the ongoing activities of IEA EBC Annex 72 (IEA EBC, 2017a).

2.4. Conclusions and outlook

The study presented in this paper applied a systematic approach to identifying and analysing GHG emissions in the building life cycle. The analysis was based on the systematic review of more than 650 individual building LCA studies, with a final sample of 269 cases fit for evaluation.

The results show that the reduction in life cycle-related GHG emissions is a global trend for buildings that have adopted new energy performance standards for building operation. At the same time, the contribution of embodied GHG emissions increases up to and beyond a ratio of 1:1 (embodied to operational) when we consider a 50-year period. The relevance of embodied GHG emissions further increases when anticipating future reductions in GHG emissions from building operations. This projection assumes current policies, i.e., 'net-zero' GHG emissions from operational energy use due to renewable energy carriers and no (substantial) reduction in embodied GHG emissions (i.e., in construction material manufacture). The investigation of the temporal distribution of GHG emissions revealed the importance of the initial 'carbon spike' from the production of building materials and systems. The initial investment of GHG emissions embodied in the investigated 'New advanced' buildings dominates the GHG emissions released in the timeframe relevant for decarbonisation. This result highlights the need to address and reduce operational as well as embodied impacts in the context of limited GHG budgets. It was further shown that existing life cycle-related benchmarks (for example, the Swiss SIA 2040) can be achieved with different strategies, i.e., high or low embodied GHG emissions, opening the discussion of the effectiveness of 'GHG investments'.

In conclusion, the results of this study highlight the need to address and further reduce the life cycle related GHG emissions of buildings by optimizing embodied emission investments for new construction and promoting 'carbon-effective' investments for the refurbishment of existing buildings. Considering the IPCC-backed call for action towards a global net-zero GHG emissions economy by 2040, profound changes are needed in the construction and use of buildings. First, as an integrated part of the transition in the energy sector, energy systems and technologies implemented for new and refurbished buildings today have to support fossil-free, zero-emission building operation by 2040. Second, attention must be paid to reducing the embodied GHG emissions invested in buildings to net-zero emissions, i.e., industries that produce construction materials need to offer net-zero GHG emission materials by 2040. To support effective climate-change mitigation, embodied GHG missions invested until then must be 'carbon-effective' and respect limited carbon budgets. In this context, aspects of sufficiency and optimization of occupational density as well as other potential strategies for reducing the demands of new construction activity deserve further attention – after all, reducing the area of square metres built is still the most effective way to reduce both embodied and operational GHG emissions. This crucial transition of the building and construction sector demands a notable and cross-sectoral effort. It requires the relevant (construction) industries to decarbonise their production to achieve net-zero embodied emissions for future building construction. Furthermore, building owners and users are urgently challenged to implement activities and practices that further reduce GHG emissions for building operation and to move towards net-zero emissions. To support this transition in building construction and operation, a clear policy narrative (e.g., introduction of a roadmap and/or regulations) is an important lever with which to enable the concerted action of all industries and actors who influence GHG emissions in the life cycle of buildings.



3. TOWARDS BENCHMARKING EMBODIED CARBON OF BUILDINGS IN EUROPE

Bibliographic data

Title: Benchmarking whole life embodied carbon of buildings at scale: data-driven baseline analysis for buildings across Europe.

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Highlights

- Whole life embodied carbon of new buildings in Europe is found to be on average around 600 $kgCO_2e$ per newly built m2, even reaching beyond 1.200 $kgCO_2e/m^2$, in extreme cases.
- Most of the whole life embodied carbon - around 2/3, or close to 400 $kgCO_2e$ on average - is emitted upfront, i.e., during the building material production and construction process (life cycle stages A1-A5).
- Substantial differences between conclusions from per-m^2 and per-capita values hint at the importance of sufficiency-oriented building design and use, flexible typologies and high-density occupational patterns.
- Substantial data gaps across Europe are identified and should be closed through regulatory frameworks regarding the general documentation of building LCA performance, supplemented with a development of dedicated building archetypes models tailored to national contexts.
- We recommend moving beyond ad-hoc data compilation and analysis, towards a permanent, openly accessible, central database on whole life carbon performance of EU buildings.

Author contributions

Martin Röck: Conceptualization; Methodology; Software; Formal analysis; Investigation; Data Curation; Writing (Original draft, review and editing); Visualization; Project administration.

Andreas Sørensen: Software; Formal analysis; Investigation; Data Curation; Visualization.

Buket Tozan: Formal analysis; Data curation.

Harpa Birgisdottir: Conceptualization; Supervision.

Karen Allacker: Writing (Review and editing); Supervision.

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Data availability

The case study data, documentation templates and scripts used for processing are available via (Röck and Sørensen, 2022). A detailed data descriptor is presented in the successive chapter concerning the data of (Röck et al., 2020c) and the data of this study, presented in the following.

The following chapter presents a draft manuscript for submission to a peer-reviewed journal.

Abstract

Whole life embodied carbon is gaining increasing attention from decision makers involved in the procurement, design, and operation of buildings. As previous meta-studies have shown, the embodied carbon emissions of new building construction dominate life cycle emissions across several decades and reducing them is critical to effectively mitigate the climate impacts of building construction and operation.

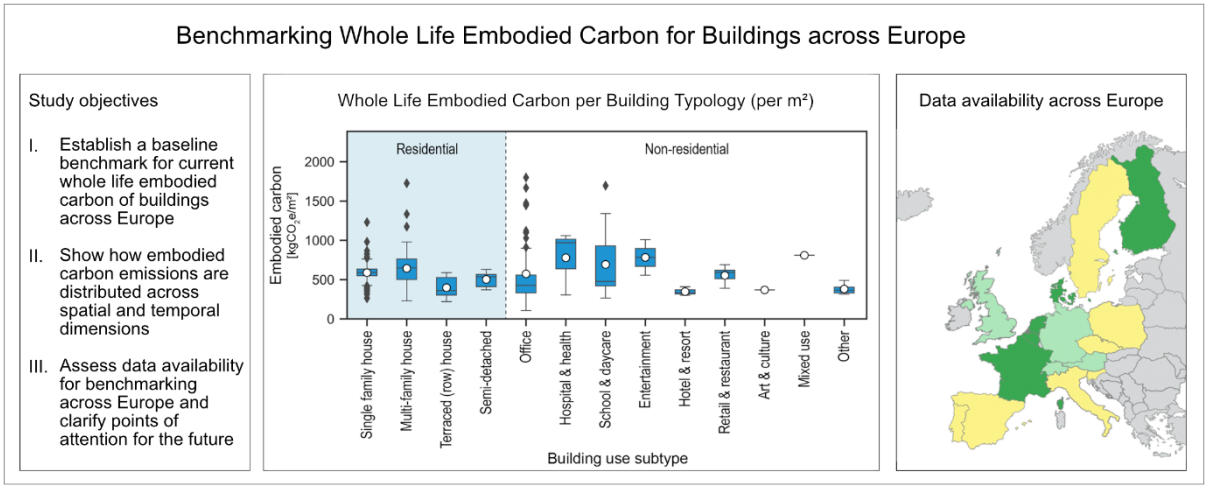
In this article we address this need by presenting the findings from a whole life embodied carbon meta-analysis based on 744 case studies, indicative for diverse building typologies and different national contexts across Europe. The whole life embodied carbon results are used to inform the development of benchmarks for the baseline of whole life embodied carbon of new buildings constructed around 2020. Furthermore, we provide insights into the lessons learned from the collection, processing and analysis of these case studies from different data partners across Europe.

This article presents benchmarks for the baseline of whole life embodied carbon of common building typologies as assessed in different national contexts across Europe. This study includes a critical analysis of the contributor behind whole life embodied carbon in terms of life cycle stages and building elements as well as construction methods and main structural materials.

Keywords

Whole Life Carbon; Embodied Carbon; Life Cycle Assessment; Buildings; Construction; Life Cycle; Benchmarks; Baseline; Sufficiency.

Graphical abstract



3.1. Introduction

3.1.1. Embodied carbon benchmarks for buildings

As the effects of the accelerating climate and ecological crises are becoming evident, the need for transformational climate action is rising. Based on decades of climate science and driven by the increasing pressure from civil society, policymakers in the European Union (EU) and beyond are making bold claims to reduce greenhouse gas (GHG) emissions for their respective regions and activities. Building construction and operation are amongst the most significant activities driving current GHG emissions, representing 37% of global GHG emissions (Global Alliance for Buildings and Construction (GABC) and United Nations Environment Programme (UNEP), 2020). At the same time, increasing the energy efficiency of both existing and new buildings, as well as shifting to sustainable construction practices, are major opportunities for decarbonising the economy in the coming decades.

While past efforts have mostly focused on increasing energy efficiency in building operation, recent research on GHG emissions across the full life cycle of buildings highlights the increasing importance of embodied GHG emissions, in relation to producing and processing construction materials. "Embodied carbon" refers to all the GHG emissions associated with materials and construction processes throughout the whole life cycle of a building. A recent global meta-study building's whole life and embodied carbon (Röck et al., 2020c) investigated this matter, based on the analysis of hundreds of building life cycle assessment (LCA) studies. The meta-study reveals a trend of increased embodied GHG emissions for new buildings (Figure 3) and highlights the relevance of understanding and reducing the embodied GHG emissions in buildings in order to enable effective climate change mitigation: "While the average share of embodied GHG emissions from buildings following current energy performance regulations is approximately 20–25% of life cycle GHG emissions, this figure escalates to 45–50% for highly energy-efficient buildings and surpasses 90% in extreme cases. Furthermore, this study analyses GHG emissions at time of occurrence, highlighting the 'carbon spike' from building production. […] Considering global GHG reduction targets, these results emphasise the urgent need to reduce GHG emissions of buildings by optimising both operational and embodied impacts." (Röck et al., 2020c)

These embodied emissions in buildings are rarely addressed in policy strategies and instruments. However, if embodied carbon is not included in building decarbonisation targets, a failure to meet global decarbonisation targets is highly likely. This is because the total climate impact of buildings would remain only partly addressed. Thus, the need and potential for reducing embodied emissions require attention and alignment as part of European and global efforts to combat climate change. Setting a robust baseline for embodied emissions at the building level can provide relevant guidance for policymakers and the building industry.

3.1.2. Objective and research questions

The objective of this study is to develop the foundations of such a performance system for new buildings across Europe. This article presents a baseline of current embodied carbon levels in new buildings, as well as review of data availability and quality to quantify embodied carbon of buildings. The study synthesises insights from pioneering countries and institutions across Europe to inform GHG emission reduction policies within instruments such as the Energy Performance of Buildings Directive, the Taxonomy for Sustainable Activities and the EU Climate Transition Benchmark Regulation. Additionally, as life cycle perspective of buildings is receiving increased attention across decision makers in the building and real estate field, the study seeks to inform the current debate involving policymakers and industry alike and to stimulate the development and application of benchmarks for

embodied carbon in the EU and beyond. The study objectives are pursued by seeking answers to three main research questions:

I. What is the whole life carbon baseline for new buildings across Europe?
II. How are the embodied carbon emissions distributed across space and time?
III. What is the state of data availability of whole life carbon data across Europe and which data needs should be addressed in future?

3.2. Methods and materials

3.2.1. Methodological approach

This article applies an approach of systematic mapping with subsequent meta-analysis (Haddaway et al., 2020; James et al., 2016; Nakagawa et al., 2020) along five main steps:

1. Data availability across Europe is screened to identify partners in five frontrunning countries able to provide about 50 case studies or more.
2. Data are collected based on a standardised reporting template for systematically capturing information on building design characteristics, whole life carbon assessment methods, as well as assessment results, to enable transparency and support comparability, as much as possible.
3. Data are pre-processed and harmonised for joint analysis of the case studies per country as well as across countries, for example to provide understanding of results for specific building types.
4. Indicative benchmarks are derived for different building typologies, structural systems and materials, as well as for contribution of life cycle stages and building parts, respectively.
5. Finally, the influence of assessment methods is investigated for informing interpretation and recommendations regarding robustness of indicative results within and across countries.

3.2.2. Data screening

Data screening set the basis for analysing embodied carbon of new buildings in the European construction industry with the goal of identifying at least five countries where data partners would be able to supply a suitable sample of building LCA data. The study team defined a minimum quantity threshold of 50 cases per country to gain a preliminary understanding of the data availability and to facilitate meaningful statistical analysis based on a reasonable number of cases, including various types of building use, structural systems, and materialization. Furthermore, dataset quality had to be ensured through reasonably consistent and transparent data, i.e., information on data origin (who conducted the assessment?) and assessment methods (under which methodological conditions were results obtained?).

During the screening phase data was requested and in part retrieved from national partners various European countries, including for Austria, Germany, Switzerland and the United Kingdom. Furthermore, potentially suitable data was identified and retrieved from existing studies and databases on embodied and whole life cycle carbon, such as: The Carbon Leadership Forum (CLF) Embodied Carbon Benchmark Study (Carbon Leadership Forum (CLF), 2017); the Royal Institution of Chartered Surveyors' (RICS) Building Carbon Database (Royal Institution of Chartered Surveyors (RICS), 2020); and the building LCA meta-study data by (Röck et al., 2020c).

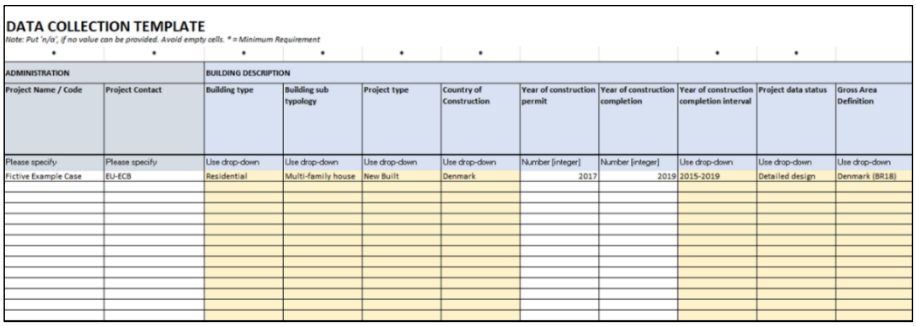
Table 5: Main five pilot countries and number of cases per building use type

Building use type	**Member State**					**Total**
	BE	**DK**	**FI**	**FR**	**NL**	**EU-ECB**
Non-residential	-	34	31	27	18	**110**
Residential	105	38	28	434	29	**634**
Total	**105**	**72**	**59**	**461**	**47**	**744**

The data screening process resulted in five countries being identified for which sufficient data could be used, namely: Belgium, Denmark, Finland, France and the Netherlands. The final dataset (Table 5) combining data from these five countries is in the following termed the EU embodied carbon of buildings (EU-ECB) dataset, the composition of which is further elaborated in the results of data screening chapter.

3.2.3. Data collection

Data collection departed from the definition of categories and attributes found relevant to be collected and analysed by the authors of the meta-study of IEA EBC Annex 72 (R. Frischknecht et al., 2019a; Röck et al., 2020c). To facilitate data collection along predefined categories and parameters, and ensure consistency of units and data types, a data collection template (DCT) was developed and provided to data partners for structured data collection (Figure 14).



DATA COLLECTION TEMPLATE

*Note: Put 'n/a', if no value can be provided. Avoid empty cells. * = Minimum Requirement*

ADMINISTRATION		BUILDING DESCRIPTION								
Project Name / Code	Project Contact	Building type	Building sub typology	Project type	Country of Construction	Year of construction permit	Year of construction completion	Year of construction completion interval	Project data status	Gross Area Definition
Please specify	Please specify	Use drop-down	Use drop-down	Use drop-down	Use drop-down	Number [integer]	Number [integer]	Use drop-down	Use drop-down	Use drop-down
Fictive Example Case	EU-ECB	Residential	Multi-family house	New Built	Denmark	2017	2019	2015-2019	Detailed design	Denmark (BR18)

Figure 14: Exemplary view of the data collection template (DCT) spreadsheet form used for data collection.

To investigate the timing of emissions across the life cycle, this study documented emissions per the life cycle stage they occur in according to EN 15978/EN 15643. Embodied carbon emissions are thus broken down into the life cycle stages they occur in, i.e.: Production (A1-3), construction process (A4-5), in-use embodied carbon occurring for cleaning, maintenance, and replacement (B1-4), and end-of-life for deconstruction process and transport (C1-2), as well as waste processing and disposal (C3-4). We can determine the quantity of carbon emissions that are produced "upfront" during the manufacture and construction of new buildings using this perspective on embodied carbon emissions, i.e. A1-3 and A4-5, respectively, at specific points during the use phase (B1-4) or at the end-of-life (C1-2, C3-4). We furthermore gathered data on the number of users in each building to determine the embodied carbon baseline per capita to further investigate the impact of various building uses and the associated differences in occupational density. The number of users for residential buildings was estimated based on the number of beds or 'number of bedrooms +1' (Allacker, 2010). In non-residential buildings, the number of working desks ('office buildings'), patient beds ('hospitals'), and students or children cared for ('schools and daycare') were used to estimate the number of users, respectively.

A comprehensive list of data attributes applied in the primary data collection in this study, as well as recommendations on the prioritisation of attributes in future data collection efforts is provided in chapter 4 (Open database on embodied and whole life carbon of buildings).

3.2.4. Data processing

The use of existing LCA data on building cases from different countries requires consideration of differences in the data, e.g., variations in assessment methods and scope of studies, as well as limitations in data sharing due to confidentiality concerns. Therefore, substantial pre-processing and harmonization steps were implemented to prepare the data for a consistent analysis.

To process and analyse the data obtained through the data collection from national partners and other data sources, a workflow was developed utilizing Python scripts for data processing, to prepare and export the combined and cleaned EU-ECB datasets as well as for analysis of baselines and patterns. In some cases, databases have been received in their native format instead of the developed DCT. In such cases the data is pre-processed individually using tailormade Python scripts to transform the data and fit it to the format of the DCT. The pre-processing steps include removing rows with invalid data, translating and regrouping data into common formats and categories from the DCT and collecting all data sources into one combined dataset.

Embodied emission values are harmonised to a common reference study period (RSP) of 50 years per m² gross floor area (GFA). For the data collected via the DCT, we already gathered data per m² GFA and per year ($kgCO_2e/m^2GFA/a$) and based on the RSP of the respective case. Hence, the harmonisation of net floor area (NFA) to GFA is not required. However, harmonisation of the reference study periods is still needed to improve comparability. The approach applied in this study for harmonizing to a common RSP, builds on the disaggregated emission data collected per life cycle stage. Embodied carbon (EC) values were harmonised to a common reference study period (RSP) of 50 years per m² gross floor area (GFA). For the data collected via the data collection template, emission values should be per m² GFA and per year ($kgCO_2e/m^2_{GFA}/a$), based on the RSP of the respective case. Hence, the harmonization of net floor area (NFA) to GFA is not required. However, harmonization of the RSPs is still needed to improve comparability. The approach for harmonizing EC values, builds on the disaggregated emission data per life cycle stage. The formulas applied for harmonization of emission values to a common reference study period (RSP) are:

$$(1) \quad GHG_{t,\,h} = GHG_{a,o} * RSP_o$$
$$(2) \quad GHG_{t,\,h} = GHG_{a,o} * RSP_h$$
$$(3) \quad GHG_{a,\,h} = GHG_{t,h} / RSP_h$$

where,

- GHG = GHG emission values
- RSP = Reference study period
- a = annualised
- h = harmonised
- o = original
- t = total

This harmonization approach advances on the approach applied in (Röck et al., 2020c) with regards to consideration of differentiated scaling factors applied to non-RSP dependent emission values for life cycle stages A/C versus RSP-dependent use phase related emissions of life cycle stage B.

3.3. Whole life embodied carbon meta-analysis

3.3.1. Data availability across Europe

Relevant stakeholders across Europe were contacted and questioned about the status of building LCA methodologies, tools, and data, as well as availability of building-level benchmarks and targets, to identify possible collaborators and data sources for the whole life embodied carbon analysis.

Figure 15 presents a summary of the results from the country screening and data collection across European countries, highlighting those countries in dark green, where national data partners were able to provide at least 50 case studies on whole life embodied carbon of different buildings. The figure illustrates that, within the countries included in the study, samples of sufficient size and quality could

only be collected in Belgium, Denmark, Finland, France and the Netherlands. In four additional countries, some data could be identified, but it did not pass the threshold of 50 cases. The indicative baseline for EU buildings defined in this article are based on the building LCA data from these five countries. Table 1 summarises the number of cases obtained for each of these five countries.

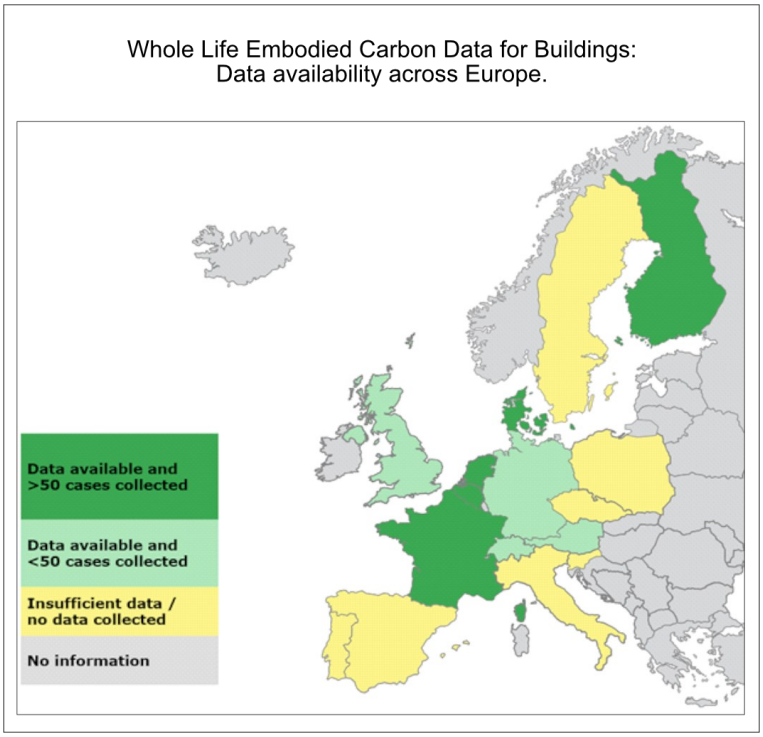


Figure 15: Whole Life Embodied Carbon Data for Buildings - Data availability across Europe.

The findings from data screening reveal substantial variation in building LCA/WLC data availability, which limited a broader coverage of countries to assess current embodied carbon levels across Europe. This impacted the assessment of the baseline, as well as the determination of indicative benchmarks required to guide the reduction of said emissions. The variation in the data landscape and the need for this evidence base highlights the urgency for expanding and improving data collection and suggests that lessons could be learnt from the Member States included in this study at the forefront of data collection.

3.3.2. Whole Life Embodied Carbon

Benchmarks by building typology - per m²

We first examine the whole life embodied carbon for various types of building use each of the five countries separately, as well as a combined value, which gives a summary of values discovered across those five countries. Residential buildings embodied carbon (EC) values range from roughly 400 to 800 $kgCO_2e/m^2$, with a mean value of about 600 $kgCO_2e/m^2$. We see a wider range of EC values for non-residential structures, with mean values averaging around 600 $kgCO_2e/m^2$ and values ranging from about 100 to 1200 $kgCO_2e/m^2$.

Figure 16 presents the whole life cycle embodied carbon for the various building typologies, based on subtypes of building use (i.e., further refining residential and non-residential typologies, respectively). The first four horizontal axis categories represent residential building types. The highest per-m^2 values are found in multi-family houses, with an average of around 700 $kgCO_2e/m^2$. Terraced houses have the lowest per-m^2 values, with average values of around 350 $kgCO_2e/m^2$. The other horizontal axis categories represent non-residential building types. The highest per-m2 values are observed for 'hospital and health' and 'sport and entertainment' buildings, with average EC values of around 1.000 $kgCO_2e/m^2$

and 800 $kgCO_2e/m^2$, respectively. 'Office' buildings have an average EC value of around 450 $kgCO_2e/m^2$, with a wide range of EC values and multiple outliers. Furthermore, it is noted that "school and daycare" structures exhibit a wide range and high values, despite having an average value of only about 500 $kgCO_2e/m^2$.

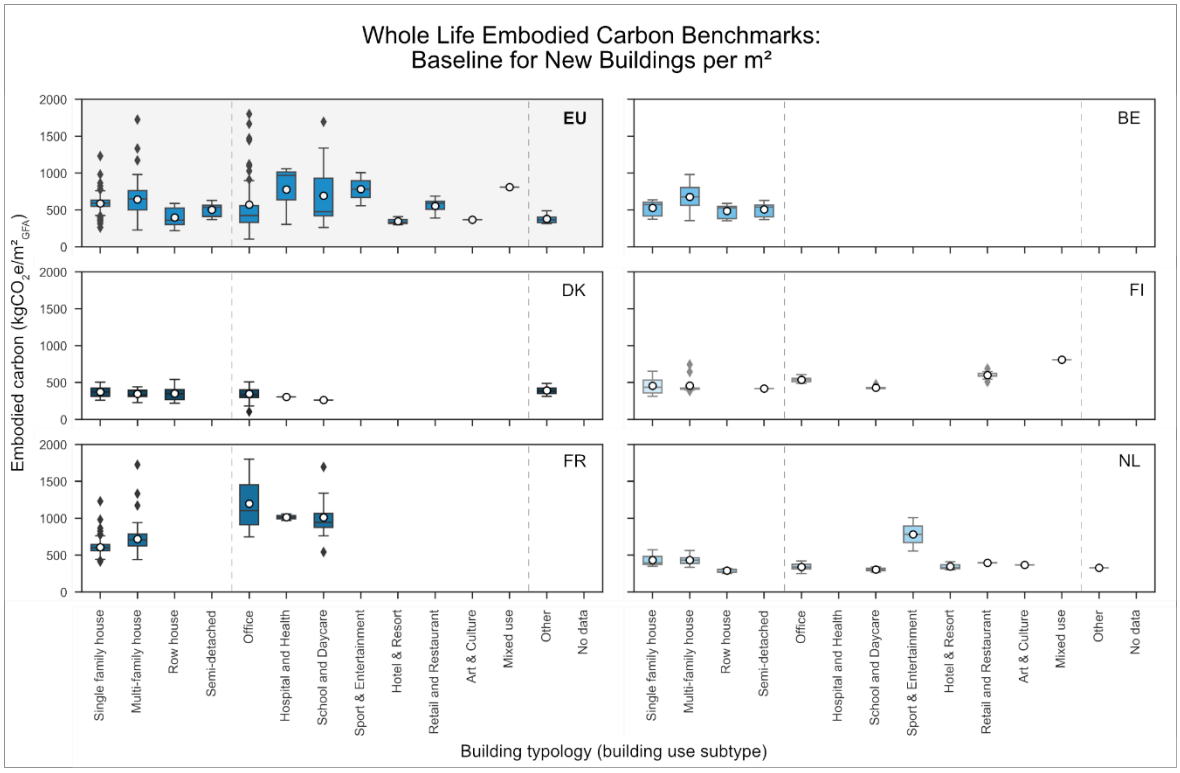


Figure 16: Harmonised embodied carbon per m² by building use subtype across the whole dataset (EU-ECB), as well as for subsets of data from individual countries (BE - Belgium; DK – Denmark; FI – Finland; FR – France; NL – Netherlands)

Benchmarks by building typology - per capita (by number of users)

The analysis of whole life embodied carbon per-capita values for different building typologies reveals numerous important observations and differences to the per-m^2 analysis – as presented in Figure 17. On average, single-family houses show to cause the most embodied carbon per capita across all (residential) building types. Multi-family homes have the lowest per capita EC baseline of residential buildings, with an average of about 23 tCO_2e/cap. The range of EC values per capita for both hints at the fact that the number of users in the individual house/apartment has a substantial influence on this type of metric. Figure 17 further presents the average per-capita value for non-residential buildings, such as office buildings (roughly 18 tCO_2e/cap); hospital and healthcare buildings (about 33 tCO_2e/cap); and for school and daycare buildings (very low at about 7 tCO_2e/cap). Schools and daycare facilities hence show the lowest per capita emissions, likely due to the higher occupational density (users per m^2) when compared to other non-residential or residential building types. Because of difficulties in producing reliable estimates of the number of users for various buildings, data on per capita values for non-residential buildings are only available for a very small number of subtypes.

Benchmarks by structural system and material

Figure 18 presents whole life embodied carbon per m² for various building structures and material types grouping results based on the combined specification of the type of structural system (massive, frame) and primary structural material (steel, concrete, brick, or wood), respectively. All major choices exhibit comparable values, with massive concrete structures having the greatest average value (about 700 $kgCO_2e$/m2) and the widest spread (between around 250 and 900 $kgCO_2e$/m2, with outliers surpassing

1850 $kgCO_2e/m2$). Massive brick cases show a range of outliers over the whiskers (1.5*IQR), up to 1700 $kgCO_2e/m2$, with an average of about 650 $kgCO_2e/m2$. Values for large-scale wood structures exhibit minimal volatility, with a reliable average of about 600 $kgCO_2e/m2$. Figure 18 demonstrates the wide variety for concrete frame buildings, which can range from 400 to 1200 $kgCO_2e/m2$, with 600 $kgCO_2e/m2$ being the norm. Frame wood buildings have the lowest embodied carbon values per m2, averaging 450 $kgCO_2e/m2$ and ranging from 300 to 800 $kgCO_2e/m2$. Surprisingly, hybrid concrete/wood frame construction cases exhibit an average $CO_2e/m2$ value of roughly 700 kg, equivalent to massive concrete. Similar to hybrid concrete/wood frame structure and substantial concrete cases, the average value for steel frame structure cases is around 700 $kgCO_2e/m2$. Cases that were difficult to distinguish because of missing data were labelled "other" or "no data" and do not deviate from the usual range of values seen in the well-known structural and material classes.

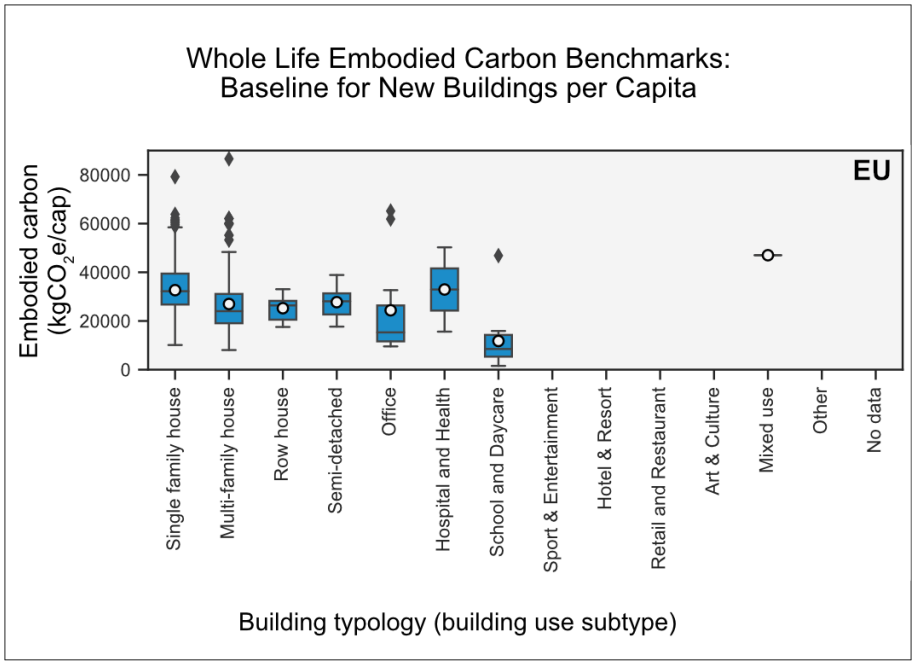


Figure 17: Harmonised embodied carbon per capita by building use subtype across the whole dataset (EU-ECB)

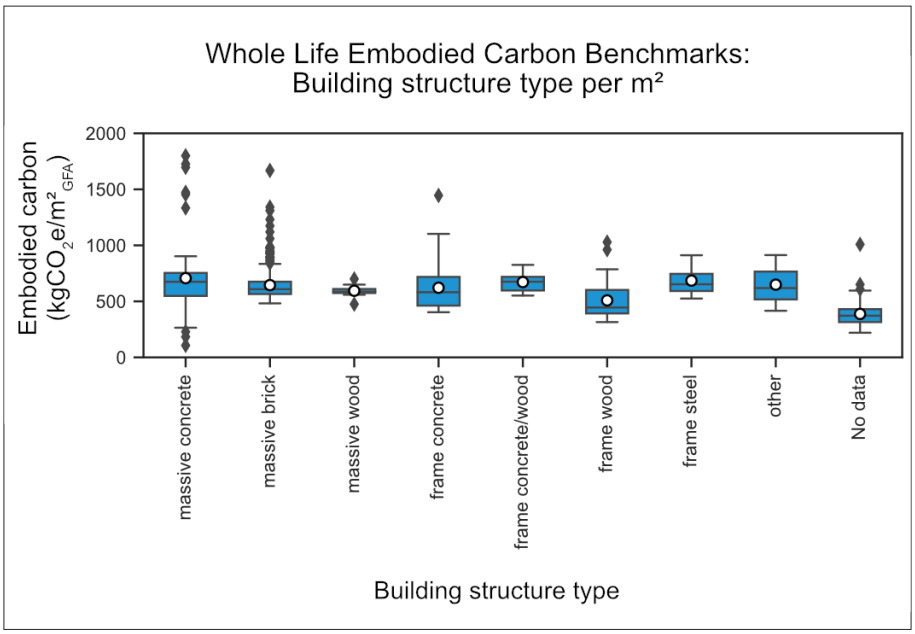


Figure 18: Harmonised embodied carbon per m² by type of building structure based on the EU-ECB dataset.

The analysis reveals that, when compared to massive structures, frame structures alone do not necessarily result in lower average embodied carbon values. With average values between 100 and 200 $kgCO_2e/m2$ lower than alternative material options for massive and frame cases, respectively, cases employing wood as their primary structural material result in the lowest values for each type of structural system. Thus, wood frame cases are shown to have the lowest average embodied carbon values. Further analyses for different types of structure and materials and for cases from different countries are available in the project documentation reports (Röck et al., 2022c).

3.3.3. Whole Life Embodied Carbon Hotspots

Benchmark contribution of life cycle stages

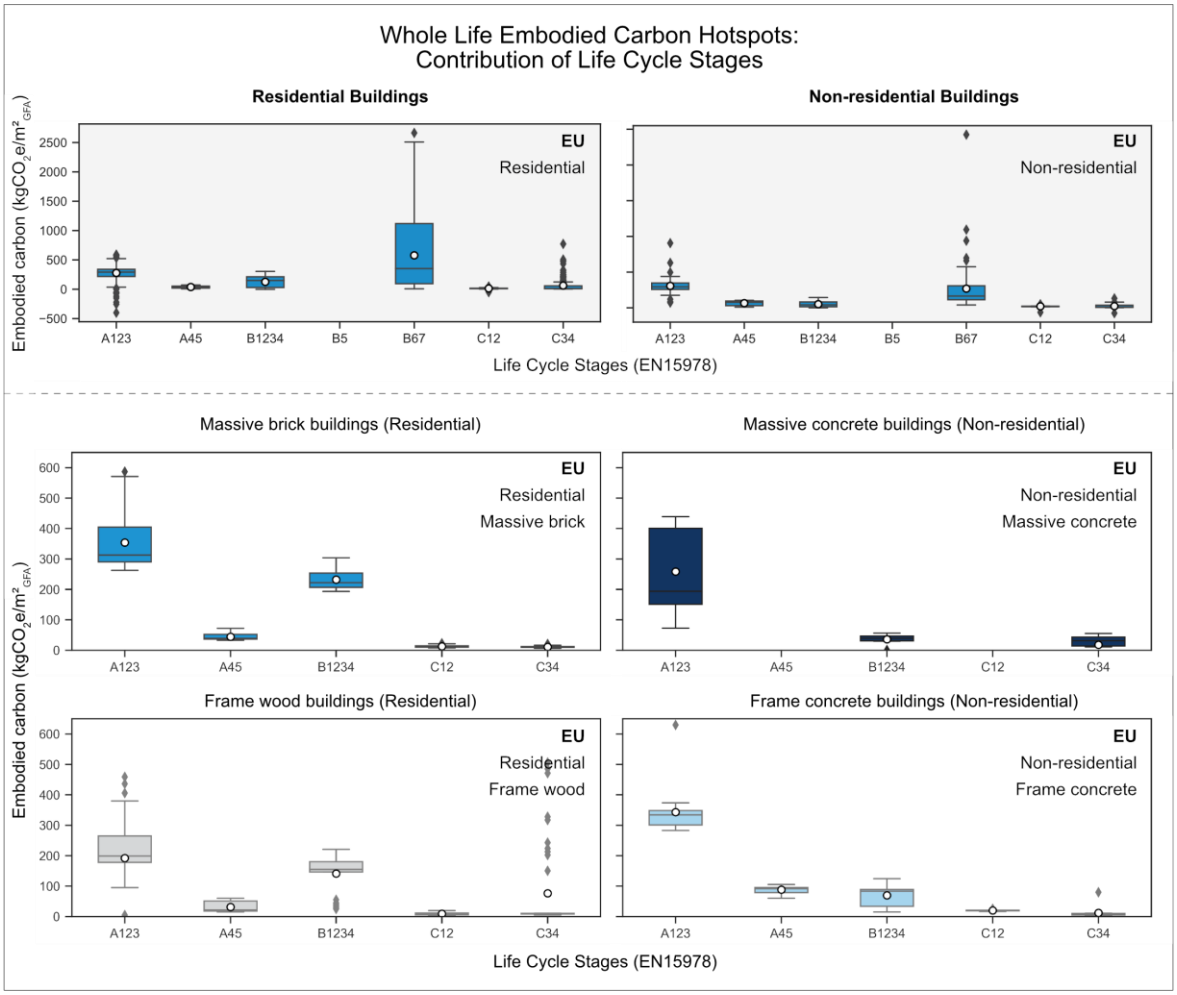


Figure 19: Whole Life Embodied Carbon Hotspots: Contribution of Life Cycle Stages to results for residential and non-residential buildings, respectively, as well as for selected types of structural systems and materials. Showing results for the combined EU-ECB dataset with data from all five countries.

Figure 19 presents the whole life embodied carbon contributions from different life cycle stages and clearly demonstrates the overarching importance of the production stage (A1-3), responsible for most to of the life cycle related embodied carbon emissions. The production stage (A1-3) contribution shows a mean value of roughly 300 $kgCO_2e/m2$ and a range of approximately 70 to 520 $kgCO_2e/m2$, with outliers going even higher. The second largest proportion of embodied carbon emissions occur during the usage phase in relation to building component and system repair and replacement (B1-4), with a mean value of roughly 120 $kgCO_2e/m2$, which represents the total of emissions from cleaning, maintenance, and replacement operations occurring during a 50-year reference study period. Similar to

emissions from the production phase (A1-3), embodied carbon emissions from the use phase (B1-4) exhibit a wide range of values between 0 and 350 $kgCO_2e/m2$, which is most likely due to factors like the type of building use, the structural system and material, component, and system choices, the type and quantity of BIPV, as well as climate and weather conditions as a cause of the aging process. It is also important to note the differences in the study's focus when it comes to the specific life cycle modules that are taken into account during the usage stage, i.e., not all studies include all use stage modules (B1-4), with features like cleaning or maintenance typically being left out. The embodied carbon emissions from the consumption stage (B1-4) can, in rare circumstances, exceed the average amount seen during the production stage (A1-3). The remaining life cycle stages only make a small dent in the total amount of carbon emissions. The stage of the construction process (A4-5) displays a mean value of around 40 $kgCO_2e/m2$. Deconstruction and transport (C1-2) for the end-of-life stage reveals a mean value for emissions of less than 20 $kgCO_2e/m2$, while waste processing and disposal (C3-4) has a mean value for emissions of roughly 60 $kgCO_2e/m2$. The significant number of outliers seen in the latter (C3-4) could represent the impact of various end-of-life scenarios as well as potential methodological variations in modelling these processes. Table 6 offers a summary of the average absolute and relative contributions of life cycle stages.

Benchmark contribution of building parts

In addition to being interested in the temporal dimension, i.e., the "when" (in which life cycle stages) of embodied carbon emissions, we also want to understand the spatial distribution, i.e., "where" the major contributors are in terms of the contribution of major building components. The embodied carbon per m^2_{GFA} for various building components is shown in Figure 20.

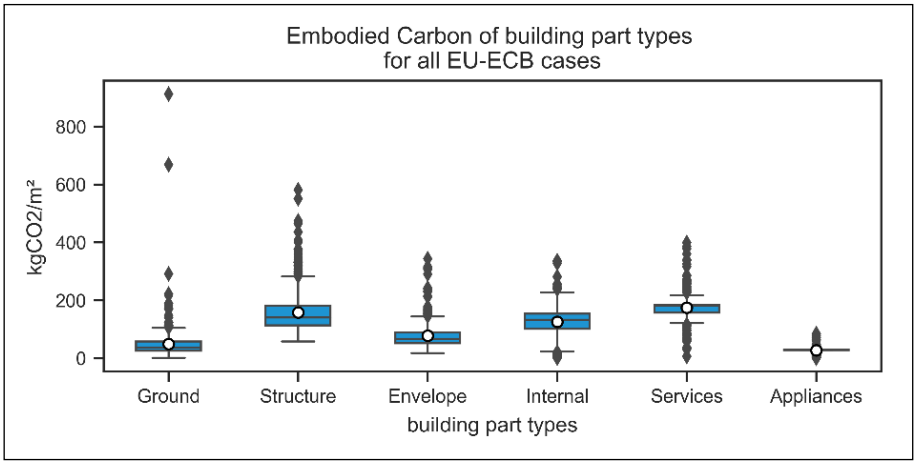


Figure 20: Whole life embodied carbon contributions per m² GFA for different building parts (Results based on cases from France/CSTB only due to insufficient level of detail reported for other cases)

Figure 20 displays the embodied carbon per square meter for several construction component groups (Ground, Load-bearing structure, Envelope, Internal, Services and Appliances), which are further elaborated in the data descriptor appended to this chapter. It demonstrates that, on average, the technical services (such as heating, cooling, domestic hot water, and sewage systems) account for the majority of the life cycle embodied carbon emissions, with a mean value of about 200 $kgCO_2e/m2$ and a range of 170 to 230 $kgCO_2e/m2$. Major contributions are also seen from internal elements such as partition walls, floor and wall finish, with a mean value of about 150 $kgCO_2e/m2$ and a range of 30 to 250 $kgCO_2e/m2$, as well as the load-bearing structure (such as structural frame, walls, and floors), with a mean value of about 170 $kgCO_2e/m2$ and a range of 50 to 320 $kgCO_2e/m2$. The core ranges from 20 to 170 $kgCO_2e/m2$, with the envelope contributing roughly 90 $kgCO_2e/m2$ (external insulation, windows, etc.). The average contribution of ground-related building components, such as foundations and basements,

is about 50 $kgCO_2e/m2$, with a range of nearly 0 to 120 $kgCO_2e/m2$. Appliances (such as laundry machines and kitchen equipment) constantly produce roughly 40 $kgCO_2e/m2$. Table 7 shows the mean contribution of different building parts to full life cycle embodied carbon in both absolute and relative terms.

Important to note is that this contribution analysis is based on the data obtained from France, where proxy values are being used to close data gaps in case of missing information on certain buildings parts, such as technical systems and appliances. These proxies on purpose over-estimate the contribution of said building parts to create an incentive for explicitly including the elements in the detailed assessment.

Table 6: Mean contribution to full life cycle embodied carbon [$kgCO_2e/m^2$] from different life cycle stages, based on EU-ECB baseline (Röck et al., 2022c).

	Production stage	**Construction process**	**Use stage**	**End of life stage**	
	A1-3	**A4-5**	**B1-4**	**C1-2**	**C3-4**
Absolute (mean)	300	40	120	20	60
Relative (mean)	56%	7%	22%	4%	11%

Table 7: Mean contribution to life cycle embodied carbon emissions [$kgCO_2e/m^2$] from different building parts

	Ground	**Load-bearing structure**	**Envelope**	**Internal**	**Services**	**Appliances**
Absolute (mean)	50	170	110	150	190	40
Relative (mean)	7%	24%	15%	21%	27%	6%

3.4. Discussion

3.4.1. Variation in data samples from different countries

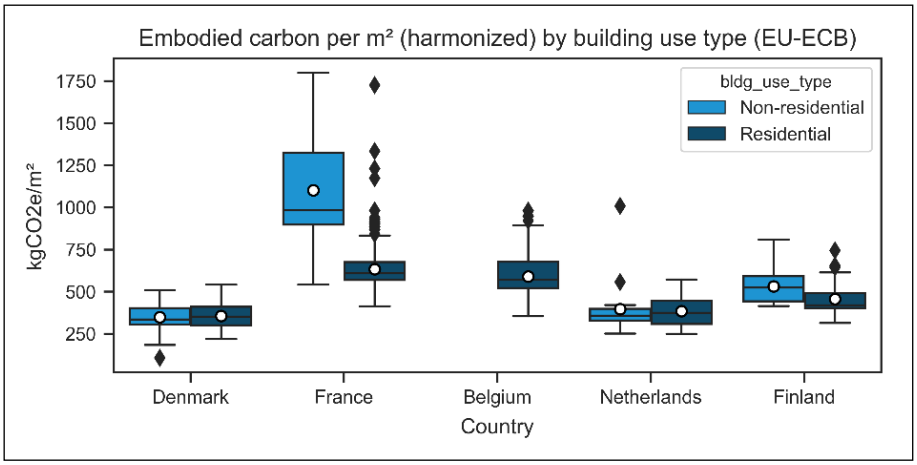


Figure 21: Whole life embodied carbon per m² by building use type for the five countries in the EU-ECB dataset

The values presented in previous chapters draw from the combined EU-ECB dataset, i.e., data from the five countries as described in Table 5. In Figure 21, we show the embodied carbon emission values per m² GFA for the main types of building use in the respective country datasets side by side.

What immediately stands out in Figure 21 are the high values displayed for non-residential buildings in the data from France. These show a mean value for full life cycle embodied carbon emissions of about to 1.100 $kgCO_2e/m^2$, ranging from 550 to more than 1.800 $kgCO_2e/m^2$. This is considerably higher than the values observed for non-residential buildings in the data from Denmark or the Netherlands, which display mean values between about 350 to 400 $kgCO_2e/m^2$, respectively. Data on non-residential buildings from Finland suggest slightly a higher mean value close to 550 $kgCO_2e/m^2$, ranging from 450 to 850 $kgCO_2e/m^2$. The building cases obtained for Belgium do not include non-residential building cases. For residential buildings the picture is more consistent, even though differences between country sets prevail to some degree. The values for residential buildings in the dataset for Denmark and the Netherlands display comparable mean values between about 350 to 385 $kgCO_2e/m^2$, respectively, and values ranging from about 200 to 650 $kgCO_2e/m^2$ for both. Values for residential buildings in Belgium and France are of comparable magnitude and a bit higher, with mean values of about 590 to 635 $kgCO_2e/m^2$ and a range of 400 to 850 $kgCO_2e/m^2$. The variation of average values between the different countries is hence around 250 $kgCO_2e/m^2$. Residential buildings from Finland show mean values of just above 450 $kgCO_2e/m^2$, ranging from around 400 to 650 $kgCO_2e/m^2$. Table 8 gives an overview of the number of cases and specific mean values for the main building use types from different countries.

Table 8: Life cycle embodied carbon (mean) for different building use types per country [$kgCO_2e/m^2$]

Metric \ Building use type		BE	DK	FI	FR	NL	EU-ECB
Mean	**Non-residential**	-	348.33	532.43	1101.61	397.07	593.09
	Residential	591.07	355.95	456.72	633.57	384.63	590.70
	All types	591.07	352.35	496.50	660.99	389.40	591.05

The variation observed between countries are comparable to what we found for the mean full life cycle embodied carbon emission values of different building use subtypes (variance of up to ~650 $kgCO_2e/m^2$) or types of structural system and material (~250 $kgCO_2e/m^2$), respectively. The variation of values observed for different countries is hence expected to occur due to various aspects, such as: differences in building design choices (e.g. common types of structural systems and main construction materials in the respective country), differences in the composition of the datasets (e.g. regarding the number of cases for different building types as well as number of cases in total), as well as due to differences in assessment methodology, background data and tools applied for the assessment of life cycle carbon emissions in the respective countries.

3.4.2. Variation in scope of assessment methods

In aiming to understand the drivers of variation even further, we investigated the potential influence of building assessment scope regarding the life cycle stages and building parts covered in the respective case study. Values presented in the following are based on cases that include different life cycle stages, considering Production (P); construction process (C); cleaning, maintenance and replacement (M), deconstruction and transport (D); as well as waste processing and disposal (W). The building parts scope abbreviation considers building parts, namely: ground (G), load-bearing structure (L), envelope (E), internal elements (I), technical systems (S), as well as appliances (A).

Table 9 shows the mean harmonised total of life cycle embodied carbon emissions for each life cycle stage and building parts scope combination, based on the combined EU-ECB dataset. Table 10 shows how the full life cycle embodied carbon values from each of these combinations compare to the ‘full scope’, i.e. GLEISA-PCMDW, studies of the same buildings type. Ratios are based on harmonised

mean values per m², as presented in Table 9. Table 9 shows that embodied carbon emission mean values tend to increase, the more complete the scope of the assessment is. Average values for embodied carbon emissions herein range from about 350 to 820 $kgCO_2e/m^2$ for non-residential buildings and about 345 to 620 $kgCO_2e/m^2$ for residential buildings, respectively. As would be expected, the scope combination with the highest mean value stems from the cases with a 'full scope', i.e., the PCMDW-GLEISA combination. However, we also see some unexpected results. For non-residential cases, we observe a large difference between cases that do and do not include appliances (A), where mean values show 64% EC compared to full scope cases. For residential cases, we observe a large difference between GLEISA and LEISA cases for residential buildings of around 19%, which suggest that such difference could stem from including, or not, the ground structure (G) in the assessment (while in non-residential cases this seems to have a negligible influence of only 1%). For residential cases, besides the mentioned large influence of ground structure, we observe a very small variation for the different building parts scopes. Studies seem to cover 93% and 97% compared to full scope as when including internal elements and appliances, respectively. In general, we observe a strong difference between studies of different life cycle scopes. For studies with the GLEIS building parts scope, we observe mean values 20% to 35% for PMW below the related PCMDW cases of non-residential and residential buildings, respectively. We note that these differences could stem from our definition of the life cycle stage M, which was assigned as soon as one of the related processes (maintenance, cleaning, and replacement) was within the scope of the study. Studies not including replacement of building parts may hence have this scope assigned but yield substantially lower results. Furthermore, comparison for the other PMW scoped studies is difficult, as only 1-2 studies of this life cycle scope are available per building parts scope.

Table 9: Life cycle embodied carbon (mean) for different building use types and scopes of life cycle stages and building parts (harmonised) [$kgCO_2e/m^2$]

	Non-residential		Residential	
Parts \ LCS	**PCMDW**	**PMW**	**PCMDW**	**PMW**
GLEISA	819.80	264.69	618.19	-
LEISA	810.00	-	481.63	-
GLESA	-	-	599.19	-
GLEIS	523.18	349.19	575.49	356.67
GLES	-	404.50	-	-
GLEI	-	-	-	343.00

Table 10: Ratio [%] of life cycle embodied carbon for different building use types and scopes of life cycle stages and building parts when compared to 'full scope', i.e., GLEISA-PCMDW, based on harmonised mean values per m²

	Non-residential		Residential	
Parts \ LCS	**PCMDW**	**PMW**	**PCMDW**	**PMW**
GLEISA	100%	32%	100%	-
LEISA	99%	-	78%	-
GLESA	-	-	97%	-
GLEIS	64%	43%	93%	58%
GLES	-	49%	-	-
GLEI	-	-	-	55%

The findings of this analysis suggest that the scope of building case studies regarding building parts and life cycle stages included in the assessment alters the outcome substantially. In order to identify the influence of difference in that regard, we recommend defining documentation standards for building LCA studies that do consider and request not only information on the scope of studies, but also the provision of detailed, disaggregated carbon emission values for the individual building parts and their different life cycle stages. Having more data with this level of detail and disaggregation could enable an increased understanding and benchmarking of the contribution of different buildings parts and life cycle stages as well as it could support the application of machine learning methods to infer missing values and close persisting data gaps.

3.4.3. Contextualization with existing studies

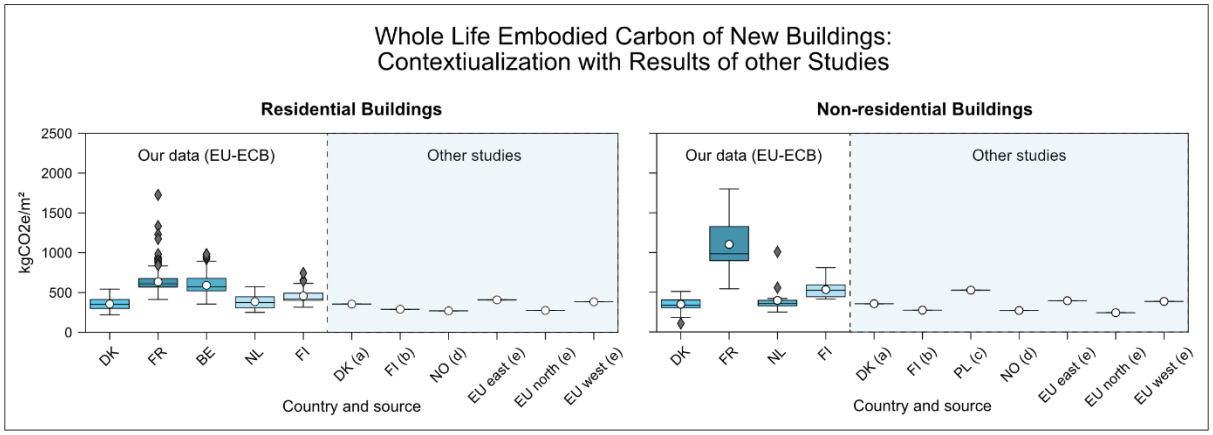


Figure 22: Comparison of whole life embodied carbon benchmarks with existing reference values by country and sources for residential buildings (left) and non-residential buildings (right), respectively.

Figure 22 presents the results of our analysis of whole life embodied carbon values, as found based on the EU-ECB data, in comparison to benchmarks and reference values found in other studies for different countries. Figure 22 shows that for residential buildings (top), reference values from other studies are comparable to our (mean) results. This is particularly the case for our results for Denmark (DK), which are very similar to those in the existing study by Zimmermann et al.(Zimmermann et al., 2020). This was expected as the majority of Danish cases in our sample are from that same study, albeit with additional cases from other Danish data partners. Our results for Finland (FI) indicate significantly higher results than were presented in the existing study by OneClickLCA (OneClickLCA (Bionova Ltd), 2021a). Here again, our sample is based on data from multiple Finnish data partners which might explain the difference in results, potentially due to a variation in the comprehensiveness of the assessment scopes. Our results for residential buildings from France, (FR), Belgium (BE), and the Netherlands (NL) do not have direct reference values to compare for the respective country, but reference values for different EU regions from another OneClickLCA study (OneClickLCA (Bionova Ltd), 2021b) suggest that the NL results are in line with the reference values for Western Europe (EU west). At the same time, the mean values for both France and Belgium in our analysis are considerably higher than the values obtained from said study for both Northern Europe (EU north) and Western Europe (EU west). Various reasons could have led to this difference. For the cases from France and Belgium particularly, the data from these cases were very comprehensive in terms of the life cycle stages and building parts covered, and so this could explain the higher results in comparison to the reference study, which covered a limited scope assessment. For non-residential buildings, the mean values in our results are comparable to the reference values from other studies for Denmark and the Netherlands. For Finland, again, our results are considerably higher than the values from the reference

study. The outstanding results are those for non-residential buildings in France. These are far above the values found in any of the other countries or studies on the respective region (EU west).

Table 11 provides details on the studies used to contextualise the embodied carbon results as shown in Figure 22. The reference values for Norway and Poland do not have a direct comparison. Nevertheless, the related studies have been added for reference and to inform other benchmarking efforts in the future.

Table 11: Overview of other studies used to contextualise whole life embodied carbon results.

Abbr.	Country	Title	Ref.
a)	DK	Zimmermann et al., Klimapåvirkninger fra 60 bygninger SBi 2020:04, 2020	(Zimmermann et al., 2020)
b)	FI	OneClickLCA, Carbon Footprint Limits for Common Building Types, 2021	(OneClickLCA (Bionova Ltd), 2021a)
c)	PL	Komerska et al., Preliminary Study on the GWP Benchmark of Office Buildings in Poland Using the LCA Approach, 2020	(Komerska and Kwiatkowski, 2020)
d)	NO	Kjendseth Wiik et al., Klimagasskrav til materialbruk i bygninger, 2020	(Kjendseth Wiik et al., 2020)
e)	EU	OneClickLCA, Embodied carbon benchmarks for European buildings, 2021	(OneClickLCA (Bionova Ltd), 2021b)

3.4.4. Limitations of this study

Representativeness of the samples

The data samples collected and analysed in this study are not representative of the building stock in a given country. The threshold for the number of cases to be provided per country was set to only 50 buildings. Several of the national data partners provided considerably more cases, with cases per country ranging from 47 to 486, respectively (see Table 5). The results obtained overall as well as per country can hence only give a first indication of common levels of embodied carbon for different building types in different countries. The authors of this study recommend consideration of the following options in order to obtain more representative building LCA samples in the future: the analysis of representative levels of embodied carbon in existing and new building types could benefit from the application of representative building archetypes and their assessment using LCA. In this study, data obtained from the Belgian data partners are based on LCAs of the building archetypes from the TABULA/EPISCOPE project[2]. This approach of using representative archetypes (e.g. as defined for building energy or material modelling) should be investigated further regarding its suitability for LCA-based modelling of embodied carbon values in future benchmarking studies.

In/consistency of assessment methods

The collection and analysis of building LCA data from different European countries were expected to reveal differences in the applied assessment methods. As expected, we identified various methodological differences, e.g., regarding the scope of building parts considered; the scope of life cycle stages considered; the LCI background data used; reference study periods (RSP), among others. Differences in RSPs were anticipated and we could apply a harmonization procedure to reduce the influence of this aspect on embodied carbon results. We are furthermore aware of methodological

[2] Building archetypes developed within the framework of the Intelligent Energy Europe projects TABULA and EPISCOPE. Starting from the common TABULA concept the project partners developed national building typologies representing the residential building stock of their countries. Further information via https://episcope.eu/

differences regarding the modelling of end-of-life emissions in different countries, which however have not been documented and analysed in further detail.

A note on module D, benefits and loads considered outside the system boundary: although requested to be documented separately in our initial data collection, benefits and loads outside the system boundary (module D1) were not taken into account in the visualization, primarily because these are considered beyond the system boundaries. Methodological disagreements about the handling of module D however does influence the values observed for C3-4 as in some cases practitioners decided to account for benefits and loads beyond the system boundary (module D) in stages at the end-of-life (C3-4), contrary to currently valid assessment standards. Benchmarking via cross-national meta-studies is systemically challenged by the varying interpretation of standards and guidelines in assessment practice in different countries, within or even outside the freedom granted by related standards.

Issues with inconsistencies in scoping and allocation are not new to building LCA, with recent studies showing, for example, the influence on different accounting perspective on operational emissions (B6) (Maierhofer et al., 2022), thereby emphasizing the need for clear guidance on assessment scope and minimum documentation requirements for building LCA on both operational and embodied impacts.

3.4.5. Further research and recommendations

Develop benchmarks for baselines and targets considering national contexts

We recommend that benchmarks and targets for the reduction of embodied carbon take into account the timing of emissions, e.g. by using a reference unit for expressing life cycle total, rather than annualised values and by considering emissions per life cycle stage in addition to mere whole life cycle totals. The contribution and optimization potential of individual building parts strongly depends on the building typology, the structural system and materialization, among other building characteristics. We hence recommend that individual building design projects should be optimised with regards to whole life (embodied) carbon through iterative assessments at the early design concepts stage, ahead of construction permit submission; during procurement as well as after complete, to verify as-built situation with targets and allow for further improvement and fine-tuning, e.g., of technical system and related operational energy and emission. For defining appropriate targets and benchmarks, it is recommended to consider the scope and assessment methodology applicable to the respective situation. Scope and methodology here may involve the life cycle stages and building parts considered, as well as whether process-based or input-output-based LCA background data was used, among other things. Targets and benchmarks should aim to provide values for ‘full scope’ assessments. Correction factors and proxy values could be applied to account for missing elements in incomplete studies (as is the case in the French methodology, which provides proxy values with an added safety margin for studies lacking technical systems in their inventory).

Elaborate data collection and ensure representative samples

We suggest aiming for obtaining building LCA data on representative samples for the respective countries. Existing approaches from, e.g., environmental modelling of building stocks might provide useful insights as to which criteria to apply for building stock characterisation and definition of representative samples. Furthermore, existing data from projects such as EPISCOPE/TABULA may be a good starting point for defining appropriate archetypes. Further elaboration of data collection schemes is required to include more information on relevant aspects for understanding and interpretation of assessment results, such as, e.g. applied carbon reduction strategies, if any; further information on buildings material inventory; detailed carbon emission results by building parts and life cycle stages; Provision of detailed information on building geometry (floor area (gross/net), building footprint, number of floors/height); Information on building location and context (climate zone, seismic zone,

urban/rural). A long list of attributes and their priority for future data collection is proposed based on the experiences of this and previous meta-studies on buildings' whole life carbon is provided in the data descriptor in chapter 4 (Open database on embodied and whole life carbon of buildings). There are potentials for alignment with Life Level(s) consortium's mapping procedure and common Level(s) reporting template, WBCSD building system carbon framework, and RICS whole life cycle carbon reporting guidelines.

Streamline analysis of building life cycle related climate impacts

Further elaboration of a methodology for systematically analysing embodied carbon hotspots of buildings, investigating contribution of different life cycle stages, building parts and materials, as well as other environmental impacts is recommended in the future. Further elaboration of a methodology for inferring missing values as well as identifying the influence of individual parameters in driving EC results is moreover recommended. In the current analysis, the embodied carbon values are analysed for subsets of the data based on different parameters (e.g. building use type), which do however include variation in other parameters (e.g. type of structure). Finally, is is expected that the application of methods like machine learning could enable an improved understanding of parameter influence. Comparison with existing studies to consider detailed building characteristics (geometry, type of use, energy performance, etc.) is recommended in order to establish a framework for contextualising the results of full life cycle embodied carbon assessment studies, building LCA results in general.

Harmonization of assessment methods and results reporting

To improve the situation regarding both availability and comparability of building LCA data, the regulation and requirement of building LCA across EU countries are essential. Countries should ensure compliance with EN standards and seek methodological consistency regarding scope of building parts, life cycle stages, background data and reference study period, at least at a country level. Hence, if a country regulates the LCA of buildings, it should be precise on the LCA requirements. Efforts for harmonization of building LCA methods across Europe (and beyond) should consider the usability of building LCA results for comparative analysis and benchmarking. Alignment should be sought on European level regarding the building parts and life cycle stages to be considered in full building LCA, to improve comparability across countries. Common formats for documentation of detailed building LCA results as well as related methodological aspects and description of the building under study are required. Recent developments such as the European Level(s) initiative can provide a good basis for this, albeit the level of detail in the reporting of building properties as well as life cycle inventories and LCA results should be improved, considering and encouraging the use different building element classification systems (Soust-Verdaguer et al., 2023). In context of harmonization of LCA methods and benchmarking, particular attention should be paid to the developments and methodological requirements in the building LCA standard EN 15978 as well as latest findings and recommendation from international IEA EBC Annex 72 project on 'Assessing life cycle related environmental impacts caused by buildings' (IEA EBC, 2017b).

3.5. Conclusions

This study analysed the whole life embodied carbon of new buildings across Europe based on LCA data cases from five European countries. To this end, the study team assessed data availability across Europe and eventually collected and analysed data from Belgium, Denmark, Finland, France and the Netherlands – which together provided a total of 769 cases for informing the embodied carbon analysis. The data from the different sources were collected using a predefined data collection template to ensure standardised information (e.g., predefined parameters, categories, and units). The results values were harmonised to a reference study period of 50 years and a reference unit per m² GFA.

The baseline for whole life cycle embodied carbon emissions ranges from around 400 to 800 $kgCO_2e/m^2$ with a mean value of around 550 $kgCO_2e/m^2$ for residential buildings, and from about 100 to 1200 $kgCO_2e/m^2$ for non-residential buildings, with a mean value of 450 $kgCO_2e/m^2$. The analysis of embodied carbon emissions per capita shows for residential buildings a mean value of around 32 t CO_2e/cap, with values ranging from 5 to almost 60 t CO_2e/cap. For non-residential buildings values range from about 2 to 35 t CO_2e/cap, mean value is around 14 t CO_2e/cap. Conclusions regarding which building subtype has the highest embodied carbon emission intensity change when using a per-capita perspective over the established per-m^2 metric. This is the case for multi-family houses, which have higher per-m^2 values than single family houses but display lowest values of all residential building types in a per-capita perspective, due to their occupancy density being higher than compared with single family houses. However, this analysis is currently based on a simplified approach of calculating where occupancy density is calculated using the estimated number of occupants. A more refined understanding of the number of users and full-time equivalents could change perspectives in future research. The analysis of the embodied carbon emissions baseline for different types of structural systems and materials shows important differences. Frame structures do not necessarily lead to lower average embodied carbon emissions compared to massive structure. Cases where wood is used as their main structural material in both massive and frame systems lead to the lowest values for the respective type of structural system. The average values are 100 to 200 $kgCO_2e/m^2$ lower than for other material options for massive and frame cases, respectively. The investigation of the contribution of the different life cycle stages shows that the largest contributions of embodied carbon emissions occur in the production stage (A1-3), with mean values of about 300 $kgCO_2e/m^2$ (56% of whole life cycle embodied carbon emissions), ranging from about 70 to 520 $kgCO_2e/m^2$. Second largest proportion of embodied GHG emissions occur during the use phase (B1-4), mean values of about 120 $kgCO_2e/m^2$ (22%), which represents the total of emissions from cleaning, maintenance, replacement activities taking place over a 50-year reference study period. There are large variations in both the values for the manufacturing stage (A1-3) and the values for the use stage (B1-4) embodied carbon emission values show a large variation, which probably depend on the type of building use, the structural system, and the choice of materials. Analysis of the contribution of different building parts reveals that the main contributors to whole life cycle embodied carbon emissions, on average, are technical services (e.g. heating, cooling, domestic hot water and sewage systems) and structural elements (e.g. structural frame, walls, floors), with a mean value of around 190 $kgCO_2e/m^2$ (ranging from 170 to 230 $kgCO_2e/m^2$) and 170 $kgCO_2e/m^2$ (ranging from 100 to 320 $kgCO_2e/m^2$), respectively. Interior elements (e.g., partition walls, floor and wall finish) also contribute significantly, with a mean value of about 150 $kgCO_2e/m^2$ (ranging from 30 to 250 $kgCO_2e/m^2$).

Based on the experience with data collection and analysis in this project and in previous meta-analyses, we recommend extended documentation requirements for building LCA cases in the data descriptor appended to this chapter. There advance on the current data collection template, for example regarding documentation of the scope of the assessment, as well as t providing detailed, disaggregated information for individual building parts and the respective life cycle stages. Initiatives such as the EU Level(s) framework could furthermore provide good opportunities for the implementation of such documentation requirements across Europe and specifically in the EU Green Deal policy initiatives.



4. OPEN DATABASE ON EMBODIED AND WHOLE LIFE CARBON OF BUILDINGS

Bibliographic data

Title	CarbEnMats: An open database on whole life carbon, energy and material intensity of buildings (CarbEnMats-Buildings-DB)
Authors	Martin Röck, KU Leuven (BE) and TU Graz (AT)
	Andreas Sørensen, Ramboll (DK)

Highlights

- While interest in whole life carbon (WLC) carbon emissions of buildings is increasing, open datasets with substantial numbers of observations and geographical coverage are lacking. Open building data with life cycle information, such as energy and material use, and whole life carbon emissions are required to inform benchmarking as well as contribution analysis.
- The article presents the largest open compilation of data on whole life carbon emissions, energy use and material intensity of buildings published to date and offers a unique data source towards benchmarking whole life carbon, energy use and material intensity.
- The open database on whole life carbon, energy and material intensity of buildings (CarbEnMats-Buildings-DB) provides data on more than 1.200 building cases and includes information on more than 300 relevant attributes.
- The attributes provide information on cases' context and site, building design, assessment methods, energy and material use, as well as detailed information on whole life carbon emissions, which is provided at different levels of spatiotemporal resolution.
- The data collection template (DCT) spreadsheet as well as scripts for data processing and harmonization (IPython Jupyter Notebooks) are shared alongside this descriptor.

Author contributions

Martin Röck: Conceptualization; Methodology; Software; Validation; Investigation; Data Curation; Writing (Original draft, review and editing); Visualization; Project administration.

Andreas Sørensen: Software; Validation; Formal analysis; Investigation; Data Curation; Writing (Original draft).

Funding and acknowledgements

The processes and scripts as well as data collection template (DCT) and information contained in this dataset have been developed within data collection and benchmark analysis initiatives of the *IEA EBC Annex 72* (Röck et al., 2020), where the Austrian contribution was financially supported by the Austrian Ministry for Transport, Innovation and Technology (BMVIT), IEA Research Cooperation via the Austrian Research Promotion Agency (FFG) Grant #864142, and the project *Towards Embodied Carbon Benchmarks for Buildings across Europe (EU-ECB)* (Röck, Sørensen, Steinmann, et al., 2022; Röck, Sørensen, Tozan, et al., 2022), which was funded by the Laudes Foundation. Martin Röck, dual PhD candidate at KU Leuven and TU Graz, received funding through a DOC Fellowship of the Austrian Academy of Sciences (ÖAW) [2019/1]. The primary authors of this data descriptor thank all partners and contributors who supported the development of the dataset. We acknowledge data inputs from the IEA EBC Annex 72 taskforce, including Marcella Ruschi Mendes Saade, Maria Balouktsi, Freja Nygaard Rasmussen, Endrit Hoxha, Barbara Truger, Daniel Satola, Guillaume Habert Harpa Birgisdottir, Rolf Frischknecht, Thomas Lützkendorf, and Alexander Passer. As well as data contributions from the EU-ECB project team involving Buket Tozan, Jacob Steinmann, Lise Hvid Horup, Xavier Le Den, and Harpa Birgisdottir and respective national data partners, on the different subsets combined in this dataset and their respective analyses are presented in respective journal articles, conference contributions and technical reports (Röck et al., 2022b, 2022c, 2022a, 2020a, 2020c).

Data availability

The dataset, the data collection template and its components (spreadsheet form, python scripts) are published under a CC BY-SA 4.0 license. The authors encourage interested parties to review – reuse – refine, i.e., to use the data, modify the scripts, and eventually share-alike.

The following chapter presents a draft manuscript for submission to a peer-reviewed journal.

Abstract

Increasing interest in buildings' whole life carbon (WLC) emissions demands open data as the foundation for benchmarking as well as analysis of parameters driving energy, and material intensity, as well as, eventually, whole life and embodied carbon. Open datasets on buildings have mostly been addressing operational energy and emissions and only few data have been published on building's material intensity. Datasets combining energy and material intensity and offering insights on building's whole life carbon emissions remain largely unavailable – until now.

This article presents the *Open Database on Whole Life Carbon, Energy and Material Intensity of Buildings (CarbEnMats-Buildings-DB)*, which contains data on more than 1.200 building cases. The dataset includes more than 300 attributes addressing context and site, building design, assessment methods, energy and material use, as well as detailed information on whole life carbon emissions, with a focus on embodied carbon (EC) emissions. WLC data is provided at different levels of spatiotemporal resolution. The dataset was established via dedicated data collection template (DCT) spreadsheets and processed through dedicated python scripts (Jupyter Notebooks), shared alongside this descriptor.

This dataset is expected to be valuable not just for research and modelling purposes but decision making in the policy context and across the building industry.

Keywords

Whole life carbon (WLC); Life cycle assessment (LCA); built environment; buildings; construction; environmental impacts; embodied impacts; embodied GHG emissions; embodied carbon; benchmarks; climate mitigation; climate adaptation; life cycle analysis; policy support.

4.1. Background and summary

Whole life carbon of buildings is gaining increasing attention among decision makers concerned with climate and industrial policy, as well as building procurement, design, and operation. The need and potential for reducing whole life carbon across Europe requires the definition and implementation of a performance system for both operational and embodied carbon at the building level that provides relevant guidance for policymakers and the building industry. However, thus far open buildings datasets have been published mostly focusing on building's operational energy consumption and related parameters (Ibarra et al., 2023; Luo et al., 2022, 2022; Miller et al., 2020; Thorve et al., 2023). Recent years furthermore brought large scale datasets on building geometry (footprint, height) (Heris et al., 2020; Yang and Zhao, 2022) as well as publication of some datasets on building construction systems and material intensity (Guven et al., 2022; Heeren and Fishman, 2019). Heeren and Fishman's database seed on material intensity (MI) of buildings (Heeren and Fishman, 2019), an important reference to this work, was a first step towards an open data repository on material-related environmental impacts of buildings. In their 2019 descriptor, the authors present data on the material-coefficients of more than 300 building cases, intended for use in studies applying material flow analysis (MFA), input-output (IO) or life cycle assessment (LCA) methods. Guven et al. elaborated this effort with the publication of a construction classification system database for understanding resource use in building construction (Guven et al., 2022)[]. However, thus far, there is lack of publicly available data that combines material composition, energy use and also considers life cycle-related environmental impacts, such as GHG/carbon emissions.

The Open Database on Whole Life Carbon, Energy Use and Material Intensity of Global Buildings (CarbEnMats-Buildings-DB) published alongside this descriptor provides information on more than 1200 building cases. The dataset includes attributes on geographical context and site, main building design characteristics, assessment methods, as well as information on energy and material use, and related life cycle-related greenhouse gas (GHG) emissions, commonly referred to as whole life carbon (WLC), with a focus on embodied carbon (EC) emissions. The dataset compiles data obtained through systematic review of the scientific literature as well as systematic data collection from both literature sources and industry partners. By applying a uniform data collection template (DCT) and related automated procedures for systematic data collection and analysis we facilitate data processing, analysis and visualization along predefined categories and attributes, and support consistency of data types and units. The descriptor includes specifications related to the DCT spreadsheet form used for obtaining these data as well as explanations on the data processing and feature engineering steps undertaken to clean and harmonise the data records. The validation focuses on describing the composition of the dataset, values observed for attributes related to whole life carbon, energy and material intensity.

The data published with this descriptor offers the largest open compilation of data on whole life carbon emissions, energy use and material intensity of buildings published to date. This open dataset is expected to be valuable for research applications in context of MFA, I/O and LCA modelling, but also offers a unique data source for benchmarking whole life carbon, energy use and material intensity of buildings to inform policy and decision making in context of the decarbonization of building construction and operation as well as commercial real estate in Europe and beyond.

4.2. Methods

4.2.1. Data collection

The dataset has been established through systematic review of suitable data available within the published scientific literature (Röck et al., 2020c) as part of the *IEA EBC Annex 72 - Assessing Life*

Cycle Related Environmental Impacts Caused by Buildings (R. Frischknecht et al., 2019a), as well as through screening and data acquisition from industry partners within the project *Towards Embodied Carbon Benchmarks for Buildings across Europe* (Röck et al., 2022b, 2022c). The dataset was hence established in four main phases:

1. 2018-2019: The foundation of this database was established within the systematic review, data collection and meta-analysis of the scientific literature on embodied versus operational carbon of buildings conducted by experts of IEA EBC Annex 72, with analyses published in (Röck et al., 2020a, 2020c).
2. 2019-2020: Consecutive elaboration of the database by experts of IEA EBC Annex 72 with additional attributes (e.g., contextual attributes (such as seismic region), building geometry parameters, increased detail in results documentation (per life cycle stage)) as well as inclusion of further case studies by adding the data from the primary sources reviewed in (Amiri et al., 2020; Satola et al., 2021).
3. 2020-2022: Extension of the database with more than 700 additional cases from countries across Europe within the ECB project, albeit with a limited set of attributes. Data provided/entered by the project team and external data partners. Details on the data curation, processing and engineering as well as analysis have been presented in (Röck et al., 2022c, 2022a; Röck and Sørensen, 2022).
4. 2022-2023: Elaboration of the database with engineering of additional secondary attributes, such as computation of material intensity factors based on the primary information obtained in phases 1-3.

Building data was collected via a dedicated data collection template (DCT) spreadsheet (.xls/.gsheet) developed in several iterations for data collection within the aforementioned projects, starting from the definition of attributes found relevant from experience of the involved experts and inspired by previous studies and meta-analyses (Chastas et al., 2016; De Wolf et al., 2014; Heeren et al., 2015; Koezjakov et al., 2018; Passer et al., 2012; Säynäjoki et al., 2017a; Kathrina Simonen et al., 2017).

4.2.2. Attributes

General remarks

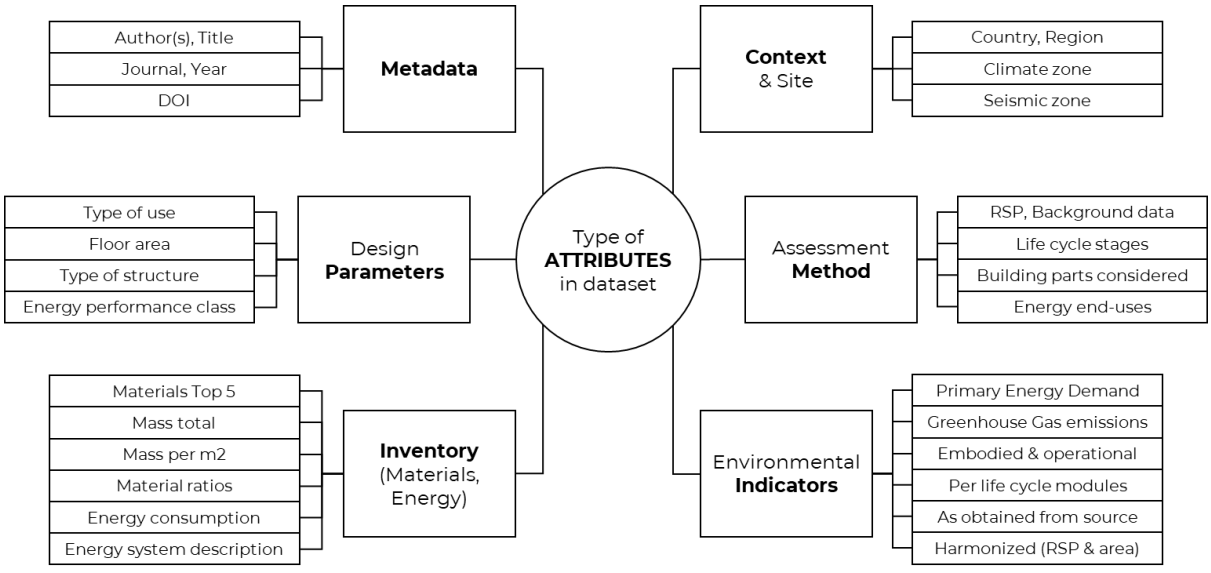


Figure 23: Conceptual overview of attribute types and examples.

The dataset includes a total of total of 313 attributes (i.e., columns). Figure 23 presents an overview of the attribute types and some examples of attributes included in the dataset. The main types of attributes

are attributes related to: Metadata; Context and site; Building design; Assessment method; Inventory data; Indicator results. Attributes are furthermore structured in subgroups, such as: General; Geometry; Energy; Materials; Carbon; Analytics.

The data is distinguished into two types of 'measurement' based on their respective sources:

- Primary = Attributes requested to report in DCT, manual or automated input from original data source.
- Secondary = Attributes computed during processing, harmonization, and or feature engineering.

All attributes (primary and secondary) are listed with respective descriptions and data type/unit remarks, as well as prioritization (A-D) in the attribute description table (SI).

Administration

Table 12: Primary attributes for 'metadata'

Prio	Code	Description	Data type / unit remarks
A	meta_DOI_URL	DOI or reference (e.g., link) to the article/source	String (Free text)
B	meta_authors	Authors of the article/source	String (Free text)
B	meta_year	Year of publication/source	String (Free text)
B	meta_title	Title of publication/source	String (Free text)
B	meta_journal	Title of journal/publisher	String (Free text)

Context and site

Table 13: Primary attributes for 'context and site'.

Prio	Code	Description	Data type / unit remarks
A	site_country	Country of Construction	Categorical (Predefined)
B	site_region_local	City or region (state, county) the case study building is located in.	String (Free text)
B	site_climate_zone	Climate zone acc. Koeppen-Geiger-Classification.	Categorical (Predefined)
B	site_seismic_hazard	Seismic hazard level, acc. global quake model.	Categorical (Predefined)

Secondary attributes: site_country_code (Country abbreviation, based on official two letter code); site_region_world (World region, based on Official Listing of Countries by World Region).

Primary attributes site_climate_zone and site_seismic_hazard were imputed, where feasible.

Building design

Table 14: Primary attributes for 'building design'.

Prio	Code	Description	Data type / unit remarks
A	bldg_use_type	Building type	Categorical (Predefined)
A	bldg_use_subtype	Building sub typology	Categorical (Predefined)
B	bldg_project_type	Project type/concept with implications on scope of the assessment, i.e., new construction, a refurbishment case, comparative study, etc.	Categorical (Predefined)
C	bldg_project_status	Project type	Categorical (Predefined)
B	bldg_year_permit	Year of construction permit	Numerical [integer]

A	bldg_year_complete	Year of construction completion	Numerical [integer]
B	bldg_year_complete_interval	Year of construction completion interval	Categorical (Predefined)
B	bldg_users_total	Number of users [n] (Residential= Occupants or beds; Office = desks or fulltime employees (FTE); Schools = Pupils; Hospital = Beds)	Numerical [decimal]
B	bldg_area_definition	Gross Area Definition [m2]	String (Free text)
A	bldg_area_gfa	Gross Floor Area [m2]	Numerical [m2]
B	bldg_area_hfa	Heated Floor Area [m2]	Numerical [m2]
B	bldg_area_interval	Area interval (GFA) [m2]	Categorical (Predefined)
B	bldg_floors_ag	Number of floors above ground [n]	Numerical [decimal]
B	bldg_floors_bg	Number of floors below ground [n]	Numerical [decimal]
B	bldg_roof_type	Roof type in terms of geometry	Categorical (Predefined)
B	bldg_area_value	Floor area of the building as per source. If possible, gross floor area (GFA).	Numerical [m2]
B	bldg_area_specification	Type of 'area', e.g., gross floor area (GFA), net floor area (NFA), or heated floor area (HFA), energy reference area (ERA), etc.	Categorical (Predefined)
B	bldg_height	Building height (in meter), on highest point, i.e., ridge of the roof, if pitched roof.	Numerical [m]
C	bldg_volume_gbv	Volume of the building (gross building volume), i.e., the total space enclosed incl. volume of walls, roofs.	Numerical [m3]
C	bldg_area_envelope	Area of the building envelope (facades + roof)	Numerical [m2]
D	bldg_area_windows	Area of windows, transparent/translucent surface of the envelope (vertical parts).	Numerical [m2]
D	bldg_area_walls_ext	Area of walls, opaque surface of the envelope (vertical parts).	Numerical [m2]
B	bldg_footprint	Building footprint, i.e., the area covered by the building on the plot. Considered equivalent to projected roof area.	Numerical [m2]
D	bldg_orientation	Building orientation interval (dropdown), i.e. orientation of the 'main' facade (facing towards direction x) - based on (Chi et al., 2020)	Categorical (Predefined)
D	bldg_attached_faces	Building geometry boundary condition as number of faces that are touching another building. Interpreted as: 0 = detached; 1 = semidetached; 2+=terraced	Numerical [integer]
C	bldg_ratio_window_to_wall	Ratio of window area / external wall area (vertical parts of envelope).	Numerical [decimal]
C	bldg_shape_factor	Shape factor = Envelope area/gross volume (dt. 'Oberflächenvolumenverhältnis')	Numerical [decimal]
D	bldg_ratio_window_to_floor	Window to floor ratio = Envelope area, window/glazing area, window/wall ratio.	Numerical [decimal]
D	bldg_ratio_wall_ext_to_floor	External wall to floor ratio = External wall area / gross floor area	Numerical [decimal]
A	bldg_energy_class_general	Energy Performance Class (ES = pre-2005 (pre-EPBD); NS = post-2005 (acc. EPBD); AS = Advanced, e.g., NZEB, passive house)	Categorical (Predefined)
A	bldg_energy_class_country	Energy performance class acc. to country definition	String (Free text)
C	bldg_certification	Sustainability certification	String (Free text)
C	bldg_wall_ext_uvalue	U-value, or thermal transmittance (reciprocal of R-value), of external walls/facade.	Numerical [W/m2K]
C	bldg_roof_uvalue	U-value, or thermal transmittance (reciprocal of R-value), of the roof(s).	Numerical [W/m2K]
D	bldg_inertia	Inertia (thermal mass and storage) of the building, related to its materialisation and energy concept.	Categorical (Predefined)
C	bldg_energy_provision	Description of energy system used for energy provision, e.g., heat pump and PV, district heating. If 'other', describe in comment, if no information available 'no data'. (Based on the KBOB database)	Categorical (Predefined)
C	bldg_energy_sources	Primary energy sources used for building climatization.	Categorical (Predefined)
C	bldg_energy_distribution	Type of the heating/cooling system. E.g., floor heating, radiators, A/C system, etc. If 'other', describe in comment, if no information available 'no data'. (Based on the Swiss KBOB database)	Categorical (Predefined)
C	bldg_bipv_description	Type and scope of BIPV (building integrated PV). If present, mentioning, e.g., area (m²) and power (kWpeak) as well as specific type of the system.	String (Free text)

B	bldg_QTO_type	Project data status	Categorical (Predefined)
B	bldg_struct_type	Structure type and main material	Categorical (Predefined)
C	bldg_wall_internal_type	Type of internal/partion walls	String (Free text)
C	bldg_wall_internal_area	Amount of internal/partition walls	Numerical [m2]
D	bldg_construction_method	Construction method (as stated in paper)	String (Free text)

No straight secondary attributes here. Where feasible, primary attribute values were imputed for: bldg_year_complete_interval; bldg_area_interval; bldg_ratio_window_to_wall; bldg_shape_factor; bldg_ratio_window_to_floor; bldg_ratio_wall_ext_to_floor.

Assessment method

Table 15: Primary attributes for 'assessment methods'.

Prio	Code	Description	Data type / unit remarks
A	lca_goal_scope	Goal of the study, as stated in source	String (Free text)
B	lca_reference_unit	Reference unit the results are primary expressed for, as stated in source (Not to be confused with functional unit, as here no performance criteria are specified)	String (Free text)
B	lca_functional_unit	Functional unit, i.e., functional equivalence specified for the assessment, as stated in the source.	String (Free text)
A	lca_RSP	Reference Study Period	Numerical [integer]
B	lca_software	LCA software	String (Free text)
A	lca_database	Primary environmental database / background data (& version)	String (Free text)
C	lca_scenarios_decarbonisation	Future decarbonisation scenarios considered (energy mix for operation, or manufacturing of materials)	String (Free text)
B	lca_database_version	Background data version (or I-O source)	String (Free text)
B	lca_database_other	Background data source - if 'other'	String (Free text)
B	lca_lcia_method	Impact assessment method (for GHG emissions, GWP indicator)	String (Free text)
B	lca_model_type	Type of LCA model	Categorical (Predefined)
D	lca_indicators_other	Documents if and which other environmental impact categories (besides Energy, GHG emissions) are reported in the source.	String (Free text)
A	scope_parts_1_ground	1 Ground, Substructure (Groundwor; floor beds; retaining walls; foundations)	Categorical (Predefined)
A	scope_parts_2_structure	2 Structure primary elements, carcass (Structural building frame; external and internal walls; floors; stairs; roofs)	Categorical (Predefined)
A	scope_parts_3_secondary	3 Secondary elements, openings (Openings in walls, floors and roofs; windows; doors)	Categorical (Predefined)
A	scope_parts_4_finishes	4 Finishes (External and internal wall finishes; floor, ceiling and roof finishes)	Categorical (Predefined)
A	scope_parts_5_mechanical	5 Services, mainly mechanical (Heating, cooling, water systems (HVAC); sanitary)	Categorical (Predefined)
A	scope_parts_6_electrical	6 Services, mainly electrical (Electrical supply; lighting; communication; transport; security)	Categorical (Predefined)
B	scope_parts_6+_renewables	6+ Renewable Energy Systems ('Yes' if assessment includes PV, heat pump, or other renew. energy systems)	Categorical (Predefined)
A	scope_parts_7_facilities	7 Facilities ('Fixed' facilities: Sanitary; food processing facilities, etc.)	Categorical (Predefined)

A	scope_parts_8_fittings	8 Fittings ('Mobile' fittings: user (furniture); food processing; storage; etc.)	Categorical (Predefined)
A	scope_LCS_A123	A1-3 Production	Categorical (Predefined)
A	scope_LCS_A4	A4 Transport	Categorical (Predefined)
A	scope_LCS_A5	A5 Construction	Categorical (Predefined)
A	scope_LCS_B1	B1 Use	Categorical (Predefined)
A	scope_LCS_B2	B2 Maintenance	Categorical (Predefined)
A	scope_LCS_B3	B3 Repair	Categorical (Predefined)
A	scope_LCS_B4	B4 Replacement	Categorical (Predefined)
A	scope_LCS_B5	B5 Refurbishment	Categorical (Predefined)
A	scope_LCS_B6	B6 Operational energy use	Categorical (Predefined)
A	scope_LCS_B7	B7 Operational water use	Categorical (Predefined)
C	scope_LCS_B8	(B8 Mobility)	Categorical (Predefined)
A	scope_LCS_C1	C1 De-construction	Categorical (Predefined)
A	scope_LCS_C2	C2 Transport	Categorical (Predefined)
A	scope_LCS_C3	C3 Waste processing	Categorical (Predefined)
A	scope_LCS_C4	C4 Disposal	Categorical (Predefined)
A	scope_LCS_D	(D) Reuse, recovery, recycling	Categorical (Predefined)
A	scope_handling_D	Handling of module D?	Categorical (Predefined)
B	scope_LCS_B6_heating	Scope of operational energy values, i.e., including either of: Heating, Ventilation, Cooling, Domestic Hot Water, Lighting, Appliances	Categorical (Predefined)
B	scope_LCS_B6_ventilation		Categorical (Predefined)
B	scope_LCS_B6_cooling		Categorical (Predefined)
B	scope_LCS_B6_DHW		Categorical (Predefined)
B	scope_LCS_B6_lighting		Categorical (Predefined)
B	scope_LCS_B6_appliances		Categorical (Predefined)

Secondary attributes: scope_parts (Scope summary for building parts included in assessment scope); scope_LCS (Scope summary for life cycle stages included in assessment scope); scope_LCM (Scope summary for life cycle modules included in assessment scope).

Inventory data

Table 16: Primary attributes for 'inventory data'.

Prio	Code	Description	Data type / unit remarks
A	inv_energy_consumption	Operationa energy consumption value [per m²GFA/year]	Numerical [kWh/m2/a]
B	inv_energy_consumption_description	Description of operational energy consumption values used for assessing the use phase (B6). E.g., Building performance simulation; benchmark estimation, statistic data; meter data	String (Free text)
B	inv_energy_consumption_type	Type of building energy source, performance simulation or real-world measurement as documented in the paper, otherwise considered based on estimation or benchmarks.	Categorical (Predefined)
A	inv_mat_mass_total	Total mass of the building (all materials)	Numerical [kg]
A	inv_mat_mass_total_m2	Total mass of the building per m² (all materials)	Numerical [kg/m2]
A	inv_mat_1_type	1st: Material [dropdown]	Categorical (Predefined)
A	inv_mat_1_mass	1st: Quantity [kg]	Numerical [kg]
B	inv_mat_2_type	2nd: Material [dropdown]	Categorical (Predefined)
B	inv_mat_2_mass	2nd: Quantity [kg]	Numerical [kg]
B	inv_mat_3_type	3rd: Material [dropdown]	Categorical (Predefined)

B	inv_mat_3_mass	3rd: Quantity [kg]	Numerical [kg]
B	inv_mat_4_type	4th: Material [dropdown]	Categorical (Predefined)
B	inv_mat_4_mass	4th: Quantity [kg]	Numerical [kg]
B	inv_mat_5_type	5th: Material [dropdown]	Categorical (Predefined)
B	inv_mat_5_mass	5th: Quantity [kg]	Numerical [kg]

Secondary attributes include: inv_mat_mass_total_capita (Total mass of the building per capita (all materials)); inv_mat_mass_sum_top_5 (Sum mass of top 5 materials reported); inv_mat_mass_ratio (Ratio of total mass to top 5 sum).

Furthermore, the mass of individual materials (as reported via the top 5 materials) and their respective material intensity (MI) were computed and are indicated by a prefix to the attribute code:

- mass_* (Computed mass of individual top 5 materials and respective mapping to Eurostat material classes (See classification of building materials));
- mi_* (Computed material intensity (MI) of individual top 5 materials and respective mapping to Eurostat material classes (See classification of building materials))

Detailed information on the list of materials and their respective mapping to Eurostat classes is presented in data processing, classification of building materials chapter.

Indicator results

Table 17: Primary attributes for 'indicator results'.

Prio	Code	Description	Data type / unit remarks
A	GHG_sum_em	Sum Embodied GHG emissions (original, as per source)	Numerical [kgCO2e/m2]
A	#GHG_op_em	(= GHG_B67_m2) Sum Operational GHG emissions (original, as per source)	Numerical [kgCO2e/m2]
A	GHG_sum_em_m2a	Sum Embodied GHG emissions per m2 per year	Numerical [kgCO2e/m2/a]
A	#GHG_sum_op_m2a	(= GHG_B67_m2a) Sum Operational GHG emissions per m2 per year	Numerical [kgCO2e/m2/a]
A	GHG_A123_m2a	A1-A3 GHG emissions (original, as per source)	Numerical [kgCO2e/m2/a]
A	GHG_A45_m2a	A4-A5 GHG emissions (original, as per source)	Numerical [kgCO2e/m2/a]
A	GHG_B1234_m2a	B1-B4 GHG emissions (original, as per source)	Numerical [kgCO2e/m2/a]
A	GHG_B5_m2a	B5 GHG emissions (original, as per source)	Numerical [kgCO2e/m2/a]
A	GHG_B67_m2a	B6-B7 GHG emissions (original, as per source)	Numerical [kgCO2e/m2/a]
A	GHG_C12_m2a	C1-C2 GHG emissions (original, as per source)	Numerical [kgCO2e/m2/a]
A	GHG_C34_m2a	C3-C4 GHG emissions (original, as per source)	Numerical [kgCO2e/m2/a]
A	GHG_D_m2a	Mod D GHG emissions (original, as per source)	Numerical [kgCO2e/m2/a]
B	GHG_A1_m2a	A1 Raw material supply	Numerical [kgCO2e/m2/a]
B	GHG_A2_m2a	A2 Transport	Numerical [kgCO2e/m2/a]
B	GHG_A3_m2a	A3 Manufacturing	Numerical [kgCO2e/m2/a]
B	GHG_A4_m2a	A4 Transport	Numerical [kgCO2e/m2/a]
B	GHG_A5_m2a	A5 Construction	Numerical [kgCO2e/m2/a]
B	GHG_B1_m2a	B1 Use	Numerical [kgCO2e/m2/a]
B	GHG_B2_m2a	B2 Maintenance	Numerical [kgCO2e/m2/a]
B	GHG_B3_m2a	B3 Repair	Numerical [kgCO2e/m2/a]
B	GHG_B4_m2a	B4 Replacement	Numerical [kgCO2e/m2/a]
B	GHG_B6_m2a	B6 Operational energy use	Numerical [kgCO2e/m2/a]

B	GHG_B7_m2a	B7 Operational water use	Numerical [kgCO2e/m2/a]
B	GHG_C1_m2a	C1 De-construction	Numerical [kgCO2e/m2/a]
B	GHG_C2_m2a	C2 Transport	Numerical [kgCO2e/m2/a]
B	GHG_C3_m2a	C3 Waste processing	Numerical [kgCO2e/m2/a]
B	GHG_C4_m2a	C4 Disposal	Numerical [kgCO2e/m2/a]
C	GHG_P1_sum_m2a	Sum GHG Ground (1) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P1_A123_m2a	A1-3 GHG Ground (1) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P1_A45_m2a	A4-5 GHG Ground (1) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P1_B1234_m2a	B1-4 GHG Ground (1) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P1_B5_m2a	B5 GHG Ground (1) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P1_C12_m2a	C1-2 GHG Ground (1) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P1_C34_m2a	C3-4 GHG Ground (1) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P1_D_m2a	(D) GHG Ground (1) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P2_sum_m2a	Sum GHG Structure (2) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P2_A123_m2a	A1-3 GHG Structure (2) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P2_A45_m2a	A4-5 GHG Structure (2) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P2_B1234_m2a	B1-4 GHG Structure (2) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P2_B5_m2a	B5 GHG Structure (2) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P2_C12_m2a	C1-2 GHG Structure (2) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P2_C34_m2a	C3-4 GHG Structure (2) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P2_D_m2a	(D) GHG Structure (2) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P34_sum_m2a	Sum Envelope (3, 4) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P34_A123_m2a	A1-3 GHG Envelope (3, 4) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P34_A45_m2a	A4-5 GHG Envelope (3, 4) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P34_B1234_m2a	B1-4 GHG Envelope (3, 4) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P34_B5_m2a	B5 GHG Envelope (3, 4) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P34_C12_m2a	C1-2 GHG Envelope (3, 4) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P34_C34_m2a	C3-4 GHG Envelope (3, 4) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P34_D_m2a	(D) GHG Envelope (3, 4) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P4_sum_m2a	Sum GHG Internal (4) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P4_A123_m2a	A1-3 GHG Internal (4) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P4_A45_m2a	A4-5 GHG Internal (4) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P4_B1234_m2a	B1-4 GHG Internal (4) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P4_B5_m2a	B5 GHG Internal (4) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P4_C12_m2a	C1-2 GHG Internal (4) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P4_C34_m2a	C3-4 GHG Internal (4) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P4_D_m2a	(D) GHG Internal (4) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P56_sum_m2a	Sum GHG Services (5,6) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P56_A123_m2a	A1-3 GHG Services (5,6) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P56_A45_m2a	A4-5 GHG Services (5,6) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P56_B1234_m2a	B1-4 GHG Services (5,6) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P56_B5_m2a	B5 GHG Services (5,6) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P56_C12_m2a	C1-2 GHG Services (5,6) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P56_C34_m2a	C3-4 GHG Services (5,6) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P56_D_m2a	(D) GHG Services (5,6) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P78_sum_m2a	Sum GHG Appliances (7,8) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P78_A123_m2a	A1-3 GHG Appliances (7,8) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P78_A45_m2a	A4-5 GHG Appliances (7,8) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]

C	GHG_P78_B1234_m2a	B1-4 GHG Appliances (7,8) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P78_B5_m2a	B5 GHG Appliances (7,8) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P78_C12_m2a	C1-2 GHG Appliances (7,8) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P78_C34_m2a	C3-4 GHG Appliances (7,8) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
C	GHG_P78_D_m2a	(D) GHG Appliances (7,8) [kgCO2e/m2/a]	Numerical [kgCO2e/m2/a]
D	CED_EE_m2a	Embodied cumulative energy demand (CED) [MJ/m2/a]	Numerical [MJ/m2/a]
D	CED_OE_m2a	Operational cumulative energy demand (CED) [MJ/m2/a]	Numerical [MJ/m2/a]
D	CED_A1-3_m2a	A1-3 Cumulative energy demand (CED)	Numerical [MJ/m2/a]
D	CED_A4-5_m2a	A4-5 Cumulative energy demand (CED)	Numerical [MJ/m2/a]
D	CED_B1-4_m2a	B1-4 Cumulative energy demand (CED)	Numerical [MJ/m2/a]
D	CED_B5_m2a	B5 Cumulative energy demand (CED)	Numerical [MJ/m2/a]
D	CED_B6-7_m2a	B6-7 Cumulative energy demand (CED)	Numerical [MJ/m2/a]
D	CED_C1-2_m2a	C1-2 Cumulative energy demand (CED)	Numerical [MJ/m2/a]
D	CED_C3-4_m2a	C3-4 Cumulative energy demand (CED)	Numerical [MJ/m2/a]
D	CED_D_m2a	Module D Cumulative energy demand (CED)	Numerical [MJ/m2/a]

Secondary attributes include: GHG_EC_share (Embodied GHG emissions share on total (% contrib)); GHG_OC_share (Operational GHG emissions share on total (% contrib)); as well as the computation of 'per capita' values, namely:

- GHG_sum_em_capita_a (Sum Embodied GHG emissions per capita).
- GHG_A_capita_a (LCS A1-5 Embodied GHG emissions per capita).
- GHG_B_em_capita_a (LCS B1-4 Embodied GHG emissions per capita).
- GHG_B_op_capita_a (LCS B6-7 Operational GHG emissions per capita).
- GHG_C_capita_a (LCS C1-4 Embodied GHG emissions per capita).

Furthermore, harmonised GHG emissions values were computed as described in the next chapter. Harmonised values are indicated by the attribute code suffix *_harm or *_APEN, respectively.

4.2.3. Data processing

General remarks

To prepare the raw, primary data obtained through the data collection from academics, industry experts and national data partners, a workflow was developed utilizing IPython in Jupyter Notebook (Perez and Granger, 2007) for data processing, harmonization and feature engineering. In some cases, database entries have been received in their native format instead of the developed DCT. In such cases the data was pre-processed individually using tailormade scripts to transform (parse) the data and fit it to the format of the DCT. The pre-processing steps include removing rows with invalid data, translating and regrouping data into common formats and categories from the DCT and collecting all data sources into one combined dataset. With the combined dataset, harmonised values as well as new features (attributes) were computed to enable a broad range of analyses.

Harmonization

Embodied carbon (EC) values were harmonised to a common reference study period (RSP) of 50 years and, if needed, scaled to a value per m² gross floor area (GFA). For the data collected via the data collection template in phase 3, emission values should be per m² GFA and year (kgCO2eq/m²GFA/a) by default, based on the RSP of the respective case. Hence, the harmonization of net floor area (NFA) to GFA is not required. Harmonization of the RSPs is still implemented to improve comparability. For data collected in phase 3, the approach for harmonizing EC values, builds on the disaggregated emission

data per life cycle stage. The formulas applied for harmonization of emission values to a common reference study period (RSP) are:

$$(1) \quad GHG_{t,h} = GHG_{a,o} * RSP_o$$
$$(2) \quad GHG_{t,h} = GHG_{a,o} * RSP_h$$
$$(3) \quad GHG_{a,h} = GHG_{t,h} / RSP_h$$

where,

- *GHG* = GHG emission values
- *RSP* = Reference study period
- *a* = annualised
- *h* = harmonised
- *o* = original
- *t* = total

In a first step, the total of EC across the full life cycle of the respective case (harmonised EC total) are computed. Full life cycle EC values for life cycle stages A and C are computed using formula (1). EC values from life cycle modules in the use stage, i.e., stage B, are harmonised and scaled considering the factor between original RSP of the case study (RSP_o) and the RSP for harmonization (RSP_h) using formula (2). Annualised values are obtained through division of the respective emission value by RSP_h via formula (3). This harmonization procedure enables scaling of use-phase related EC values and is especially accurate for EC related to processes with a yearly frequency, such as cleaning and maintenance activities (module B2). For repairs (B3) and replacement (B4), the results of the harmonization procedure can only offer an approximation, as the underlying processes usually have multi-annual frequency, and it remains unclear if the change from original to harmonised RSP would affect the number of occurrences. Emission values for operational energy and water use (B6/B7) are correctly scaled using the same logic is applied as for the other use phase related emissions. The EC values for life cycle stages A and C are not scaled, as the total of emissions in these life cycle stages is not affected by the RSP of a given study.

In the dataset, the different types of values are indicated via attribute extensions, where:

- _m2 = Total GHG emissions across full life cycle or respective life cycle stage
- _m2a = Annualised GHG emissions, based on respective RSP
- _orig = Values based on original RSP from source
- _harm = Values based on harmonised RSP, distinguishing life cycle stages (Röck et al., 2022c)
- _APEN = Values harmonised for GFA and common RSP, unified life cycle (Röck et al., 2020c)

Classification of building materials

The material quantities in this dataset were obtained through selection of the top 5 materials (i.e., the five most contribution materials in terms of total mass), reporting their type and respective quantity.

Table 18: Material options for primary input and mapping with Eurostat material accounts and the MI database seed.

Material options, primary input (attributes 'inv_mat_*_type')		**Eurostat material accounts**	**Heeren and Fishman**
inv_mat_*_type	**related attribute (secondary)**	**related attribute (secondary)**	**related attribute (secondary)**
Aluminium (e.g., alum alloy)	mass_aluminium	eurostat_metal_materials	Eurostat_Metals
Bamboo	mass_bamboo	eurostat_biomass_based_materials	Eurostat_Bio-based
Brass, copper	mass_brass_copper	eurostat_metal_materials	Eurostat_Metals
Cement mortar, plaster	mass_cement_mortar	eurostat_non-metallic_minerals	Eurostat_CCA
Ceramics (e.g., fired clay bricks)	mass_ceramics	eurostat_non-metallic_minerals	Eurostat_Non-CCA-minerals

Concrete reinforced	mass_concrete_reinforced	eurostat_non-metallic_minerals	Eurostat_CCA
Concrete w/o reinforcement	mass_concrete_wo_reinforcement	eurostat_non-metallic_minerals	Eurostat_CCA
Earth (unfired clay, adobe, rammed earth)	mass_earth	eurostat_non-metallic_minerals	Eurostat_Other-materials
EPS or XPS (insulation)	mass_EPS_XPS	eurostat_fossil_energy_materials	Eurostat_Other-materials
Fungi (e.g. Mycelium)	mass_fungi	eurostat_biomass_based_materials	Eurostat_Bio-based
Glass (single, double, triple)	mass_glass	eurostat_non-metallic_minerals	Eurostat_Non-CCA-minerals
Metals (iron, steel)	mass_metals	eurostat_metal_materials	Eurostat_Metals
Plastics (various: PC, PE, PP, PU, PVC)	mass_plastics	eurostat_fossil_energy_materials	Eurostat_Other-materials
Steel (reinforcement)	mass_steel_reinforcement	eurostat_metal_materials	Eurostat_Metals
Stone (granite, limestone, etc)	mass_stone	eurostat_non-metallic_minerals	Eurostat_Non-CCA-minerals
Stone wool (e.g., insulation)	mass_stone_wool	eurostat_non-metallic_minerals	Eurostat_Non-CCA-minerals
Straw or hemp (e.g., strawbale)	mass_straw_hemp	eurostat_biomass_based_materials	Eurostat_Bio-based
Timber, wood	mass_wood	eurostat_biomass_based_materials	Eurostat_Bio-based
Other	mass_other	-	-
No data	-	-	-

During data processing, this information was transformed to obtain the mass and material intensity of each of the materials available for selection, passed on predefined options. Furthermore, the material mass and intensity was mapped with the Eurostat material categories for Material Flow Analyis (MFA) and environmental-economic accounts (Eurostat, 2018), to provide valuable information in the MFA context[3]. Table 18 shows the material options during primary input and related attribute (secondary), and mapping with Eurostat economy-wide material flow accounts (Eurostat, 2018) as well as (Heeren and Fishman, 2019), listing the respective related attributes (secondary).

Assessment scope summary indicator

Scope summary for building parts included in assessment scope (scope_parts) is an aggregated indicator obtained by transformation of the yes/no value for the respective scope_parts_* attributes into a concatenated six-character string using the first letter of each building part class.

Classification follows the building systems classification of BB-CI/SfB (De Troyer, 2008; European Commission (EC), 1976), and has been grouped as follows:

- Ground (1) (i.e., substructure, foundation, basement walls, etc.)
- Load-bearing structure (2) (i.e., structural frame, walls, floors, roofs, etc.)
- Envelope (3, 4) (i.e., openings, ext. finishes, etc.)
- Internal (4) (i.e., partitions, int. finishes, etc.)
- Services (5,6) (i.e., mechanical, electrical, renew. energy, etc.)
- Appliances (7,8) (i.e., fixed facilities, mobile fittings, etc.)

Sample values for the six-character summary string are:

[3] A full list of the material classification and its subclasses is available Annex A of the Economy-wide material flow accounts handbook (https://ec.europa.eu/eurostat/documents/3859598/9117556/KS-GQ-18-006-EN-N.pdf/b621b8ce-2792-47ff-9d10-067d2b8aac4b?t=1537260841000)

1. GLEISA = All standard elements considered = full scope
2. GLE-- = Structure, Foundation and Envelope, no internal elements or technical services
3. --E-S = Envelope and building services only.

Similarly, scope summary for life cycle stages included in assessment scope (scope_LCS) and scope summary for life cycle modules (scope_LCM) represent aggregated indicators of the respective life cycle scope attributes (scope_LCS_*), expressed per stages or modules, respectively.

Both the scope_LCS and scope_LCM attribute use a categorical string to describe the scope regarding life cycle stages and life cycle modules, following the respective standard for building LCA EN 15978.

Life cycle stages:

- A (Product stage & Construction process stage)
- B (Use stage, differentiating embodied and operational)
- C (End-of-life stage)
- D (Benefits and loads beyond the system boundary)

Life cycle modules (one parameter for each)

- A1-3: Production
- A4-5: Construction process
- B1-4: Maintenance, repair, replacement
- B5: Refurbishment
- B6-7: Operational energy & water use
- C1-2: Deconstruction, transport
- C3-4: Waste processing and disposal

Sample values for the scope summary for life cycle stages and life cycle modules are:

Life cycle stages:

- ABC- = Whole life cycle assessment (A-C), not considering mod D.
- A--- = Cradle to gate/site assessment (A), not covering use, EoL, No mod D.
- A-C- = Cradle to grave (A+C), but not covering use phase, no mod D.

Life cycle modules

- PCMRODW = All life cycle modules covered
- P-M--D- = Production; Maintenance, repair, replacement; and Deconstruction, transport.

4.3. Data records

All files related to this descriptor [will be] available on a public Github repository. The repository contains the following files:

- *README.md* is a textfile with instructions on how to use this the files and documents in this repo.
- *CarbEnMats_attributes.XLSX* is a table with the complete attribute description.
- *CarbEnMats_materials.XLSX* is the table of material options and mappings.
- *CarbEnMats_dataset.XLSX* is the building dataset in MS Excel format.
- *CarbEnMats_dataset.txt* is the building dataset in tab delimited TXT format.

4.4. Technical validation

In this chapter the dataset composition is presented based on selected attributes and their respective distribution. Further analyses of relevant attributes are presented in the related studies and reports.

4.4.1. Data overview

The database consists of 1294 datasets (i.e., rows) retrieved from four meta-analyses (Amiri et al., 2020; Röck et al., 2020c; Röck and Sørensen, 2022; Satola et al., 2021) and the respective primary sources. Table 19 outlines the number of datasets (count of cases) included from different meta-studies compiled in this database. Not all cases reviewed in the original studies could be included in this dataset, due to limitations in accessibility or level of detail required for a reasonable contribution to this dataset.

Table 19: Overview of datasets and meta-studies composed in this dataset

Source	Count	Description	Reference
Röck et al. 2020	331	Global dataset from SLR meta-analysis covering different residential and non-residential buildings as well as different construction types found in the scientific literature.	https://doi.org/10.1016/j.apenergy.2019.114107
Amiri et al. 2020	23	Dataset on wooden building case studies collected in Northern Hemisphere, different residential types and office buildings.	https://doi.org/10.1088/1748-9326/aba134
Satola et al. 2021	86	Dataset on Residential buildings in Humid Subtropical and Tropical Climates identified through SLR of scientific literature.	https://doi.org/10.3390/buildings11010006
Röck et al. 2022	769	Detailed dataset on cases from five European countries compiled for purpose of establishing embodied carbon baseline and benchmarks, various residential and non-res building types.	https://doi.org/10.5281/zenodo.5895051
Total	**1294**	**Global building LCA dataset covering different building types and materializations.**	

The data represents buildings all over the world, with most cases in Europe, as illustrated in Figure 24. The composition of the dataset with regards to key attributes is presented in Figure 25.

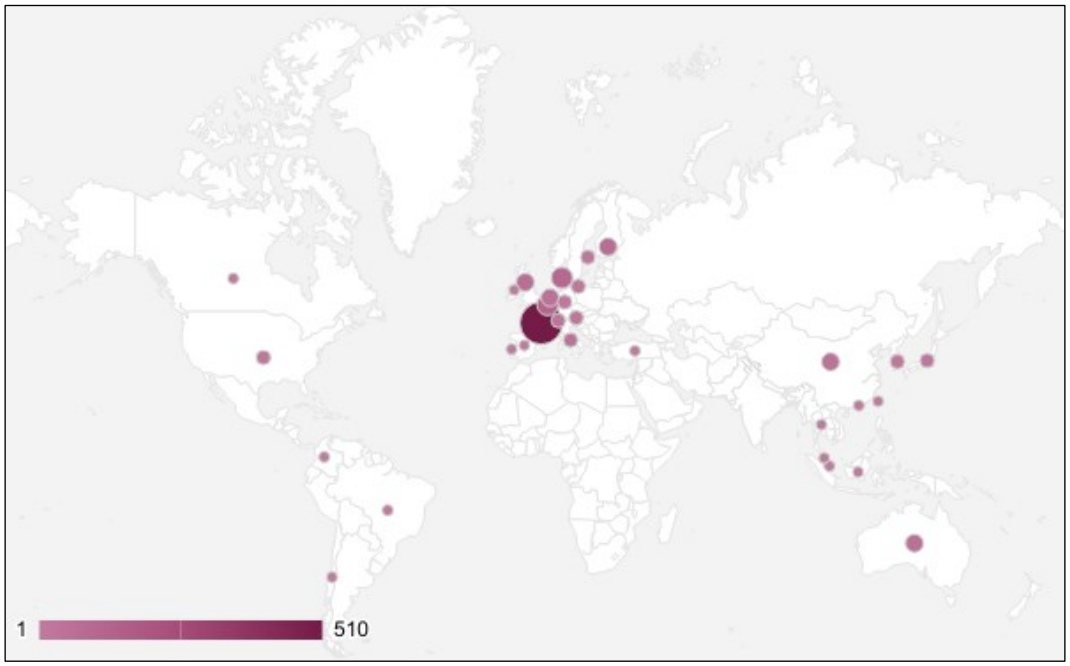


Figure 24: Geographic coverage of the dataset, global map indicating origin and count of the studies.

The data covers both residential and non-residential buildings and distinguishes various building use subtypes. Around 2/3 of the dataset are residential buildings, with 40% of cases representing single family houses (SFH) and around 25% multi-family houses (MFH). Close to 3/4 of the dataset are describing massive types of construction, such as massive brick (40%), massive wood (17%), or massive concrete (13%). The majority of cases are buildings completed within the last 10 years, with 49% of cases constructed 2015-2019 and 14% after 2020 (>2022). Another big fraction are buildings without information on the construction year (22%). Distribution of the building size in terms of floor area shows that the majority, more than 2/3 of cases are within the interval of 0-5000 m².

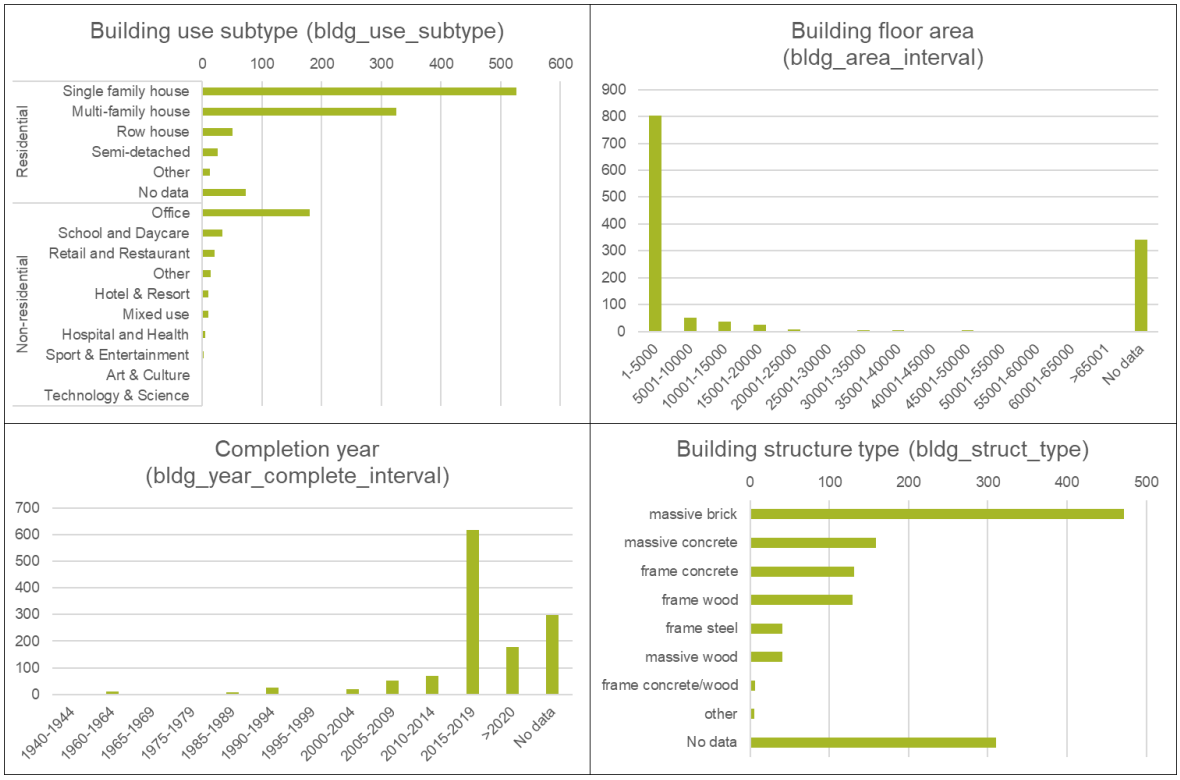


Figure 25: Distribution of cases with regards to building use subtypes (top left); building structure type (top right); building floor area interval (bottom left) and building completion year (bottom right).

4.4.2. Data consistency

Carbon values

Figure 26 presents the distribution of harmonised values for embodied carbon intensity per m² and year by individual life cycle stages (GHG_A123_m2a_harm; GHG_A45_m2a_harm; GHG_B1234_m2a_harm; GHG_B5_m2a_harm; GHG_C12_m2a_harm; GHG_C34_m2a_harm). As expected, the highest carbon intensity is observed for the production stage (A123*) with mean value around 6.5 $kgCO_2e/m^2a$, and extreme values just above 30 $kgCO_2e/m^2a$. Followed by use-phase related embodied carbon (B1234) and emissions related to end-of-life (C34). Production stage emission values are the most emission values in this dataset as they are directly related to quantity of construction materials and do not depend on additional life cycle scenarios (as is the case for assessment of emissions for all other life cycle stages). All values are affected by the methodological choices in the respective studies. For example, negative emission values observed for production stage (A123), deconstruction process stage (C12), and end-of-life (C34) are due to methodological decisions made in the respective original sources, e.g., regarding consideration of biogenic carbon uptake, recycling or energy recovery. Further information can be obtained via the respective attributes on 'assessment method' or 'inventory data', e.g., to relate emission values to material intensity. For the respective subset, an analysis of

embodied and operational carbon intensity for different types of building uses and energy performance levels is presented in chapter 2 (The relevance of embodied carbon in the life cycle of new buildings) and (Röck et al., 2020c). Furthermore, in-depth analysis of the carbon intensity of different life cycle stages, distinguished for different building use (sub)types, is presented in chapter 3 (Towards benchmarking embodied carbon of buildings in Europe) for the subset from (Röck et al., 2022c).

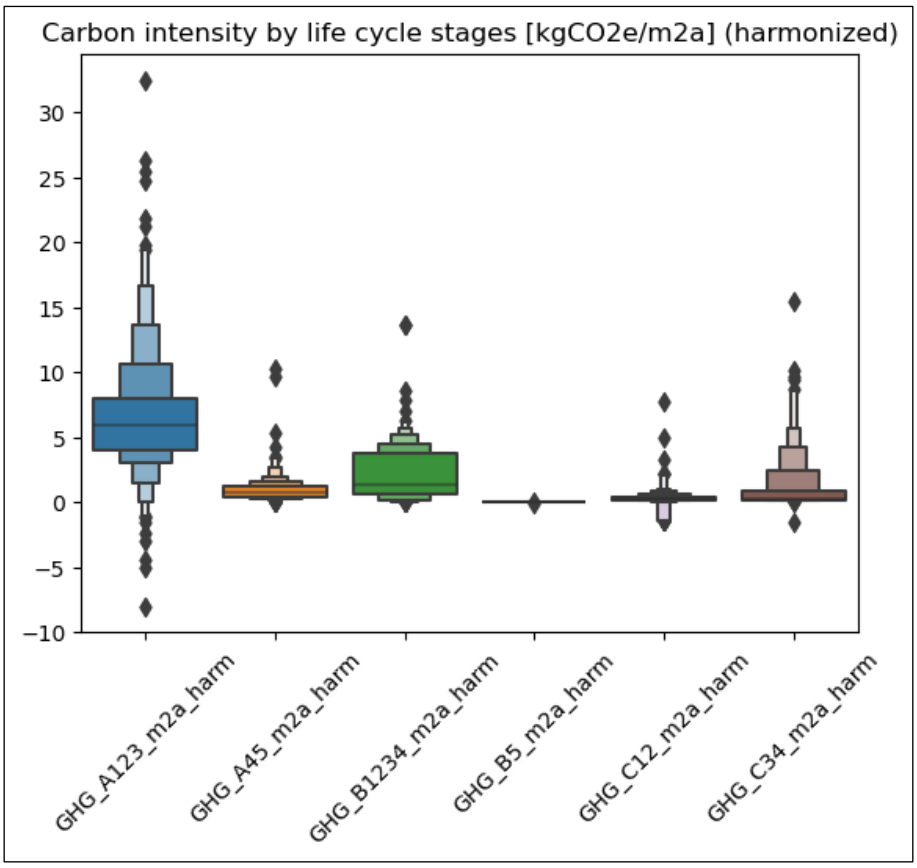


Figure 26: Carbon intensity - GHG emissions per m²/a by life cycle stages (harmonised values, RSP=50 years).

Energy values

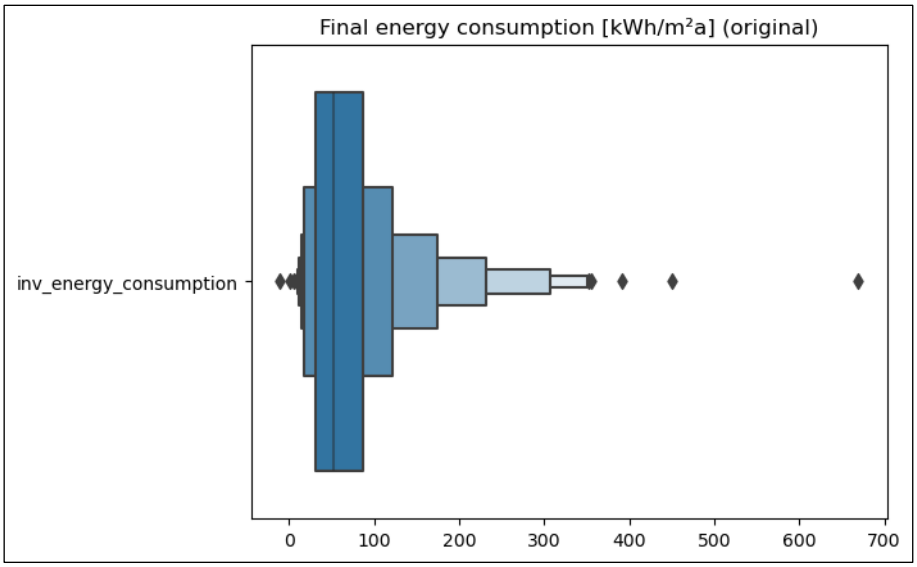


Figure 27: Energy intensity - Energy use per m²/a (original values).

Energy values have been retrieved for both the energy intensity in terms of final energy consumption as well as the resulting cumulative energy demand (CED) for both operational and material-related embodied energy. Figure 27 presents the distribution of final energy consumption (inv_energy_consumption) across the full dataset. Energy consumption if around 70 kWh/m²a (mean value) and ranges up to 350 kWh/m²a (upper IQR), with extreme values reaching close to 700 kWh/m²a.

Material values

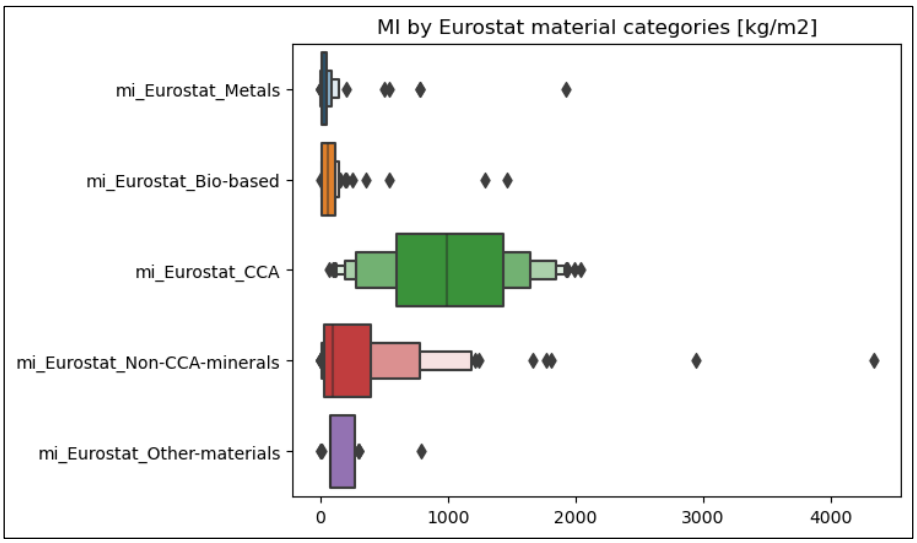


Figure 28: Material intensity - Material mass per m² calculated by main Eurostat material categories.

The dataset contains material information for the total mass of the building (inv_mat_mass_total) as well as on the type and quantity of the top five building materials in terms of mass contribution. Information on the top five materials has been processed and transformed to offer individual attributes on material mass and material intensity for each of those materials, as well as to map those material with Eurostat material categories and compute material intensity per m². Figure 28 presents the distribution of material intensity per m² by Eurostat material category for the full dataset. It shows that the highest material intensity is observed for concrete, cement and aggregate (CCA) materials with a mean value of around 1000 kg/m² and ranging up to around 2000 kg/m². Second largest intensity, on average, is observed for non-CCA minerals, with a mean value of only around 100 kg/m² albeit ranging up to 1200 kg/m² (upper IQR) or even beyond 2000 kg/m², in extreme cases.

4.5. Usage notes

Prioritization of the attributes refers to the relevance of collecting data on a given attribute, in case data collection had to be reduced to a limited set of attributes due to time or resource constraints:

- A = Minimum information scope, most relevant attributes (high value, low effort)
- B = Complete information scope, highly relevant attributes (high value, high effort)
- C = Extended information scope, nice to have (low value, low effort)
- D = Additional information, only if available (low value, high effort)

The attributes utilise three main data types:

- String/object: Usually given as ‘free text’. Also, the baseline type for unspecified data.
- Numerical: Numerical values, all implemented as floats (i.e., with possibility of decimal values).
- Categorical: A *limited* set of values (i.e., categories) which can appear as both text and numerical values.

Furthermore, selected attributes are marked with indicators to note:

- * = Attributes included in phases 1 and 2, not phase 3.
- $^{+}$ = Attributes imputed if empty, either manually or automatically.

Where specified in the attribute description document, sample values specified using closed brackets ([…]) indicate a closed list of values, i.e., all possible values are shown or indicated, while open brackets (]…[) indicate an open list, i.e., more than the value shown are possible (and contained in the dataset). In addition to the sample values, categorical attributes usually have a 'no data' option which indicates that an attribute has been reviewed but no data is available.



5. POLICY OBJECTIVES AND THE STATE OF BUILDING STOCK MODELS

Bibliographic data

Title	Environmental modelling of building stocks – An integrated review of life cycle-based assessment models to support EU policy making
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Journal	Renewable and Sustainable Energy Reviews
Date(s)	Submitted 2 February 2021; Accepted 28 July 2021
DOI	https://doi.org/10.1016/j.rser.2021.111550

Highlights

- This chapter presents an integrated review of EU policy documents and latest approaches for environmental modelling of building stocks.
- Analysis of scope, methods, tools and data shows existing studies mostly focus on housing stock and on short to medium time horizons.
- Existing studies are limited in the number of archetypes, as well as coverage of building parts, life cycle stages and environmental indicators.
- The scope and level of detail of existing models hence require elaboration to effectively support EU policy for decarbonization of building operation and construction.
- Future research is particularly needed on environmental hotspot analysis and monitoring of impacts across time and space.

Author contributions

Martin Röck: Conceptualization; methodology; formal analysis; investigation; data curation and visualization; writing (original draft, review and editing); project administration.

Elena Baldereschi: Methodology; formal analysis; investigation; writing (original draft).

Evelien Verellen: Formal analysis; investigation; visualization; writing (original draft).

Alexander Passer: Conceptualization; writing (review and editing); supervision.

Serenella Sala: Conceptualization; writing (review and editing); supervision.

Karen Allacker: Conceptualization; methodology; writing (review and editing); supervision.

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The following chapter presents the published manuscript version, available as 'open access' (CC BY-NC-ND 4.0), with minor typesetting changes. Original article available via https://doi.org/10.1016/j.rser.2021.111550.

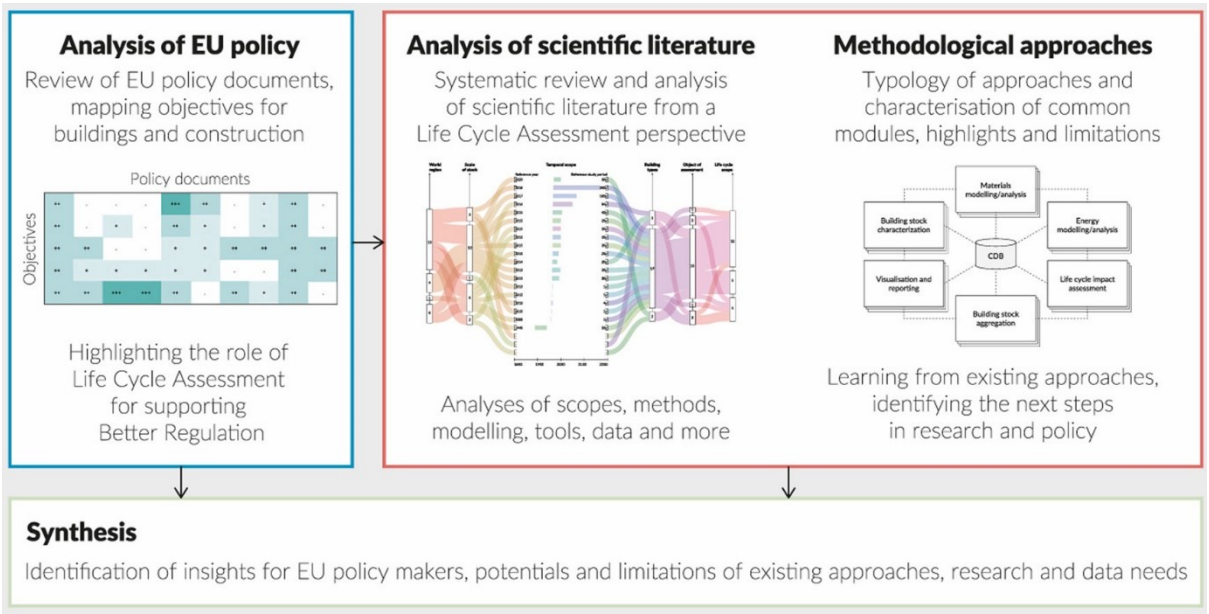
Abstract

Various environmental challenges, particularly the rising severity of the impacts of climate change, require a systematic shift in and decarbonization of the global economy. Due to their high environmental impacts, buildings and construction have a special role in decarbonization. Environmental modelling of building stock dynamics can help policy makers and inform decision making. This study presents a systematic review of both the latest scientific literature on environmental modelling of building stocks and related EU policy initiatives. Our findings illuminate the strengths and limitations of existing approaches as well as the potential of such modelling and the required directions for future development to provide effective policy support. Based on the assessment of 104 scientific papers, our study shortlisted and analysed 22 environmental building stock modelling approaches. While promising, these show various limitations on their effectiveness in supporting decarbonization efforts while avoiding burden shifting. Future building stock models should offer extended system boundaries and comprehensive life cycle assessment, improved hotspot analysis and impact monitoring across spatiotemporal scales. A long-term perspective on the entire building stock covering climate and other environmental impacts is needed, as outlined in the latest standards. By linking existing studies to related EU policy objectives, we identify various studies that investigate scenarios and strategies relevant to EU policy makers and highlight research gaps. Future research should enable comprehensive environmental assessment of building stocks across scales and emphasise the monitoring of multiple environmental impacts of building stock development to ensure compliance with environmental targets and minimization of trade-offs.

Keywords

Life cycle assessment (LCA); Built environment; Spatial and temporal dynamics; Scenario analysis; Environmental impacts; Embodied impacts; Embodied carbon; Material flow analysis; Mitigation; Adaptation; Life cycle analysis; Environmental policy; Policy support; European green deal; Renovation wave; Energy retrofit; Systematic literature review.

Graphical abstract



5.1. Introduction

As the severe effects of climate and ecological crises are increasingly felt across the globe, the need to rapidly depollute and decarbonise the world economy is becoming urgent. For effective climate change mitigation, a systemic approach is needed, focusing on defining sustainable solutions to reduce key drivers of impacts while avoiding trade-offs (Sala et al., 2016a). Systemic approaches have to evolve from simply assessing improvements in relative efficiency towards addressing sustainability from an absolute perspective, i.e., ensuring that development occurs within environmental boundaries (Steffen et al., 2018). Recent developments such as the COVID-19 pandemic highlight the need to rethink the role of humans in the planetary ecosystem and to maximise the potential of a green stimulus within the global economy.

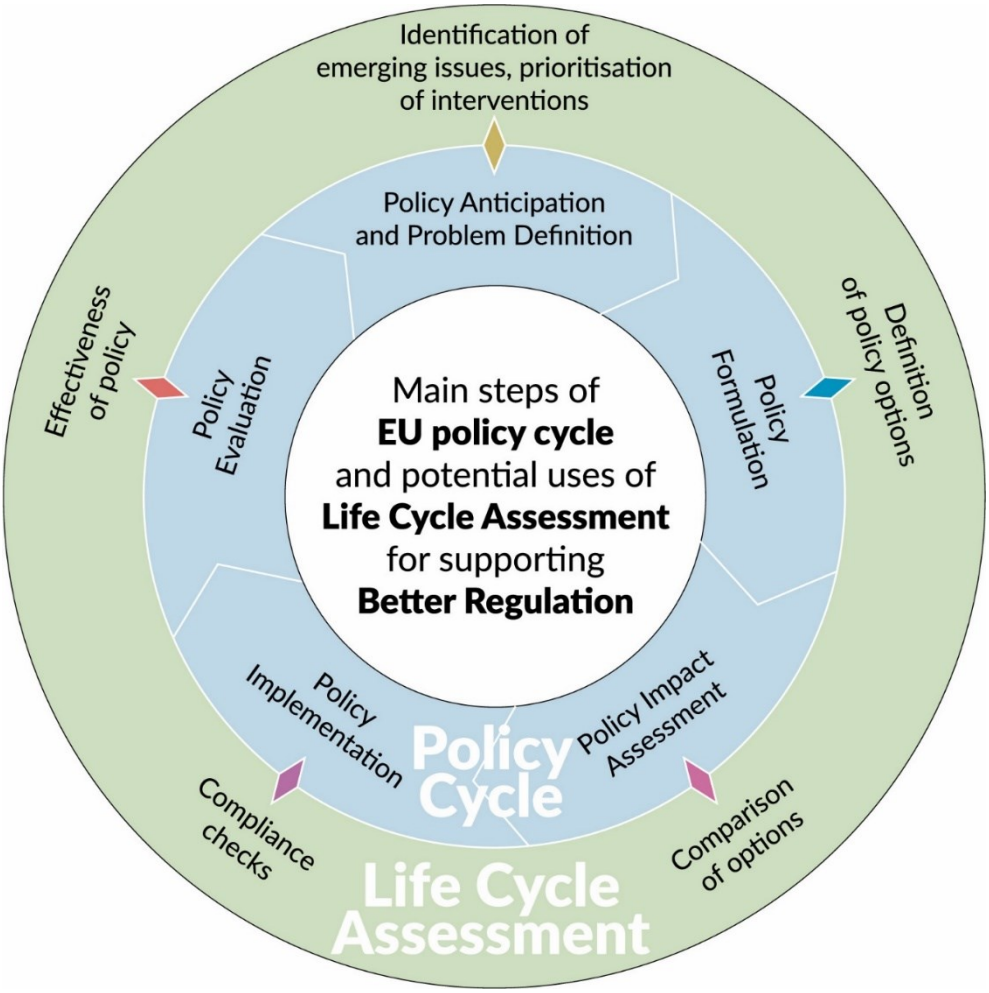


Figure 29: Main steps of the EU policy cycle and the potential uses of Life Cycle Assessment to support Better Regulation (adopted from (Sala et al., 2021)).

Building construction and operations are crucial to the success of efforts to limit climate change, as they account for approximately 40% of global greenhouse gas (GHG) emissions (Global Alliance for Buildings and Construction (GABC) et al., 2019) and are among the key contributors to the environmental impacts of consumption in Europe (Ivanova et al., 2017; Sala and Castellani, 2019). The built environment is at the heart of the sustainability transformations envisaged under the Sustainable Development Goals (SDGs). Various proposals for quantifying environmental targets related to buildings and construction have been put forward. Such targets, e.g., GHG emission budgets, have been calculated for several countries with the aim of harmonizing spatial, temporal, and sectoral target

definitions across scales (Habert et al., 2020a). While a reduction in GHG emissions related to building operations has been achieved in recent years due to stricter energy-efficiency regulations, so-called embodied GHG emissions have increased in both relative and absolute terms (Röck et al., 2020c). Considering that an additional 26 million m2 of buildings are to be constructed and operated in Europe by 2050 (International Energy Agency (IEA), 2013), it is of overarching importance to optimise and reduce GHG emissions related to building operation and construction to enable effective climate change mitigation. However, in developed regions of the Global North such as in the European Union (EU), most buildings that will be standing in 2050 have already been built and are in use today. Hence, enabling renovations and energy-efficiency improvements of the existing building stock is recognised as a crucial challenge.

The EU is a global leader in both climate ambition and action. The various environmental policies launched within the so-called EU Green Deal are amongst the most ambitious in the world, calling for reductions of GHG emissions in the EU economy of 55–60% from 1990 levels by 2030. Various policy initiatives acknowledge the importance of the built environment regarding both the operation of buildings and their production and construction. The “renovation wave”, which aims at increasing yearly renovation rates to at least double, is touted as one of the main initiatives for reducing EU GHG emissions and stimulating green investment. This renovation wave and the recent call for a “New European Bauhaus” represent key institutional efforts to support the implementation of ambitious EU policies on building construction and operation. The effective implementation of these initiatives depends on the deployment of suitable methods and tools to support environmental modelling, monitoring and management of the EU building stock.

To inform policy makers and other decision makers on the environmental implications of decisions, the life cycle assessment (LCA) method is increasingly applied. The general application of LCA is internationally standardised (ISO 14040) with several standards in the EU context defining the specifics of its application, e.g., to assess construction products (EN 15804) or buildings (EN 15978). Recent studies have highlighted the role and increasing importance of LCA in EU policymaking (Sala et al., 2021). Furthermore, LCA is listed as a tool for policy support in the Better Regulation Toolbox, an EU initiative aiming at improving the policy process. The use of LCA is foreseen in different steps of the EU policy cycle, as outlined in Figure 29. LCA use cases range from supporting the policy anticipation and problem definition (identification of issues for which a policy intervention is needed), up to policy impact assessment (comparing different policy options) as well as policy implementation and assessment of policy effectiveness.

To develop and identify effective policies to reduce building related GHG emissions and other environmental impacts, not only the modelling and assessment of individual buildings but also a move to the system level are required, taking into account the characteristics and dynamics of building stocks at scale. Several research projects have focused on methodological questions surrounding building stock modelling – primarily utilised for modelling building-related energy use – and its practical implications. In 2004, as one of the results of the International Energy Agency's (IEA's) Energy in Buildings and Communities Programme (EBC) Annex 31 on “Energy-Related Environmental Impact of Buildings”, Moffatt et al. (Moffatt, 2004a) proposed a conceptual framework with modules relevant to bottom-up building stock aggregation (BSA) models from an energy modelling perspective. The proposed concept is still relevant and has frequently been adopted in contemporary studies, the scope of which has increasingly been extended to achieve more holistic environmental modelling of building stocks and related dynamics. In 2017, Mastrucci et al. (Mastrucci et al., 2017a) presented a comprehensive review on the topic, including a categorization of stock modelling approaches ranging from the urban to the transnational scale. The study covered papers published from 2006 to 2015. More recently, in 2019,

Göswein et al. (Göswein et al., 2019) presented a review on environmental modelling of urban building stocks, focusing on the modelling of spatial and temporal dynamics and the combination of both. While their study focused on the urban scale, it provided valuable findings on modelling and method-related differences and proposed a framework for identifying suitable approaches to providing insights to the different stakeholders concerned, amongst them policy makers.

5.2. Objective and research questions

The objective of this study is to review the latest research on the environmental modelling of building stocks and provide insights into the potential of and requirements for environmental modelling of building stocks to be used to support EU policy making. This study addresses two main research questions:

1. What is state of the art regarding methods for modelling and assessing environmental impacts of building stocks and related spatial and temporal dynamics?
2. What are the EU policy objectives related to building stock development and to what degree are existing modelling approaches suitable for supporting the assessment and implementation of these objectives?

To answer these questions, we conduct a systematic review of scientific literature from an LCA perspective to ensure a holistic approach in addressing building-related environmental impacts. This review focuses on the spatiotemporal scope of assessment methods, data sources, and tools and software and critically evaluates the comprehensiveness and performance of environmental hotspot analysis across spatiotemporal dimensions. We include an in-depth review and analysis of methodological aspects and databases, model-related characteristics such as data granularity and data sources and an analysis of the presentation of results and their critical evaluation within studies. Furthermore, we link the findings on building stock modelling approaches to the relevant EU policy objectives to identify the potential of and requirements for the implementation of these approaches as well as research needs from a policy support perspective.

The novelty of this study stems from its integrated analysis of scientific literature and policy objectives. This paper aims to make a considerable advance on the analyses in previous studies by linking the findings to EU policy objectives to provide insights into the potential of and need for policy-making support through environmental modelling of building stocks and related dynamics.

5.3. Material and methods

This study addresses the research questions in three main steps, as shown in Figure 30:

1. An analysis of relevant EU policies to identify policy objectives related to building stock development, building construction and operation.
2. A systematic review and analysis of the scientific literature to identify the state of the art of environmental modelling of building stock dynamics from an LCA perspective; and
3. A synthesis of the findings from the scientific literature in relation to EU policy objectives and discussion of the potential of environmental modelling of building stocks to support EU policy and the directions in which such approaches should be developed for this purpose, as well as gaps in the research related to EU policy.

Chapters 3.1. and 3.2. Provide details on the method adopted for the review of policy documents and the scientific literature, respectively.

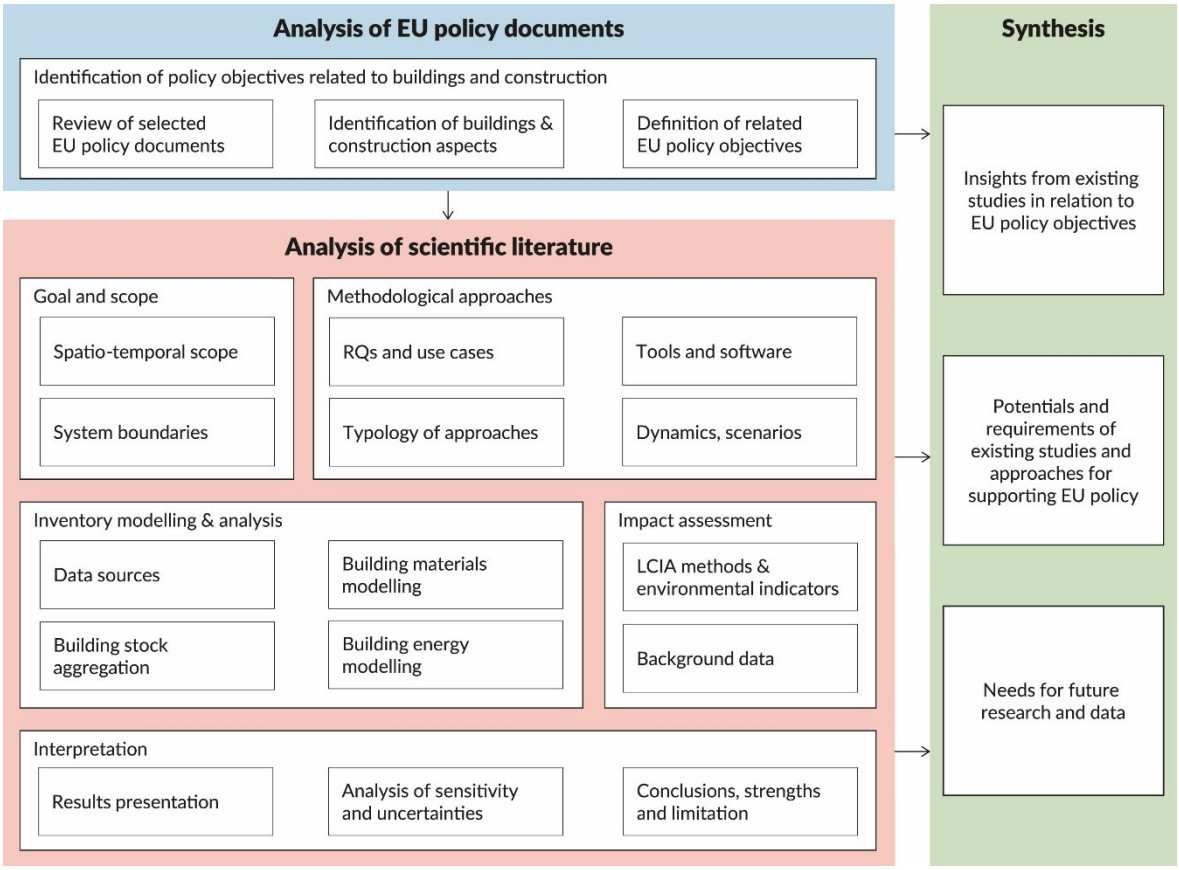


Figure 30: Outline of the three main steps in this study: 1) analysis of EU policy documents; 2) analysis of the scientific literature; and 3) synthesis of the findings to identify the potential and requirements of such modelling to provide enhanced policy support.

5.3.1. Review of EU policy documents

To analyse EU policy initiatives related to buildings and construction, we reviewed various relevant policy documents issued by the European Commission (EC) in recent years. We identified and reviewed documents related to the following policy initiatives referring directly or indirectly to buildings and construction (full references are provided in the table of policy documents at the end of this paper):

- European Green Deal
- Circular Economy Action Plan (2020)
- Biodiversity Strategy for 2030
- European Climate Law
- EU Renovation Wave
- New Industrial Strategy
- A Clean Planet for All
- Bioeconomy Strategy
- EU Sustainable Development Goals (SDGs)
- Waste Framework Directive

We screened these documents and searched them for keywords related to environmental assessment of building stocks and building construction and operations. We collected relevant paragraphs and topics from the documents and synthesised these into a set of policy objectives relevant to EU building stock development and building construction and operations.

5.3.2. Review of scientific literature

We conducted a systematic literature review (SLR) to identify the state of the art of the published scientific literature (Haddaway et al., 2020; Higgins and Green, 2008). Based on the research questions, search keywords were defined for use in the Scopus and ScienceDirect scientific databases; the searches covered article titles, abstracts and author-specified keywords. The search string, defined through an iterative process, was [(LCA OR life cycle analysis OR life cycle assessment) AND (building stock)]. We limited the results by article type to research articles and review articles (i.e., we excluded conference proceedings, books, theses, etc.). We considered studies whose year of publication was from 2016 to 2020 to build on the related 2017 review of Mastrucci et al. (Mastrucci et al., 2017a), which included studies up until 2015. We conducted the database search in May 2020.

Following a step-by-step process in line with the SLR protocol, we refined the initial search results by including only those studies fulfilling the following four criteria:

- Analysing a building stock using a bottom-up or hybrid (bottom-up and top-down) approach;
- Applying a life cycle-based approach for assessing operational and/or embodied impacts;
- Focusing on building stocks at the urban to transnational scales (including national or regional scales); and
- Assessing at least one environmental indicator (i.e., material and energy flow studies without an environmental impact assessment were excluded).

A total of 104 unique papers were identified and then filtered in terms of relevance in three steps by screening their title, abstract and full text. After these screening and exclusion steps, 22 papers were identified as the final sample (Almeida and Ferreira, 2017; Chandrakumar et al., 2020; Drouilles et al., 2019a; Feng et al., 2020a; Gabrielli and Ruggeri, 2019a; Ghose et al., 2020a; Heeren and Hellweg, 2019b; Krarti and Dubey, 2017a, 2017a; Moncef Krarti and Dubey, 2018a, 2018b; Lavagna et al., 2018a; Mastrucci et al., 2020a, 2017c; Österbring et al., 2019a; Peñaloza et al., 2018a; Pittau et al., 2019a; Pombo et al., 2019a; Seo et al., 2018a; Andre Stephan and Athanassiadis, 2017; Zygmunt and Piczulski, 2019a) for systematic data extraction and analysis. A flowchart of the SLR, data extraction and analysis is provided in Supplementary Information Figure S1.

Based on the final sample of studies, we conducted systematic data extraction, documenting information related to various pre-defined features and aspects, focusing on LCA-related dimensions. The relevant features were defined based on findings in the literature and following guidelines and standards related to environmental footprint assessment (EF guidelines) and LCA (ISO 14044) of construction products (EN 15804) and buildings (EN 15978). The feature groups defined for the data extraction process are presented in Supplementary Information Table S1. The final sample of studies is presented in Supplementary Information Table S2.

5.4. Results of the analysis of EU policy documents

5.4.1. Policy initiatives underpinning the European Green Deal

The reviewed policy documents relate to a set of policy initiatives for developing a sustainable, climate-neutral, circular and bio-based economy in the EU. Several of these policy initiatives have been developed under the umbrella of the European Green Deal, which sets the EC's priorities for the period 2019-24. In brief, the policies aim to support the decoupling of economic growth from resource use; enable the incremental implementation of the net-zero GHG emissions target by 2050, with intermediate goals for 2030; and ensure that people and regions are involved and not left behind in this transition. Each of the policy documents adds a piece of the puzzle by outlining specific targets and strategies for

their specific field of action and related stakeholders. An extended summary of relevant points identified in each policy document is provided in Supplementary Results: Analysis of EU Policy Documents.

5.4.2. EU policy objectives for building construction and operation

Based on the document review and synthesis, we defined five policy objectives related to EU building stock development and building construction and operations:

1. Improvements to energy efficiency: Following up on the previous success of EU energy efficiency policies for buildings, such as the Energy Performance in Buildings Directives (EPBD), this objective focuses on further improving the energy operational efficiency of both existing and new buildings. For existing buildings, emphasis is placed on increasing renovation rates to at least double the current rates, i.e., to ~3% per year, through the so-called renovation wave.
2. Increases in renewable energy: This objective describes the EU's ambition to increase renewable energy production to ensure low-carbon energy provision as the backbone of the European low-carbon economy. This entails an overall increase in the share of renewables in the EU energy and electricity mix as well as renewable energy production on site (e.g., building-integrated photovoltaics).
3. Circularity and low-carbon material uptake: This objective involves fostering the uptake of low-carbon construction materials, e.g., by increasing the use of bio-based materials and applying circularity principles through reuse and recycling. This objective also relates to efforts to reduce construction waste and the overall ambition of enabling a European circular bioeconomy.
4. Climate change adaptation and resilience: Enabling and enhancing climate change adaptation of EU buildings is crucial for improving resilience with an eye towards future changes in functional requirements. This objective covers efforts to support adaptable building design in anticipation of future changes in building use as well as in external conditions, e.g., due to climate change, for both existing and new buildings.
5. Monitoring of environmental performance: This objective aims to ensure the implementation of the EU's environmental targets through the assessment of environmental impacts over time, with special attention to ecosystem management, land use and land use change. For buildings, this involves monitoring the environmental performance of buildings throughout their life cycle to ensure compliance with environmental targets and the SDGs.

In Figure 31, we provide a visual mapping of the reviewed EU policy documents and their focus in relation to these five policy objectives.

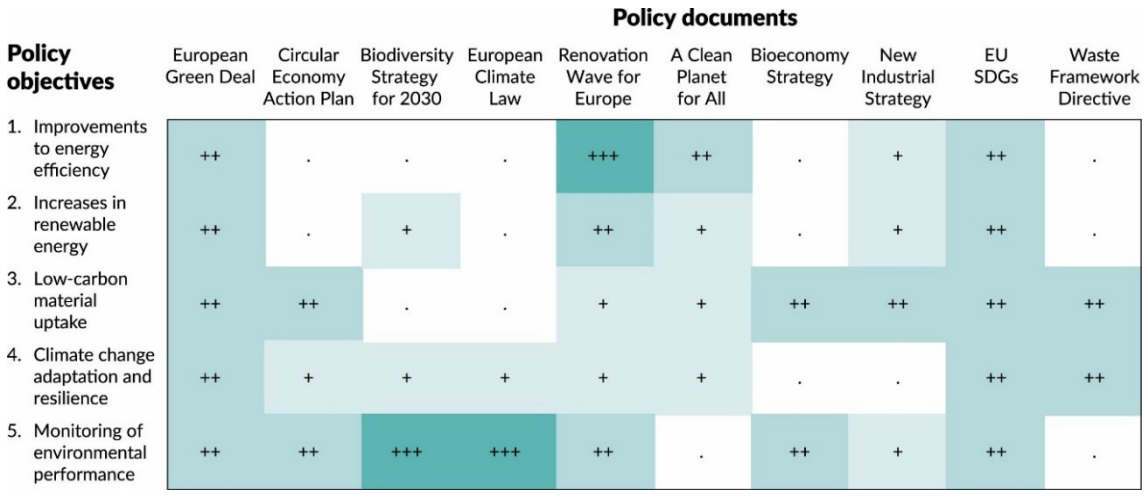


Figure 31: Mapping of reviewed EU policy documents with defined policy objectives, highlighting their focus.

5.5. Results of the analysis of scientific literature

5.5.1. Goal and scope of studies

The results of the analysis of the goal and scope of the investigated studies are presented in the subsequent paragraphs, focusing on spatial and temporal aspects. The understanding of spatial and temporal dynamics related to the evolution of building stocks builds on the research presented by Mastrucci et al. (Mastrucci et al., 2017a) and Göswein et al. (Göswein et al., 2019) in their respective reviews. In our analysis, we differentiate modelling of the building stock and modelling at the building level. Building stock modelling is conducted at the scale of the investigated building stock, with the relevant timeframe of the study and information on building types considered in the model, whereas building information modelling relates to the building life cycle and parts and the energy end uses considered. In line with the European standard for environmental life cycle assessment of construction products and buildings (EN 15804, EN 15978), we documented the consideration of life cycle stages and their respective modules, namely: the product stage (modules A1-A3); the construction process stage (A4, A5); the use stage, differentiated into modules related to embodied impacts (B1–B5) and impacts from operational energy and water use (B6, B7); and the end-of-life stage (C1–C4). We also documented the handling of benefits and loads outside the system boundary (module D), as these are related to end-of-life recycling and potential reuse.

Figure 32 provides an overview of the spatial and temporal scope of the building stocks analysed in the investigated studies. We found that the majority of the studies in our final sample (13 of 22) investigate building stocks in a European context. Other regional contexts found are Australia and Oceania (4), the Greater Middle East (4) and North America (1). Most studies in our final sample investigate building stocks at a national scale (10), although the scale of building stocks studied ranges from the transnational (3) to the regional (1), urban (6) and portfolio scales (2).In terms of temporal scope, i.e., the timeframe of the study, most studies focus on prospective analyses and study building stock development and related environmental impacts based on stock development projections for several years, decades, or sometimes centuries into the future. Ten out of the 22 studies use a timeframe between 2013 and 2055 with a building stock reference study period (RSP) ranging from 25 to 40 years. Three studies deploy an extended timeframe of 84–200 years, taking 2016 to 2018 as their starting points. Five studies offer a snapshot of the state of the building stock in 1–4 specific years, with 2005–2013 as the reference years. The types of buildings investigated in the studies are mostly residential buildings (17 of 22), with two of these studies specializing in single-family houses (SFHs) and one on multi-family houses (MFHs). Two studies focus on other building types, such as office or university buildings. Three studies assess a full building stock covering various building types, including and beyond residential and office buildings. The majority of the studies focus on the retrofitting of existing buildings (15), taking different building types into consideration. Twelve out of the 22 studies in our sample take a life cycle approach to investigating both embodied and operational environmental impacts, while a total of ten studies focus exclusively on either embodied (5) or operational (5) impacts. While we documented the consideration of all life cycle stages and modules as defined in EN 15978, we here present the two general categories: embodied, i.e., material-related, impacts and operational impacts, i.e., those related to building energy and water use. The comprehensive analysis of the life cycle scope of the studies is presented in Supplementary Information Table S3.

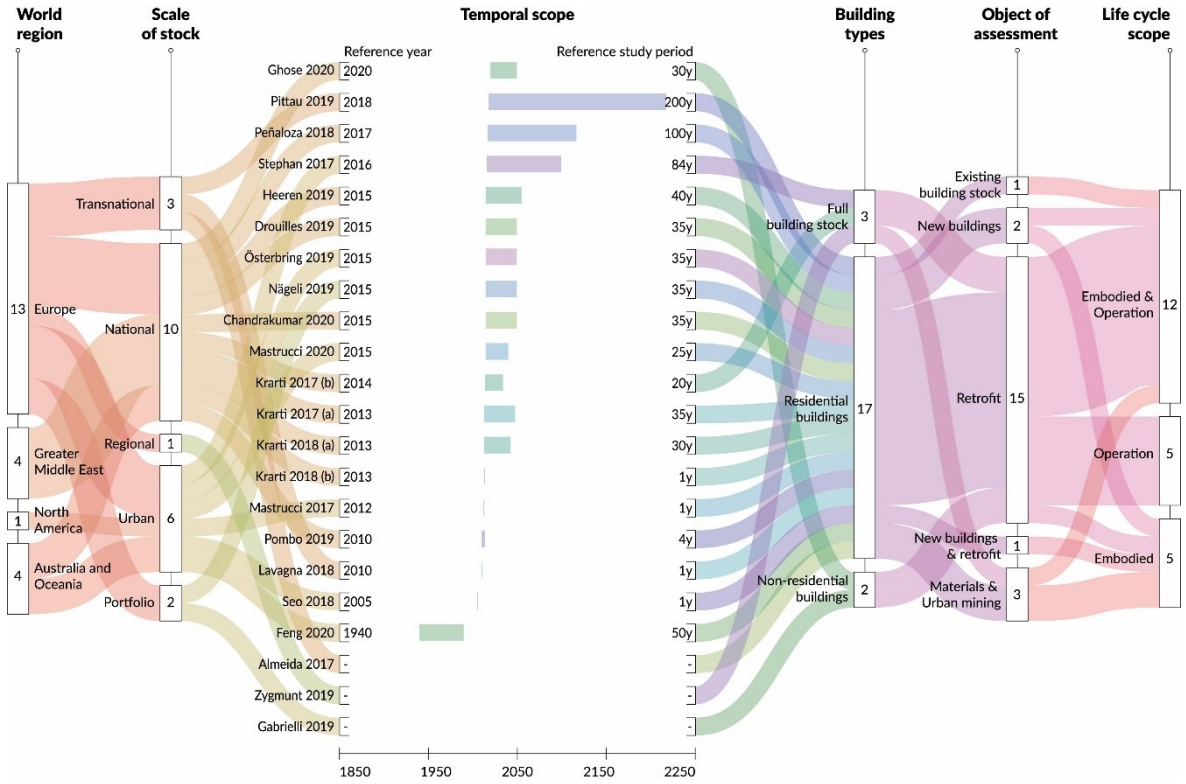


Figure 32: Spatial and temporal scope of building stock modelling in the investigated studies.

Upon analysing the individual studies shown in Figure 32, we found that the studies mainly investigate prospective timeframes of 25–35 years, i.e., reaching up to (or close to) 2050 and hence enabling an assessment of environmental targets and mitigation pathways up to mid-century. Only few studies project further into the future. Pittau et al. (Pittau et al., 2019a)apply an extensive temporal scope of 200 years to study refurbishment strategies for the European residential building stock with bio-based materials. Their study projects embodied GHG emissions as well as potential carbon storage from the use of different conventional and bio-based materials for a timeframe of 2018 until 2217. Pénaloza et al. (Peñaloza et al., 2018a) and Stephan and Athanassiadis (Andre Stephan and Athanassiadis, 2017) deploy timeframes of 100 and 84 years, respectively. Some studies analyse environmental impacts related to the building stock in a given year, e.g., the life cycle-based environmental impacts of the European building stock in 2010 (Lavagna et al., 2018a). One study conducts a retrospective analysis of the environmental impacts of building stocks in the 20th century based on the timeframe of 1940–1990 in a region of Canada (Feng et al., 2020a). In other cases, the expected environmental impacts of end-of-life treatment of materials are investigated for an urban building stock in Luxembourg (reference year 2012) (Mastrucci et al., 2017c) and Australia (reference year 2005) (Seo et al., 2018a). For three studies, we were unable to clearly identify the reference year and/or the duration. Additional information and details on the spatial and temporal scope of the individual studies together with a characterization of their modelling approaches are presented in the following chapters and available in the Supplementary Data file. The analysis of the spatial and temporal scope at the building level, i.e., life cycle stages, building parts and energy end uses considered in the different studies, revealed that none of the studies provide a complete assessment covering all these aspects in a comprehensive manner. Only two studies cover the full building life cycle, i.e., cradle to grave, without limitations (Drouilles et al., 2019a; Lavagna et al., 2018a). Six studies approach a cradle-to-grave scope but show limitations due to the exclusion of some life cycle modules. The remaining studies have different scopes, with some focusing on cradle-to-gate or cradle-to-site, in-use or end-of-use life cycle modules. In the case of four studies, we could not clearly identify the life cycle stages covered from the documentation

provided in the papers. An overview of the temporal scope regarding life cycle modules considered in the individual studies is available in Supplementary Information Table S3. An elaborate description and discussion of the building parts as well as the energy end uses covered in the investigated studies is provided in chapter 5.3.2 Material modelling and chapter 5.3.3 Energy modelling, respectively.

5.5.2. Dynamic aspects and scenario variables

The definition of static and dynamic aspects in the LCA of buildings stocks follows the definition of Mastrucci et al. in their related review (Mastrucci et al., 2017a), where 'static' means the assessment of the situation at a given time or the comparison of two distinct states in time. In contrast, 'dynamic' modelling considers the evolution of the building stock over time. The review of Göswein et al. (Göswein et al., 2019) suggested a further differentiation of dynamic aspects considering spatial, (evolutionary) temporal, and spatial-cohort dynamics. In this study, we adopt a combined approach considering three types of dynamics. First, spatial dynamics, as the spatial differentiation in the baseline model, e.g., of building characteristics in different geographical or climatic areas. Second, temporal dynamics, as consideration of changes over time, e.g., changes to demand for space, user behaviour, and technological innovation in energy or material production. Third, spatial-temporal dynamics, as changes over both space and time, e.g., diversification of properties for some buildings (spatial dynamic) over time (temporal dynamic) due to retrofit activities or changes in use.

Table 1 presents an overview of the dynamic aspects identified in the final sample of studies. The table is structured to cluster cases based on related steps in environmental modelling, i.e., modelling of foreground inventory, background inventory, or impact assessment. We define the foreground inventory as the definition of types and quantities of buildings, elements and systems as well as construction materials and operational energy and water along the life cycle of the buildings. The background inventory relates to the conditions of material and energy related processes and the use of respective LCA data for modelling the life cycle of materials and energy flows (as specified in foreground inventory), e.g., production of 1 kg of material type X, or 1 kWh of energy type Y.

Table 1. Examples of dynamic aspects identified in the final sample of studies.

Dynamic aspects in modelling steps			**Types of dynamics**		
Step	**Aspects**	**Examples**	**Spatial**	**Temporal**	**Spatial-temporal**
Foreground inventory	Demand for space, occupant behaviour and comfort	Population projections; Typology of family; Floor area per capita; Presence time of occupants; Thermal comfort levels	Building stock classification in different climatic zones or geoclusters [Almeida 2017, Lavagna 2018, Pittau 2019, Ghose 2020]	Projections for population and floor area demand [Penaloza 2018, Ghose et al 2020, Mastrucci et al 2020];	Demand projections and sensitivity of floor area per capita [Heeren 2019]; Building stock size and number of buildings to be renovated [Pittau 2019]; User behaviour and related energy demand reduction scenarios [Pombo 2019]; Sensitivity of dwelling size development [Penaloza 2018]; Influence of changes to cooling and heating set point, as well as illuminance [Ghose 2020]
	Building typologies and archetype definitions	Number and definition of representative buildings; Differentiation of archetypes; Changes in culture of design and construction	Differentiation of building types and construction period [Mastrucci 2017, Stephan 2017, Zygmunt 2019, Heeren 2019, Mastrucci 2020,	Future need for detached housing based on population assumptions [Chandrakumar 2020]; Future changes to market share of different building types (SFH, MFH) in new buildings [Penaloza 2018];	Scenarios for energy retrofit (e.g., energy system switch to renewable energy, improved energy performance of the building envelope) [Almeida 2017, Seo 2018, Gabrielli 2019, Österbring 2019, Nageli, 2019, Drouilles, 2019, Pombo

			Ghose 2020]; Considering building quality and refurbishment needs [Gabrielli 2019]	Changes in renewal rates, building materials and energy standards, building technology upgrades [Heeren 2019];	2019, Zygmunt 2019, Feng 2020]
	Building elements and materials, technical systems and energy use	Material choice; uptake of technological innovation; degradation of technical performance of materials or systems; Integration of renewable energy systems	-	Investigation of future recycling rate scenarios [Mastrucci, 2017]; Material flow and embodied impacts of different future renovation scenarios [Mastrucci 2020, Pittau 2019]; Scenarios for future changes to rate of timber typologies, low-impact concrete in new buildings [Penaloza 2018]	Localised yearly material output from building stock turnover based on number of new constructions, rebuilt or refurbished buildings [Heeren 2019]
Background inventory	Material production, processing, end-of-life	Increased recycling content of new construction materials; Changes in recycling technologies and energy recovery practices;	-	Changes to energy mix for material production [Penaloza 2018]	-
	Energy mix scenarios	Changes to energy mix (electricity, heat), e.g., due to national policies and regulations or market mechanisms	-	Energy consumption and future electricity mix changes [Chandrakumar et al 2020]; Electricity grid evolution [Ghose et al 2020]	-
Impact assessment	Carbon uptake and emissions	Carbon uptake during growth of bio-based materials; Biogenic carbon storage in construction products; Biogenic carbon emissions at the end of life of products;	Influence of biogenic carbon consideration for different building types [Chandrakumar 2020]	Dynamic impact assessment based on time-dependent impact aggregation matrix and carbon storage from bio-based materials [Pittau 2019]; analysis of dynamic carbon footprint methodology [Mastrucci et al 2020]	-
	Characterization and weighting	Temporal changes to characterization and/or weighting factors; Regionalisation of impact factors based on process location;	-	-	-

In the final sample for this review, half of the studies present a static assessment of the building stock. This means, for example, that for the energy modelling, the heating degree days (HDD) are considered constant and energy mixes are kept unchanged throughout the study timeframe. Some static models, however, include scenarios or variations to improve the model accuracy by considering, e.g., different renovation scenarios or varying energy mixes (Feng et al., 2020a; Nägeli et al., 2019a; Seo et al., 2018a). In their scenario analyses, some studies focus on different renovation scenarios (Krarti et al., 2017; Moncef Krarti and Dubey, 2018a, 2018b; Mastrucci et al., 2020a; Österbring et al., 2019a), while others vary energy mixes to study their influence on the environmental impacts during operation (Chandrakumar et al., 2020; Ghose et al., 2020a; Peñaloza et al., 2018a). Five studies include dynamic climate or weather data (Drouilles et al., 2019a; Krarti et al., 2017; Krarti and Dubey, 2017a; Moncef Krarti and Dubey, 2018a, 2018b). It should be noted that the four studies of Krarti et al. (Krarti et al.,

2017, 2017; Moncef Krarti and Dubey, 2018a, 2018b) are, for the most part, based on a common methodology. In terms of temporal dynamics, two studies explicitly present the change in environmental impacts over time (Mastrucci et al., 2020a; Pittau et al., 2019a), and four studies present the change in material flows (Ghose et al., 2020a; Heeren and Hellweg, 2019b; Peñaloza et al., 2018a; Pittau et al., 2019a). Finally, individual studies focus on other dynamic aspects, e.g., the influence of changing recycling rates (Mastrucci et al., 2017c), of changing financial investment capacity per year (Österbring et al., 2019a), and of population growth (Ghose et al., 2020a) and related trends in the use of floor area per capita (Heeren and Hellweg, 2019b).

5.5.3. Inventory modelling and analysis

The subsequent chapters present our findings regarding inventory modelling and analysis for three main modules of environmental building stock models: (a) building stock aggregation, (b) material modelling, and (c) energy modelling. We also present an analysis of the various data sources used in the reviewed literature. An extended overview of the data sources as well as tools and software used in the reviewed studies for the modelling of these aspects are provided in Supplementary Information Table S4 and in the Supplementary Data file.

Building stock characterization and aggregation

Modelling

Figure 33 shows six features of the different building stock aggregation approaches and their interrelationship: the object of assessment (existing building stock, new buildings, retrofits, new buildings and retrofits, or materials and urban mining), the scale of the stock (building, urban, regional, national, or transnational), the number of buildings in the actual stock, the number of archetype variations used for modelling (as well as segmentation criteria applied to differentiate archetype variants), the aggregation approach (archetype, building by building, or sample) and life cycle scope (embodied, operational, or both).

First, as noted earlier, it is clear that almost half of the studies focus on the national level (10), just over a quarter on the urban scale (6) and the remainder on either the transnational (4), regional (1) or building portfolio (2) scales. Second, although the number of buildings in the stock is not specified in six of the papers, the literature review shows that a larger scale of the stock tends to correspond to a larger number of buildings included in the stock. However, studies with a stock model size of over 1 million buildings, for example, may cover urban, national or transnational scales. Third, from the perspective of the connection between the number of buildings in the stock and the number of archetype variants, studies including a larger number of buildings (more than 10,000) always use the archetype approach. However, the segmentation criteria applied to differentiate buildings in the stock, as well as the overall number of archetype variants used for modelling, vary widely (from 1 to 1680) and do not necessarily correspond to the size of the stock under investigation. Fourth, the archetype approach is used in two-thirds of the studies, while only one study makes use of a sample method, and six studies implement a building-by-building model. Investigating the combination of characteristics in the individual studies, we observed that all studies taking a building-by-building approach are on a relatively small scale, covering a maximum of 10,000 buildings (or they do not report the number of buildings involved), and are conducted at the building portfolio, urban or national scale. The sample method is used in one study of multi-family houses at a national scale. Figure 33 further shows the segmentation criteria used to differentiate the archetypes and number of variants modelled for each criterion. We find that the building type (e.g., residential, office) or building typology (e.g., different types of residential buildings [SFH, MFH]) are the most common criteria. Studies further use the construction period, location or climate conditions as well as material scenarios (for both new construction and retrofit studies) to

differentiate the archetypes. Overall, we find that several studies use a remarkably small number of archetype variants in their modelling of building stocks with several thousand buildings, which at times raises questions of the representativeness of the chosen archetype(s). At the same time, we find studies combining several criteria to generate several hundred archetype variants to model their building stock (Ghose et al., 2020a; Pittau et al., 2019a).

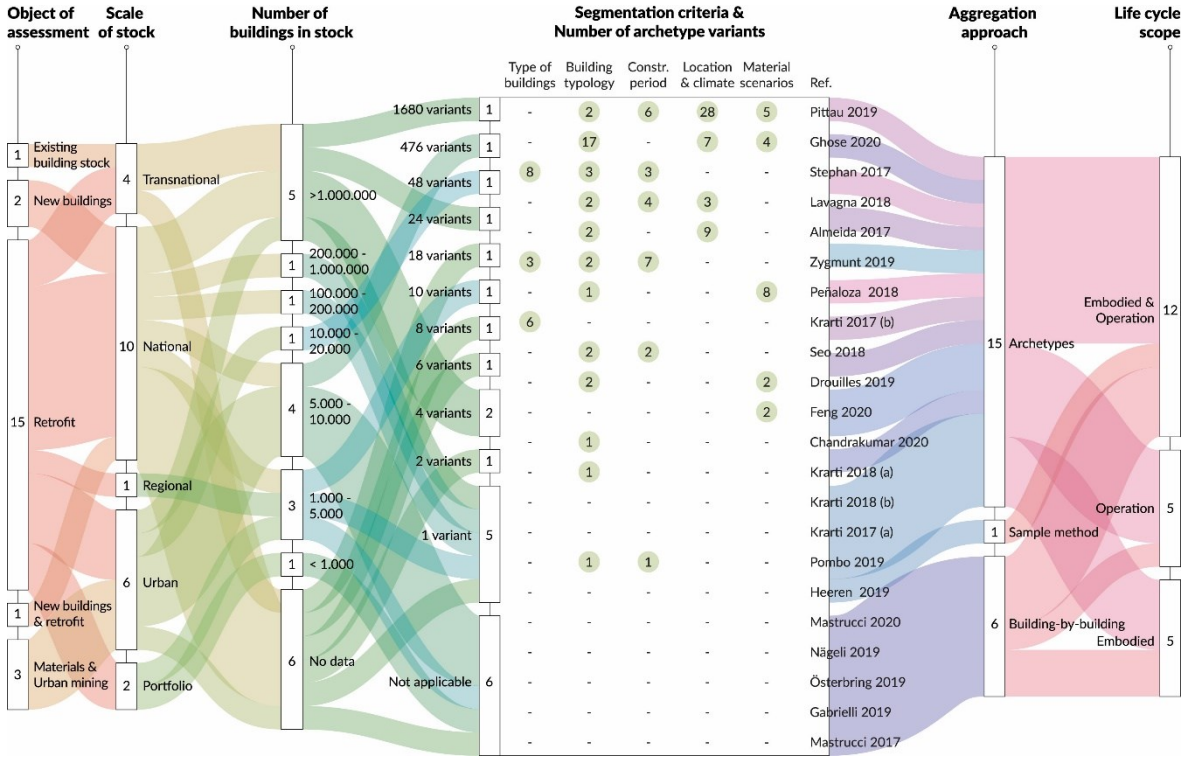


Figure 33: Building typology, scale of the study, stock size, number of archetypes, aggregation approach and goal of the study.

An overview of the building (stock) characteristics and their use for building stock characterization and clustering in the different studies is presented in *Supplementary Information Table S5*. We found that construction year and building type are the most used criteria for building stock characterization and clustering. These two characteristics commonly appear both individually and in combination. This combination is followed by the combination of the size and climate characteristics, which appears in every study clustering based on size and in three of the six studies (Almeida and Ferreira, 2017; Ghose et al., 2020b; Heeren et al., 2013; Lavagna et al., 2018b; Pittau et al., 2019b; Pombo et al., 2019b) using climate zones as a clustering criterion. The combination of building typology and renovation state/need was identified three times.

Data sources

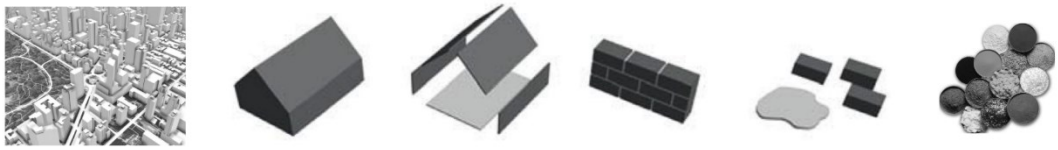
A variety of data sources were identified to obtain relevant information on building stock composition and characterization and to aggregate the building stock models. For studies not including a building-by-building case study analysis, we obtained building information by consulting various data sources to fill gaps in the data. Ten out of the 22 studies use statistical data on demographics and building information. These statistical data include national open source datasets (Drouilles et al., 2019b; Heeren and Hellweg, 2019a; André Stephan and Athanassiadis, 2017) and generalised datasets regarding building parameters such as type of use or geometry (Mastrucci et al., 2020b; Nägeli et al., 2019b; Österbring et al., 2019b; Pittau et al., 2019b). Five papers fill gaps using data from other studies on building stock levels to estimate the climate impact (Chandrakumar et al., 2020), determine quantities of building materials (Mastrucci et al., 2017d; Peñaloza et al., 2018b) or apply the methodology

developed in a previous paper (Pombo et al., 2019b) (by the same author). Another five studies use geographical information systems (GIS) data to identify building geometry and fills gaps in building use data (Heeren and Hellweg, 2019a; Mastrucci et al., 2020b, 2017d; Nägeli et al., 2019b; Österbring et al., 2019b; André Stephan and Athanassiadis, 2017). Seven studies make use of building (stock) databases such as, among others, TABULA (Lavagna et al., 2018b; Pittau et al., 2019b) to establish building stock compositions, retrofit steps and timing (Heeren and Hellweg, 2019a; Mastrucci et al., 2020b, 2017d; André Stephan and Athanassiadis, 2017) or archetype definitions. In addition, probabilistic approaches (Mastrucci et al., 2020b) and existing studies at the building level (Feng et al., 2020a) are used. An overview of data sources used for the inventory modelling in different studies is presented in *Supplementary Information Table S4* and in the *Supplementary Data* file.

Material modelling

Modelling

This chapter presents an investigation of the material inventory modelling and analyses, as identified in the reviewed literature. Overall, we identified that most studies follow the element method, i.e., they model material inventories in a hierarchical way based on building elements and their material composition. Strong variation was identified, however, in the context of the model resolution and level of detail in the hierarchical models.



	Building cluster (Level +1)	Building level (Level 0)	Building element (Level -1)	Sub-element (Level -2)	Constr. material (Level -3)	Raw material (Level -4)
Modelling	0	3	14	3	5	1
Results	13	14	2	0	2	0
n/a	9	5	6	19	15	21

Figure 34: Identified level of detail used for modelling and/or results presentation.

In Figure 34, we thus analysed the resolution of both the modelling and the reporting of material-related impacts, based on the levels of modelling used in the Belgian building and building stock LCA tool in (Trigaux et al., 2014) and referring to the levels of investigation as outlined in the European EF guidelines and their application to the building level in the PEF4Buildings pilot project (Spirinckx et al., 2019b). We found that 14 studies model the stock from the level of building elements, which are aggregated to represent buildings and the building stock. Few studies apply modelling levels below the element level. Sub-element-level modelling is used in three studies and construction material-level modelling in five; only one study includes in its inventory the modelling of raw materials (i.e., the use of raw materials in construction products, e.g., according to the Eurostat raw material categories of biomass, metal ores, non-metallic minerals, and fossil energy materials). The results are expressed mostly at the building and building stock levels. In general, we observed a lack of results presented at a higher resolution than the element level and a lack of environmental hotspot analyses across different levels, which are crucial for the environmental optimization of buildings, construction products and related supply chains. The topic of hotspots in terms of environmental indicators is discussed further in chapter 5.5.4.

Figure 35 provides further information on the scope of the reviewed studies in terms of building parts included in the assessment as well as on the level of detail for material modelling and results

presentation. We found that the studies investigate different objects, with a variety of building parts covered in the assessments. While most of the studies likely make use of quantity information and background data at the material level, many of them do not explicitly show this in the documentation of their modelling approach or the life cycle inventories presented. Analysing the most complete studies from this perspective, we found seven studies with a comprehensive scope (Drouilles et al., 2019a; Feng et al., 2020b; Moncef Krarti and Dubey, 2018c; Moncek Krarti and Dubey, 2018; Lavagna et al., 2018b; Nägeli et al., 2019b), i.e., covering building parts related to structural systems, envelopes and façades as well as internal elements and technical systems (some with limitations). The objects of assessment range from the current state of the existing building stock or investigation of retrofit measures to material-focused and urban mining studies. We found that four of the seven studies (Drouilles et al., 2019b; Feng et al., 2020b; Moncef Krarti and Dubey, 2018c; Moncek Krarti and Dubey, 2018) are modelled at the element level and present the results at the building level. Of these, the sub-element level is utilised by one study (Feng et al., 2020b). For another three studies, we also identified modelling at the sub-element level (Österbring et al., 2019b) with the results presented at the building cluster level (Lavagna et al., 2018b; Nägeli et al., 2019b). While some studies display a comprehensive focus on the building elements covered, others focus exclusively on one part of the building system. The latter is the case, for example, for retrofit studies focusing on the building envelope.



Figure 35: Building parts covered in studies and the level of detail applied in material modelling and results presentation mapped in relation to the object of assessment and aggregation approach of the studies. (Building parts: ✓ = included completely; (✓) = included with limitations. Material modelling and results: M = level used for modelling; R = level at which results are presented.)

In terms of modelling material-related inventories and the presentation of related environmental impact results, we identified a wide variety of approaches. We found that in general, various levels of detail are used for modelling when an archetype-based aggregation approach is deployed. Multiple levels of modelling are utilised in four archetype-based studies (Chandrakumar et al., 2020; Österbring et al., 2019b; Peñaloza et al., 2018b; Pittau et al., 2019b). While also differing in their use of modelling levels, studies applying a building-by-building approach tend to utilise more levels of material modelling and

more often use these levels to present the results in terms of both material inventories and environmental impacts. Utilization of several levels of modelling is presented in four out of the five building-by-building studies (Heeren and Hellweg, 2019a; Mastrucci et al., 2020b, 2017d; André Stephan and Athanassiadis, 2017).

From an overall perspective, while some studies were identified that either displayed a comprehensive scope in terms of building elements (Drouilles et al., 2019b; Feng et al., 2020b; Moncef Krarti and Dubey, 2018c; Moncek Krarti and Dubey, 2018; Lavagna et al., 2018b; Nägeli et al., 2019b) or offered a comparably detailed modelling of material-related inventories (Chandrakumar et al., 2020; Heeren and Hellweg, 2019a; Mastrucci et al., 2017d; Peñaloza et al., 2018b; Pittau et al., 2019b; André Stephan and Athanassiadis, 2017), none of the studies could be identified as providing both at the same time. However, considering the variety of combinations found in terms of objects of assessment, building part scopes, levels of material modelling and aggregation approaches, lessons can be learned from these existing approaches to advance building stock modelling practices to achieve comprehensive and detailed modelling of material-related environmental impacts.

Data sources

We found a variety of material-related data sources. Several studies utilise statistical data from building material and element databases such as the KBOB database for Switzerland (Drouilles et al., 2019b) or, in the Australian context, data from the national bureau of statistics (Seo et al., 2018b) or the dedicated CLUE building material database (André Stephan and Athanassiadis, 2017). Several studies base their analysis of material-related impacts on previous studies at the building stock level (as in (Ghose et al., 2020b), which is largely based on previous research by the same authors (Ghose et al., 2019)) or, more commonly, at the building level. Prior studies at the building level are frequently utilised, based on LCA data from BRANZ for New Zealand in the case of (Chandrakumar et al., 2020), material data on representative buildings for Luxembourg in (Mastrucci et al., 2017d), or data and reports from related research projects such as IEA EBC Annex 56 ("Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation") in (Almeida and Ferreira, 2017). Databases on building or building stock data are used in several studies, especially in the European context. Such studies use data from projects such as TABULA, EPISCOPE, ENTRANZE, ODYSSEE or the European Building Stock Observatory (Lavagna et al., 2018b; Pittau et al., 2019b) as well as building data from national or local building libraries (Mastrucci et al., 2020b, 2017d). Other data used include material-related data from building energy performance certificates (Österbring et al., 2019b) or material-relevant information from building energy cost data for maintenance and building services (Nägeli et al., 2019b). Regulations and standards are utilised to obtain information to model end-of-life scenarios and impact coefficients (Mastrucci et al., 2017d) or building envelopes according to existing thermal performance requirements (Mastrucci et al., 2020b). We further identified the use of probabilistic approaches for projecting element service life and the timing of replacements (Heeren and Hellweg, 2019a) as well as for modelling past renovations and future renovation needs with statistics-based random distributions (Mastrucci et al., 2020b). A complete overview of data sources used for inventory modelling in different studies is presented in *Supplementary Information Table S4* and the *Supplementary Data* file.

Energy modelling

Modelling

This chapter presents a detailed investigation of the energy modelling and analyses identified in the reviewed literature.

Figure 36 shows the different approaches used to model the operational energy demand and related environmental impacts. Based on the objects of assessment, we documented the scope of energy end

uses considered in the modelling. The energy end uses documented are heating (H), cooling (C), ventilation (V), domestic hot water (W), lighting (L), and other appliances (A). We observed two studies covering the full scope in terms of energy end uses (i.e., HCVWLA). These studies base their modelling on a monthly or yearly resolution of energy use. No studies combining a comprehensive end-use scope with the highest (hourly) resolution in energy modelling could be identified. We found eight studies that employ dynamic energy simulation and six that employ steady or quasi-steady modelling. When a steady simulation is applied, the resolution time step is yearly or monthly, whereas dynamic simulation is always conducted with an hourly time step resolution. We identified only three papers applying a statistical approach, and in these cases, a yearly resolution is utilised.

Among the papers with bottom-up statistical models, (Gabrielli and Ruggeri, 2019b) is the only one that develops a multiple linear regression equation to estimate building energy demand. One study uses a top-down approach to calculate the energy consumption of each archetype in the baseline scenario (Lavagna et al., 2018b). As a further development of this study, Allacker et al. (Allacker et al., 2019) perform dynamic energy simulation on the archetypes defined in Lavagna et al. (Lavagna et al., 2018b) to assess the life cycle environmental burdens and benefits of some eco-innovation measures. Chandrakumar et al. (Chandrakumar et al., 2020) use a statistical approach to calculate the variations in energy sources in the future. Seo, Foliente and Ren (Seo et al., 2018b) utilise statistical data to obtain the energy consumption of the construction sector and to quantify the embodied environmental impacts of retrofitting. Furthermore, they model heating and cooling energy requirements using an energy simulation tool to calculate the benefits of improved energy performance in residential buildings.

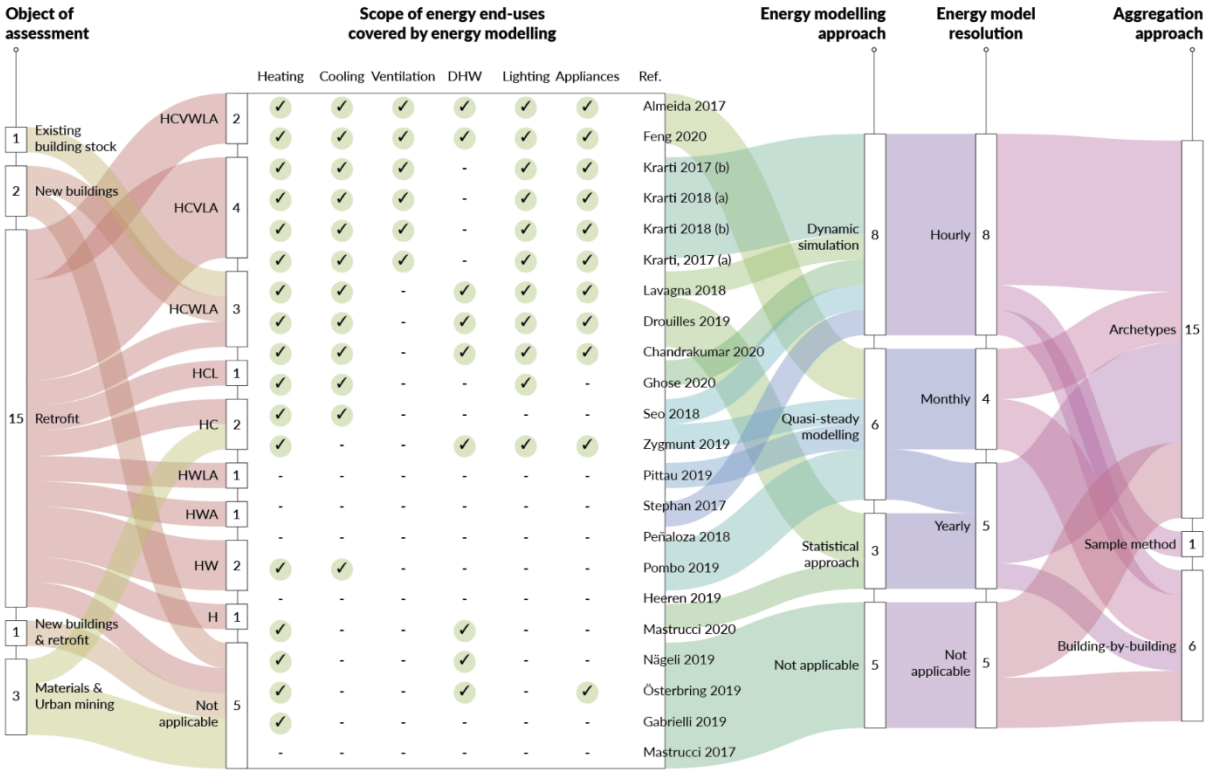


Figure 36: Energy modelling overview to present the object of assessment, scope of energy end uses (heating (H), cooling (C), ventilation (V), domestic hot water (W), lighting (L), or appliances (A)) plus the energy modelling approach, model resolution and aggregation approach applied.

Data sources

The analysis of the data sources for the energy modelling showed that statistical data and regulations and standards are the most used sources.

Statistical data are utilised for different objectives, e.g., to acquire the national energy consumption of the construction sector (Seo et al., 2018b), to obtain the share of energy carriers in households (Zygmunt and Piczulski, 2019b) or to cover heating and domestic hot water demand by type of building and construction period (Drouilles et al., 2019b). Statistical data are combined with individual national energy mixes to define the energy consumption of each archetype in Lavagna et al. (Lavagna et al., 2018b). National and international regulations and standards are mostly used as a reference to calculate energy demand through simulations (Almeida and Ferreira, 2017; Gabrielli and Ruggeri, 2019b; Nägeli et al., 2019b; Pombo et al., 2019b; Zygmunt and Piczulski, 2019b). Standards and regulations are considered to develop energy performance scenarios in two studies (Drouilles et al., 2019b; Seo et al., 2018b). Two studies define the geometric characteristics of buildings using GIS data provided by city planning offices and apply these data for energy calculations (Nägeli et al., 2019b; Österbring et al., 2019b). The same two studies also utilise building energy performance certificates (EPCs) as a data source for information on heating and ventilation systems, the average number of apartments, building height and measured energy use (Nägeli et al., 2019b; Österbring et al., 2019b).

LCA scenarios

LCA studies typically use scenario modelling to assess the influence of certain parameters on the overall results. The literature review checked for which parameters such scenario analysis was performed, identifying the following parameters: estimated service life (ESL) and reference study period (RSP), recycled content versus primary material use, refurbishment scenarios, and end-of-life scenarios.

In ten studies, special attention is paid to specifying the ESL. In three studies (Feng et al., 2020b; Ghose et al., 2020b; Österbring et al., 2019b), the ESL is defined by building element, while one study defines an overall RSP of 100 years for the building itself (Lavagna et al., 2018b). Four studies state the RSP, varying from 25 years (Seo et al., 2018b) to 60 years (Pittau et al., 2019b; Pombo et al., 2019b) after renovation, at the building level only. Pittau et al. (Pittau et al., 2019b) and Pombo et al. (Pombo et al., 2019b) further conduct a sensitivity analysis to examine a shorter ESL of building elements and buildings to evaluate the influence of ESL on the overall results. Only one study includes a sensitivity analysis to test the impacts and implications of substituting primary material with recycled content (Heeren and Hellweg, 2019a).

Various different renovation measures are investigated in seven of the studies in our sample (Almeida and Ferreira, 2017; Feng et al., 2020b; Ghose et al., 2020b; Heeren and Hellweg, 2019a; Mastrucci et al., 2020b; Pombo et al., 2019b; Zygmunt and Piczulski, 2019b). One study investigates the financial implications of renovation activities at the urban scale for different renovation measures by studying the maximum renovation rate for a certain measure as a function of households' investment capacity (Österbring et al., 2019b).

In the majority of the papers, end-of-life scenarios are not included. Pittau et al. (Pittau et al., 2019b) include three disposal scenarios. In the paper of Mastrucci et al. (Mastrucci et al., 2017d), the business-as-usual scenario is compared to a second scenario where an increased down-cycling rate for inner waste is assumed. The study of Heeren et al. (Heeren and Hellweg, 2019a) includes a sensitivity analysis for recycling and reuse scenarios for concrete, wood and thermal insulation.

In conclusion, only a small number of studies include different LCA scenarios in their modelling and analysis of the building stock in terms of material- and energy-related impacts. Furthermore, the LCA scenarios are critically investigated through sensitivity analyses in only a few of the studies.

5.5.4. Life cycle impact assessment

This chapter reviews the life cycle impact assessment (LCIA) methods and related environmental indicators adopted by the selected studies. Our analysis refers to the LCIA methods and environmental indicators suggested in the European Committee for Standardization (CEN) standards (EN 15804, EN

15978). The methods and environmental indicators analysed in the reviewed studies are available in *Supplementary Information Table S6*.

First, we found that LCIA methods are rarely mentioned in the papers, even though various environmental indicators are assessed. All studies in our final sample assess environmental indicators of global warming potential (GWP). Out of the sample, 16 studies focus exclusively on this indicator. After GWP, the most common environmental indicators are acidification potential (AP), ozone depletion potential (ODP), eutrophication potential (EP) and photochemical ozone creation potential (POCP). The categories of water resource depletion and land use are considered by only two studies. The review of the EU policy documents, however, revealed that the importance of land use and land use change is increasing, especially under the Biodiversity Strategy. A building stock impact assessment should hence include land use indicators to support EU policy goals. Finally, we noted that in current studies, normalization and weighting are rarely implemented. Normalization is applied in only two studies (Mastrucci et al., 2017d; Österbring et al., 2019b), but no details on the method for normalization are provided. One study (Lavagna et al., 2018b) uses the International Reference Life Cycle Data System (ILCD) method to normalise and weight the results.

5.5.5. Strengths and limitations of studies

As a final step towards identifying the potential of existing building stock modelling approaches to support policy as well as the required directions that such approaches should take to provide this support, we reviewed the strengths and limitations of the studies in our sample. An overview of these strengths and limitations, either as stated by the authors of the respective studies or as identified through our review, is presented in *Supplementary Information Table S7*. A summary of the findings is provided in this chapter.

Scenarios involving energy efficiency and refurbishments frequently report the potential for improvement in the considered studies. Six studies (Chandrakumar et al., 2020; Ghose et al., 2020b; Heeren and Hellweg, 2019a; Mastrucci et al., 2020b; Peñaloza et al., 2018b; Zygmunt and Piczulski, 2019b) go even further by examining exogenous factors driving stock development, such as projected population growth and future evolution of the energy mix or the renovation rate. Seven studies (Almeida and Ferreira, 2017; Feng et al., 2020b; Gabrielli and Ruggeri, 2019b; Krarti and Dubey, 2017b; Moncef Krarti and Dubey, 2018d; Moncek Krarti and Dubey, 2018; Österbring et al., 2019b; Seo et al., 2018b) furthermore include cost analyses measuring the energy or impact improvements of projects against the payback time, related job creation or investment capacity, which are mentioned as topics for future work in two studies (Ghose et al., 2020b; Nägeli et al., 2019b).

Not only the number of investigated impacts but also the level of detail in the assessments vary. One way of achieving a higher level of detail is by utilizing digital building stock information tools like GIS or building information modelling (BIM), which are implemented in four studies (Feng et al., 2020b; Heeren and Hellweg, 2019a; Mastrucci et al., 2020b, 2017d) and stated as a requirement for future research in three more papers (Ghose et al., 2020b; Mastrucci et al., 2017d; André Stephan and Athanassiadis, 2017). A higher level of detail is also seen in six studies (Ghose et al., 2020b; Lavagna et al., 2018b; Mastrucci et al., 2017d; Österbring et al., 2019b; Pombo et al., 2019b; Zygmunt and Piczulski, 2019b) considering multiple environmental indicators. This is in contrast to the other studies, which include only CO_2 or GHG emissions, although the reliance on these indicators is criticised internally in some cases (Gabrielli and Ruggeri, 2019b; Lavagna et al., 2018b; Pombo et al., 2019b). Only two papers (Drouilles et al., 2019b; Lavagna et al., 2018b) achieve a full life cycle analysis by considering all life cycle stages. Three papers go beyond an environmental impact assessment by including policy impacts (Österbring et al., 2019b), mobility (Drouilles et al., 2019b) or a social LCA (Pombo et al., 2019b). The need for a higher level of detail regarding the spatiotemporal aspects applied

in LCA is expressed in five papers (Heeren and Hellweg, 2019a; Mastrucci et al., 2020b, 2017d; Österbring et al., 2019b; Peñaloza et al., 2018b).

Finally, to validate the quality of the results, almost half of the studies (Chandrakumar et al., 2020; Gabrielli and Ruggeri, 2019b; Ghose et al., 2020b; Heeren and Hellweg, 2019a; Lavagna et al., 2018b; Mastrucci et al., 2020b; Peñaloza et al., 2018b; Pittau et al., 2019b) include an uncertainty analysis where the influence of different model parameters is considered to evaluate the susceptibility to variation in outcomes. Only one study presents an uncertainty analysis (Gabrielli and Ruggeri, 2019b) including the use of a probability distribution, although three other studies mention the need to conduct uncertainty analyses (Drouilles et al., 2019b; Mastrucci et al., 2017d; Peñaloza et al., 2018b).

5.5.6. Typology of methodological approaches

This chapter provides an overview of the various methodological approaches and their characteristics. The description of the modelling approaches and methodological modules is a synthesis of the methodological frameworks presented in the reviewed studies.

The modules are based on previous studies, e.g., IEA EBC Annex 31 (Moffatt, 2004b) and the review by Mastrucci et al. (Mastrucci et al., 2017b), who defined the building aggregation model, energy model, and LCA model as relevant components of stock modelling. We expand the definition to six basic modules common to most of the studies, as presented in Figure 37: i) building stock characterization; ii) material modelling; iii) energy modelling; iv) life cycle impact assessment; v) building stock aggregation; and vi) visualization and reporting. These represent the basic blocks of models for the environmental assessment of building stocks, as identified in our review.

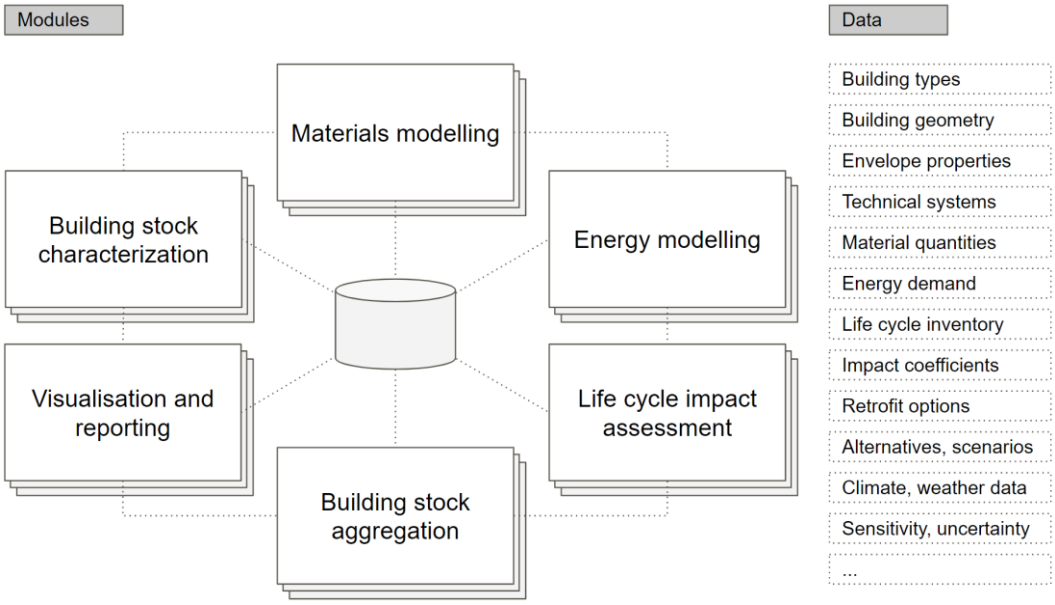


Figure 37: Common modules in the environmental modelling of building stocks and examples of relevant data.

Building stock characterization relates to the characterization and clustering of the building stock and the definition of representative buildings or archetypes or, where applicable, data processing for a building-by-building aggregation approach. Materials modelling relates to the modelling of building components and materials based on thermal, physical and other characteristics and with related calculation of replacements according to the ESL of building elements. Depending on the modelling approach, quantification of construction materials may be conducted for building elements (e.g., for application in both building-by-building and archetype-based models) or for full buildings only (e.g., for use in archetype-based aggregation). Energy modelling refers to the determination of operational

energy demand. The data and tools applied in this module strongly depend on the type of study and the energy modelling method applied (e.g., dynamic or quasi-steady approaches), which are discussed in chapter *Energy modelling*. LCIA relates to the quantification of environmental impacts through the application of impact coefficients.

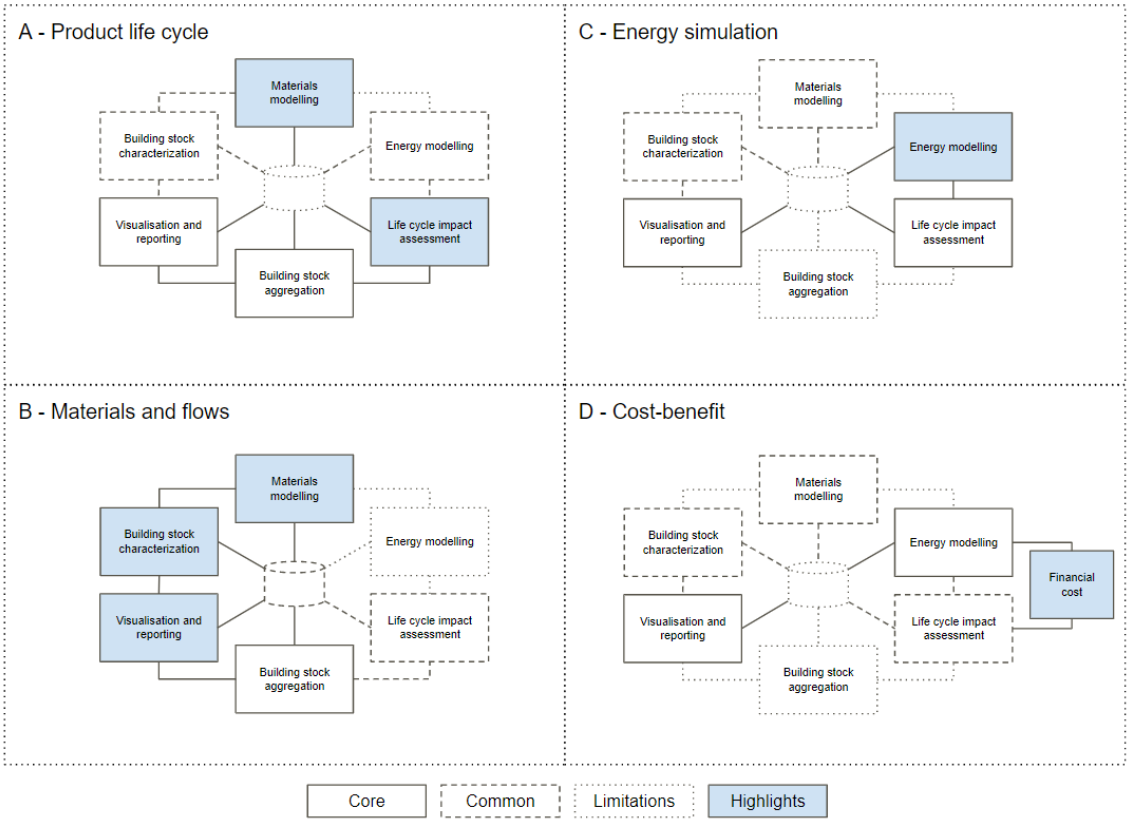


Figure 38: Overview of the different modelling approaches and their core modules, highlights and limitations.

The studies in our sample vary strongly in terms of the scope of the life cycle stages and environmental indicators covered. Hence, the data and tools used for LCIA also depend on the modelling approach and range from a simple application of impact coefficients (i.e., multiplication of material quantities with the respective coefficients, e.g., kilos of CO_2eq per kilo of material) to the use of comprehensive LCIA methods with an extended set of environmental indicators and dedicated LCA software. Building stock aggregation is the process of aggregating the information obtained through materials and energy modelling and scaling up to the level of a building stock. In most studies, especially those using an archetype-based aggregation approach, this step is carried out after the LCIA. However, especially for studies using a building-by-building aggregation approach, impact assessment is often conducted after materials and energy information have been aggregated and scaled up to the level of the building stock. The important factor here is the ability of the models to maintain the level of detail in life cycle inventories and impact assessment as they scale up to the level of the building stock. Eventually, visualization and reporting are conducted to interpret and communicate the results of the study and report the findings accordingly. Depending on the type of study, different tools and visualization options – ranging from bar charts or heat maps to show the contribution of different life cycle stages or building parts to spatialised visualizations of assessment results on geographical maps – may be utilised.

For some studies, we could observe the use of a central database or a common data environment to manage the large variety and quantity of data to be processed in complex building stock models. Furthermore, the data processed in the respective modules may follow one definition or contain multiple

alternative solutions, as is the case in investigations of different scenarios, e.g., for different retrofit strategies in material modelling or climate change scenarios in energy modelling.

Considering these six modules, we distinguished the stock modelling approaches into four types: type A, product life cycle approach; type B, materials and flows focus; type C, building energy simulation; and type D, cost-benefit analysis. Based on their specific perspectives and focuses, modelling approaches were found to fit one type or a combination of several types. Figure 38 presents the four modelling approaches, indicating the common modules, the modules that are core to the approach, and the limitations or strengths (highlights) of the approach.

Table 20 provides a detailed description of the characteristics identified for the different modelling approaches. A detailed description of an exemplary modelling approach is available in *Supplementary Information Figure S2*.

Table 20: Description of modelling approach scope and system boundaries as well as tools and software for modelling.

	Modelling approaches and their focus			
Description	**A: Product life cycle**	**B: Materials and flows**	**C: Energy simulation**	**D: Cost-benefit**
Summary				
Context	Background in environmental LCA of products. Detailed models of the building across its life cycle, scaled to stock using archetypes. Often combined with energy models (type C)	Background in industrial ecology and urban metabolism research. Customised approaches for extending material flow analysis (MFA) with LCA, use of GIS	Background in energy modelling, dynamic simulation of buildings. Mostly applied for analysing stock refurbishment. Often combined with cost-benefit models (type D)	Models focusing on identifying the financial cost-benefit optimum for retrofit measures applied at the stock level. Often combined with energy models (type C)
Strengths	Full life cycle scope (cradle to grave) Hotspot analysis at building level (parts, materials, life cycle stages)	Flexibility regarding spatiotemporal scope, level of modelling detail Scalable across stock sizes (if data available)	Support for dynamic energy simulation of future climate scenarios	Support for identification of cost-effective solutions (some studies include other market-related aspects)
Limitations	Aggregation based mostly on a limited number of archetypes, with exceptions	Energy modelling often simplified or not included at all	Limited to operation or in-use phase, focused mostly on refurbishment	Aggregation based on an often-limited number of archetypes
Scope, system boundaries, indicators				
Building stock scale	Stocks from regional to transnational scale, no urban scale studies Timeframe 30-50 years	Stocks from urban to transnational scale Timeframe 25-200 years	Stocks mostly on national scale Timeframe 4-35 years	Stocks from portfolio to national scale Timeframe 20-35 years
Life cycle stages	Cradle to grave (full life cycle)	Various: Cradle to grave (with limitations), production, end of use	Operation, in use (including materials replacement, refurbishment)	
Building parts, materials	Various: Potential to cover all building parts (e.g., structure, envelope, finishes, technical systems)		Focus on envelope (insulation, windows) and technical systems (heating, cooling, domestic hot water [DHW], photovoltaic [PV])	

Energy end uses	Comprehensive scope (heating, cooling, DHW, lighting, appliances)	Various: Often no operational energy use considered, as focus on materials	Comprehensive scope (see type A). Only type considering ventilation	Comprehensive scope (see type A, some combinations with type C)
Impact assessment, indicators	Various: Most studies focus on GHG-related indicators, independent of model type; some present comprehensive scope (e.g., CEN indicator set). Extending list of environmental indicators seems feasible for most approaches			Only GHG-related indicators (e.g., GWP)
Modelling, data and tools				
General framework, data and tools	-	Use of tools for scripting (e.g., R, Python) and database management (e.g., PostgreSQL)	-	Often combined with dynamic energy models (type C)
Building stock characterization	Statistical data (national statistics, energy performance, TABULA, EPISCOPE)	Statistical data (geoclusters), GIS tools (e.g., PostGIS, QGIS, GRASS GIS) for building by building	Statistical data (climate zone, energy performance)	Statistical data, characteristics of buildings in portfolio
Building stock aggregation	Archetype only	Both archetype and building by building	Archetype mostly, sample method	Archetype mostly, building by building
Materials modelling	Based on plans, documentation. Some use of BIM models to obtain building material information, quantities (e.g., Autodesk Revit)	Element composition based on statistics (material use) and functional requirements (regulations)	Often combined with life cycle models (type A)	Focus on operation, only one study considers embodied impacts of retrofitting
Energy modelling	Based on statistics or quasi-steady approach. Often combined with energy models (type C)	Quasi-steady approach mostly. Some use of dedicated tools for building energy use modelling (e.g., ECCABS model)	Only type using dynamic energy simulation (e.g., DesignBuilder, EnergyPlus), as well as quasi-steady approach	Quasi-steady and/or dynamic energy modelling tools (e.g., AccuRate, EnergyPlus)
Life cycle impact assessment	Use of dedicated LCA tools (e.g., SimaPro) and databases (e.g., ecoinvent)	Script-based LCA tools (e.g., Brightway2, SimaPro)	No pattern identified	Common use of impact coefficients

To relate the identified modelling approaches to the goal and scope of the studies, their life cycle inventory modelling and analysis, we present a compilation of the data extracted on the spatiotemporal scope of studies, their aggregation method and the methodological approach in Table 21.

5.6. Discussion in context of EU policy

5.6.1. Relevance of this study in the EU policy cycle

The findings of this study are expected to be useful in supporting environmental, energy and product policies related to buildings, particularly in the EU context. Learnings from the models reviewed in this study will support policies mainly in two steps of the policy cycle (as outlined in Figure 29): 1. The policy anticipation and problem definition, namely the identification of issues that need to be regulated via a policy (e.g., issues that are generating environmental impacts or concerns); 2. The modelling and comparison of environmental implications of different policy options in the policy formulation and impact assessment steps of the policy cycle. This study hence provides support on those steps for

policymaking where policies are involving issues related to the building stock, building construction and operation, particularly.

5.6.2. Learnings for supporting EU policy making

Methodological approaches

In this study, the existing methodological approaches are described and categorised into four types of methodological frameworks with different foci in their modelling, as discussed in chapter *5.5.6*. Combinations of approaches were also identified in the current literature, with multiple models (or the results from various research papers) often integrated in one study. Learning from and combining existing approaches found in the latest literature can inform comprehensive approaches to environmental modelling of building stocks to support EU policy making. Nevertheless, existing modelling approaches need to be better integrated and combined to enable comprehensive and detailed modelling of building stock evolutions and related environmental impacts to support EU policy in the coming decades.

Goal and scope

We found that most studies investigate prospective timeframes up to 2050 and hence support an assessment of environmental targets and mitigation pathways up until mid-century. Only a few studies project further into the future. Investigating building stock development until the end of the century, however, could well be relevant, especially considering mitigation scenarios that include negative emissions in the second half of the century, with biogenic carbon storage in buildings potentially playing an important role.

Table 21: Assignment of modelling approaches and overview of the spatiotemporal scope of investigated studies

						Modelling approaches			
Reference	**Scale of the study**	**Object of assessment**	**Life cycle scope**	**Aggregation approach**	**Modelling approach (Abbr.)**	**A: Product life cycle**	**B: Materials and flows**	**C: Energy simulation**	**D: Cost-benefit**
Almeida and Ferreira 2017	Transnational	Retrofit	Embodied & Operation	Archetypes	C	-	-	✓	-
Chandrakumar et al. 2020	National	New buildings	Embodied & Operation	Archetypes	A+C	✓	-	✓	-
Drouilles et al. 2019	National	Retrofit	Embodied & Operation	Archetypes	A+C	✓	-	✓	-
Feng et al. 2020	Urban	Retrofit	Embodied & Operation	Archetypes	A	✓	-	-	-
Gabrielli and Ruggeri 2019	Portfolio	Retrofit	Operation	Building-by-building	D	-	-	-	✓
Ghose, McLaren, Dowdell 2020	National	Retrofit	Embodied & Operation	Archetypes	A+C	✓	-	✓	-
Heeren and Hellweg 2019	National	New buildings & retrofit	Embodied	Building-by-building	B	-	✓	-	-
Krarti and Dubey 2017 (b)	National	Retrofit	Operation	Archetypes	C+D	-	-	✓	✓
Krarti and Dubey 2018 (a)	National	Retrofit	Operation	Archetypes	C+D	-	-	✓	✓
Krarti and Dubey 2018 (b)	National	Retrofit	Operation	Archetypes	C+D	-	-	✓	✓
Krarti, Dubey, Howarth 2017 (a)	National	Retrofit	Operation	Archetypes	C+D	-	-	✓	✓
Lavagna et al. 2018	Transnational	Existing building stock	Embodied & Operation	Archetypes	A	✓	-	-	-
Mastrucci et al. 2017	Urban	Materials, Urban mining	Embodied	Building-by-building	B	-	✓	-	-
Mastrucci et al. 2020	Urban	Retrofit	Embodied & Operation	Building-by-building	B	-	✓	-	-
Nägeli et al. 2019	Portfolio	Retrofit	Embodied & Operation	Building-by-building	D	-	-	-	✓
Österbring et al. 2019	Urban	Retrofit	Embodied & Operation	Building-by-building	B+C	-	✓	✓	-
Peñaloza et al. 2018	National	New buildings	Embodied	Archetypes	B	-	✓	-	-
Pittau et al. 2019	Transnational	Retrofit	Embodied	Archetypes	B	-	✓	-	-
Pombo, Rivela, Neila 2019	National	Retrofit	Embodied & Operation	Sample method	A+C	✓	-	✓	-
Seo, Foliente, Ren 2018	Urban	Materials, Urban mining	Embodied & Operation	Archetypes	B	-	✓	-	-
Stephan and Athanassiadis 2017	Urban	Materials, Urban mining	Embodied	Archetypes	B	-	✓	-	-
Zygmunt and Piczulski 2019	Regional	Retrofit	Embodied & Operation	Archetypes	C	-	-	✓	-

Dynamics aspects and scenario variables

While also relying on many static parameters, existing studies consider various dynamics of building stock development. Dynamic aspects cover both the inventory and the impact assessment side and our analysis shows examples of different dynamic aspects and where they occur in the reviewed studies (Table 20). Commonly identified dynamics considered are, e.g., spatial differentiation of buildings in the stock, temporal evolution of future energy mixes, or spatial-temporal changes to buildings due to renovation activities. Some studies even anticipate the effects of climate- or weather-related changes or consider the influence of dynamic impact characterization. Other dynamic aspects considered include exogenous factors driving stock development, such as projected population development, occupational density (i.e., floor area per capita), material efficiency or the influence of financial aspects on the feasibility of certain renovation measures and related changes in the renovation rate.

We identify a need for future research on the integration of dynamic aspects, particularly in relation to background inventory (e.g. spatial and temporal differentiation of background datasets) and impact assessment (e.g. regionalisation of characterization factors or temporal dynamics of GHGs climate change impact). For foreground inventory, exogenous stock drivers, such as the influence of market-related aspects (such as real estate speculation or vacancy taxes) on construction activity, and other influences on the rate of new construction or demolition, should be integrated to assess the future impacts of stock development in different scenarios. The introduction of additional temporalities in every phase of LCA for buildings and the investigation of temporal details in socio-economic behaviour could offer added value for the modelling and monitoring of environmental impacts.

The role of dynamic aspects in the LCA of buildings is increasingly considered a key aspects to be addressed, with a recent review study by Su et al. investigating this very topic in more detail (Su et al., 2021). Beyond buildings, recent studies on dynamic LCA of mobility systems showcase the operationalization of dynamic LCA by including temporal differentiation on the complete background database (Pigné et al., 2020).

Stock characterization and aggregation

We found different aggregation approaches (archetypes, building by building) applied for building stock modelling at various scales. Due to prevalent restrictions in data availability, building-by-building approaches are currently limited to building stocks at urban to national scales, which might change as more detailed building stock data (e.g., building geometry information) become more widely available. We observed that archetype-based modelling is currently the dominant approach.

We also found that larger stocks tend to have a lower ratio in the number of archetypes to the number of buildings, which raises questions about the level of detail in the modelling and should be addressed by a more refined definition of archetypes in terms of both quality and quantity. In terms of building stock characterization and clustering, we found building typology, construction year and size to be amongst the most common criteria. One way of achieving a higher level of detail is by utilizing digital building stock information tools such as GIS or BIM, which are implemented in four studies (Feng et al., 2020b; Heeren and Hellweg, 2019a; Mastrucci et al., 2020b, 2017d) and stated as a requirement for future work in three more papers (Ghose et al., 2020b; Mastrucci et al., 2017d; André Stephan and Athanassiadis, 2017). If following the predominantly applied archetype approach, further differentiation of building types –multiple variants of building layouts, e.g., for SFHs or MFHs, respectively – could enable a more representative modelling of the diversity of building layouts and occupational patterns in a given building stock.

Material modelling and analysis

Several of the existing building stock modelling studies show a fairly complete scope in terms of building parts covered; three of these are studies in a European context. At the same time, several existing studies apply multiple levels in their modelling of material-related impacts, ranging from the raw material or construction material and building element level up to the building and building cluster level. However, none of the existing studies show both a comprehensive scope in terms of the building parts covered and a high level of detail in the modelling of material-related impacts.

To date, the level of detail in both modelling and presentation of the results is limited and requires further elaboration in future research. Furthermore, spatiotemporal aspects related to embodied impacts are hardly investigated at all in current research. We found that it is mostly material-focused modelling approaches (type B) that can provide such insights and that may offer important learning opportunities for advancing the spatiotemporal modelling of environmental impacts in future building stock development if it is combined with other modelling approaches.

Energy modelling and analysis

In relation to energy modelling, the potential contribution to EU policy offered by existing approaches lies in expanding the detailed energy modelling of retrofit options to building stocks through dynamic simulation with hourly resolution, similarly to studies applying the building energy modelling-focused approach (type C).

Future research and data related to energy modelling should cover all energy end uses, consider the variation in energy demand as stock and climatic conditions change, consider the evolution of the energy mix and leverage the increasing availability of GIS data at the European level to characterise the building stock in greater detail.

Life cycle impact assessment

In terms of impact assessment, the studies extensively investigate climate change mitigation through the renovation of building stocks, following the main objective of the EU Green Deal to make the economy carbon neutral by 2050. All studies in our sample assess GHG-related indicators (e.g., GWP), with many focusing exclusively on these indicators.

To avoid burden shifting, all the impact categories listed in the related CEN standards should be considered, as these are relevant for the building sector. In addition, particular attention should be paid to land use impact indicators, as EU policies highlight the importance of preserving this resource. Normalization and weighting should be implemented to obtain a single indicator of environmental impact and support EU policy making in a more effective way. LCIA could be further developed to consider dynamic variation in characterization factors over time and space.

In terms of dynamics in impact assessment, existing research mostly investigates climate change and toxicity related impacts. For example, state-of-the-art modelling of climate change impacts requires to address the temporal evolution of the impacts adopting time-dependent characterization factors to assess the dynamic LCI in real-time impact scores for a given year (Levasseur et al., 2010b). Taking into account such dynamics has been recognised as particularly relevant for buildings, considering the multi-decades lifecycle (Negishi et al., 2019, 2018).

Interpretation of results

Existing studies are limited in terms of the sensitivity and hotspot analyses presented. To provide relevant insights for policy makers, the hotspot analysis protocol proposed in the product environmental footprint (PEF) guidelines initiative and applied in the EU PEF4Buildings project could provide a reference for elaborating methodologies for environmental hotspot analysis at various scales.

5.6.3. Insights in relation to EU policy objectives

Insights from the systematic review of scientific literature

Table 22 presents a compilation of the strategies found in the studies and their mapping with EU policy goals. To focus the synthesis on studies in a European context, the studies are grouped by their scope – i.e., whether they investigate building stocks in Europe or other world regions – as well as scale and country. A detailed description of the strategies investigated in the individual studies is provided in *Supplementary Information Table S8*.

The analysis shows that numerous studies investigate scenarios related to the objective of energy efficiency improvement in both a European context and beyond, studying stocks at the urban up to the national and transnational scales. While most studies focus on building energy efficiency improvement based on changes to the building envelope (e.g., replacement of insulation, windows), some studies also investigate improvement of building services, such as changes to heating, cooling or ventilation systems.

The environmental implications for the objective of increasing renewable energy are investigated in several studies based on anticipated changes to the energy infrastructure, e.g., the grid electricity mix. Only one study in our sample investigated the effect of on-site renewable energy provision, e.g., through the implementation of building-integrated photovoltaics (BIPVs).

Low-carbon material uptake is the topic of interest in multiple studies on settings across Europe. The substitution of conventional materials with more environmentally friendly alternatives is investigated for building stocks at the national and urban levels. Three studies specifically investigate the increased use of bio-based materials; two of these works cover transnational (EU-28) and national building stocks in the European context.

The objective of enhancing climate change adaptation and resilience is investigated in various studies covering a wide range of scenarios. Only two studies specifically investigate the effects of climate change on building stocks in a European context. Scenarios regarding the intensity and speed of implementation of measures for both mitigation and adaptation – relating to the resilience aspect – were found for building stocks at transnational, national and urban scales in the European context. Only two studies investigate the environmental implications of the evolution of building typologies regarding density (e.g., floor area per person), based primarily on assumptions of a continued increase in this metric. One study assesses the influence of user comfort-related aspects, i.e., changes in room temperature set points, albeit not for the European context. The influence of a variety of eco-innovation scenarios in the European context is specifically investigated by Baldassarri et al. (Baldassarri et al., 2017), building on the transnational study of Lavagna et al. (Lavagna et al., 2018b).

No studies were found to specifically address the policy objective of monitoring environmental impacts. This represents a major research gap, as EU policy makers require comprehensive monitoring to guide the development of building stocks within environmental targets.

Table 22: Mapping of policy objectives with scenarios and strategies investigated in the reviewed literature – Overview.

	Studies investigating EU policy objectives and related aspects	
Objectives and aspects	**Europe**	**Non-Europe**
Improvements to energy efficiency		
Building energy efficiency improvement	Transnational (EU-28) [Pittau et al. 2019]; Transnational (Europe) [Almeida and Ferreira 2017]; National (Ireland) [Moran, O'Connell, Goggins 2020]; National (Spain) [Pombo, Rivela,	National (New Zealand) [Ghose, McLaren, Dowdell 2020]; National (Oman/Saudi Arabia, Bahrain, United Arab Emirates)

	Neila 2019]; National (Switzerland) [Heeren and Hellweg 2019]; National (Poland) [Zygmunt and Piczulski 2019]; Urban (Luxembourg) [Mastrucci et al. 2020]; Urban (Sweden) [Österbring et al. 2019]; Urban (Italy) [Gabrielli and Ruggeri 2019]; Portfolio (Sweden) [Nägeli et al. 2019]	[Krarti and Dubey 2018 (a); Krarti and Dubey 2018 (b); Krarti, Dubey, Howarth 2017 (a), [Krarti and Dubey 2017 (b)]; Regional (Canada) [Feng et al. 2020]; Urban (Australia) [Seo, Foliente, Ren 2018]
Building services improvement	Transnational (Europe) [Almeida and Ferreira 2017]; National (Spain) [Pombo, Rivela, Neila 2019]; National (Poland) [Zygmunt and Piczulski 2019]; Urban (Italy) [Gabrielli and Ruggeri 2019]; Portfolio (Sweden) [Nägeli et al. 2019]	-
Maintenance planning	Portfolio (Sweden) [Nägeli et al. 2019]	-
Increases in renewable energy		
Energy infrastructure (grid mix)	National (Ireland) [Moran, O'Connell, Goggins 2020]; National (Poland) [Zygmunt and Piczulski 2019]; National (Sweden) [Peñaloza et al. 2018]	National (New Zealand) [Chandrakumar et al. 2020]; National (New Zealand) [Ghose, McLaren, Dowdell 2020]
On-site energy (BIPV, etc.)	National (Poland) [Zygmunt and Piczulski 2019]	
Low-carbon material uptake		
Materials: Substitution of conventional materials	National (Ireland) [Moran, O'Connell, Goggins 2020]; National (Switzerland) [Heeren and Hellweg 2019]; National (Sweden) [Peñaloza et al. 2018]; Urban (Luxembourg) [Mastrucci et al. 2020];	-
Materials: Investigating bio-based material use	Transnational (EU-28) [Pittau et al. 2019]; National (Sweden) [Peñaloza et al. 2018]	National (New Zealand) [Chandrakumar et al. 2020]
Climate change adaptation and resilience		
Climate change effects	Transnational (Europe) [Almeida and Ferreira 2017]; National (Sweden) [Peñaloza et al. 2018]	-
Intensity/speed of uptake (related to policy, building owners)	Transnational (EU-28) [Pittau et al. 2019]; National (Switzerland) [Heeren and Hellweg 2019]; National (Sweden) [Peñaloza et al. 2018]; Urban (Luxembourg) [Mastrucci et al. 2020; Mastrucci et al. 2017]; Urban (Sweden) [Österbring et al. 2019]	-
Typology evolution/density	National (Sweden) [Peñaloza et al. 2018]; National (Switzerland) [Heeren and Hellweg 2019]	-
Comfort/Energy simulation parameters	-	National (New Zealand) [Ghose, McLaren, Dowdell 2020]
Behavioural aspects (Market/society)	National (Switzerland) [Heeren and Hellweg 2019]	-
Eco-innovation scenarios	Transnational (EU-28) [Lavagna et al. 2018 ref. to Baldassarri et al. 2017]	-
Monitoring of environmental performance		
-	No studies found specifically addressing this objective	

Additional insights for the EU context

In the European context and beyond the scope of this review, some recently published studies may provide additional insights into the environmental modelling of EU building stocks. In their 2020 study, Gulotta et al. (Gulotta et al., 2020) present bottom-up harmonised energy-environmental models for Europe, focusing on the modelling of thermal insulation. They investigate the building stock in 28 European countries (EU-28), distinguishing three climate zones. The study uses two building typologies (SFH, MFH), adapted to represent four periods of construction and three types of geographic locations (i.e., rural, suburban and urban spatial planning contexts). Following up on a related study by Lavagna et al. (Lavagna et al., 2018b), they advance their model to include dynamic energy simulation and, again, investigate a comprehensive set of environmental indicators. A recent study by Göswein et al. (Göswein et al., 2021) investigates the implication of increased land use requirements from a radical shift to bio-based materials for new construction in Europe. An investigation of global scenarios for material efficiency in buildings, including the modelling of related emission reduction potentials for several European countries, are forthcoming by Pauliuk et al. (Pauliuk et al., n.d.).

5.6.4. Future research and data needs

To further advance the environmental modelling of building stocks and, in particular, to support EU policy making, various research and data gaps need to be addressed. As outlined in this study, existing approaches offer various types of potential in their individual modelling aspects and should be combined to provide the added value of both comprehensive and highly detailed building stock models.

Data gaps need to be addressed specifically regarding data on building stock composition and geometric parameters at scales beyond the urban and national level to support, e.g., building-by-building modelling of the whole EU building stock. To advance the prevailing archetype-based modelling, the quality and quantity of archetypes used to represent building stocks should be boosted to provide more nuanced and representative assessments. Building on European projects such as TABULA and EPISCOPE and using centrally curated building stock data such as those provided by the EU Building Stock Observatory can enable more detailed modelling while maintaining a harmonised approach to archetype definition. Furthermore, potentially useful data on the environmental modelling of buildings may be obtained from related research collaborations such as IEA EBC Annex 57 (on embodied energy and GHG emissions of buildings) and the ongoing IEA EBC Annex 72 (on comprehensive LCA for buildings across the full life cycle) or the recently started IEA EBC Annex 75 (on building renovation at the district level).

A particular research gap identified in this work is the lack of studies monitoring the environmental impacts of building stock development in relation to the environmental targets outlined by EU policy. This research gap must be addressed to enable active development of the EU building stock within environmental boundaries. In this regard, environmental benchmark data for EU buildings are lacking in terms of both existing building performance (baseline) and target values. Ongoing initiatives such as the EU Level(s) project may provide crucial insights into the performance of new buildings, which might benefit from recent research findings on building life cycle performance (Röck et al., 2020b) and environmental benchmarks (Trigaux et al., 2021) and targets for buildings (Habert et al., 2020b). Concerning environmental targets for buildings and their implementation, EU policy, standards and regulations, such as the Construction Products Regulation (CPR), will play a key role.

Furthermore, improved links to other research fields in the domain of ecosystem management may be relevant to ensure clear system boundaries and to avoid double counting, particularly considering the increased interest in using buildings as carbon sinks (Churkina et al., 2020) through the increased use of bio-based materials and related challenges of biogenic carbon modelling (Endrit Hoxha et al., 2020).

5.7. Conclusion and outlook

Our study presents an integrated assessment of scientific developments in the environmental modelling of buildings and policy objectives related to the buildings and construction sector. Through a systematic literature review and analysis, we evaluated the state of the art of environmental modelling of building stocks and spatiotemporal dynamics related to their future development. Based on the assessment of more than 100 studies, 22 were shortlisted for a comprehensive analysis. Analysing the studies from a life cycle assessment perspective, we investigated each study in the context of its goal and scope, consideration of dynamics and scenario variables, modelling and analysis of building stock characterization and aggregation, and material- and energy-related environmental impacts. We analysed the LCA methodology in terms of LCA scenarios, impact assessment methods and environmental indicators as well as the interpretation of results. Furthermore, we categorised existing methodological approaches and discussed the individual characteristics, strengths and weaknesses of approaches focusing on a product life cycle perspective, modelling of material-related impacts, building energy simulation, and the added value of assessing financial cost-related aspects.

We find that existing studies vary strongly in terms of their spatiotemporal scope at both the building stock and building level, with studies ranging from the portfolio and urban scales up to the national and transnational scales and conducting (mostly prospective) analyses with a timeframe from one or a few years up to 200 years. Our analysis of existing building stock modelling approaches provides relevant insights in terms of modelling material- and energy-related impacts but also reveals a research gap and lack of studies featuring both a comprehensive scope and a high level of detail. Furthermore, the environmental indicators covered in existing studies are very limited, with most studies focusing exclusively on GHG-related indicators. To fully comprehend environmental impacts and avoid burden shifting, all impact categories listed in recent CEN standards for environmental impact assessment of buildings should be considered.

Environmental hotspot analyses at the level of building clusters and individual buildings are scarcely found at all in the current literature, with a complete lack of studies providing such analyses at the level of detail suggested in recent EU-related documents such as the EF guidelines.

Most studies in our final sample focus their analyses on operational energy and the environmental implications of retrofitting the existing building stock. Although the EU policy objective of improving the energy efficiency of the stock is widely taken into account by existing models, further research developments should focus on the monitoring over time of environmental impacts related to all energy end uses in households. For this purpose, variations in climatic conditions and the energy mix should be considered. Few studies investigate the environmental implications of new construction activity that will take place in the coming decades. Finally, we identified a total lack of studies investigating how to monitor and actively guide EU building stock development in alignment with environmental targets and identified this as an important area for future research.



6. THE SLiCE BUILDING DATA MODEL FOR HOTSPOT ANALYSIS AND DYNAMIC ASSESSMENT

Bibliographic data

Title	SLiCE: Open Data Model for Scalable High-Definition Life Cycle Engineering and Dynamic Building Analysis
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	Karen Allacker, KU Leuven (BE)

Highlights

- Policy experts and decision makers in the building sector need to understand environmental impacts of buildings at different spatial and temporal scales, but there is a lack of scalable solutions for the practical implementation of systematic hotspot analysis in both policy research and industry practice.
- In this article we conceptualise the problem as a need for high-resolution life cycle information within the Space-Time-Indicator framework, building on geospatial analysis concepts and data structures.
- The SLiCE building data model is proposed to enable scalable life cycle assessment and environmental hotspot analysis across spatiotemporal dimensions.
- The environmental footprint (PEF/OEF) hotspot analysis protocol is used and implemented to showcase the spatiotemporal analysis of hotspots within building life cycle-related assessment information.
- Practical application of SLiCE data model and the PEF/OEF hotspot analysis protocol is illustrated by implementing it in an interactive assessment tool (Python Jupyter Notebook with UI elements).
- The SLiCE hotspot tool is applicable at micro-level, for assessment of individual buildings or components, as well as at meso- and macro-levels, for building portfolios and stocks of different scales.
- The SLiCE data model can be scaled to include spatial attributes at higher and lower scale levels, increase the resolution of temporal life cycle information, and to capture additional indicators.

Author contributions

Martin Röck: Conceptualization; methodology; data curation and visualization; writing (original draft, review and editing); project administration.

Alexander Passer: Methodology; writing (review and editing); supervision.

Karen Allacker: Methodology; writing (review and editing); supervision.

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Data and code availability

The SLiCE building data model as well as the presented implementation in the SLiCE hotspot analysis tool prototype are open source and published under a CC BY-SA 4.0 license. The authors encourage interested parties to review – reuse – refine the model and scripts and share-alike.

The following chapter presents a draft manuscript for submission to a peer-reviewed journal.

Abstract

This article responds to the needs of researchers, policy, and decision makers for comprehensive life cycle-based sustainability assessment (LCSA) insights across different industries, including for building construction and operation. Decision makers need high granularity data inputs and improved model resolution to adequately assess environmental impacts and avoid burden-shifting across spatial and temporal scales.

This article proposes the SLiCE data model for scalable, high-definition life cycle analysis of building as a potential solution to overcome the limitations of existing models and tools. The article first presents the conceptualization of the problem within the Space-Time-Indicator Nexus, explains the SLiCE data structure, and showcases a proof-of-concept for using SLiCE data for hotspot analysis within a prototypical tool utilizing IPython Jupyter Notebooks and interactive UI elements.

The SLiCE data model and the SLiCE hotspot analysis tool prototype are henceforth available for implementation within existing building LCA workflows and tools, enabling comprehensive insights on buildings' environmental impacts across spatiotemporal scales. Thereby SLiCE offers an open interface for researchers and industry professionals for joint elaboration and development towards scalable, high-definition LCA of buildings and building stocks.

6.1. Introduction

Politicians, policy and decision makers across the world are urged to step up decarbonization efforts to ensure an adequate response to the climate and ecological crisis. The European Union (EU) is seen as a pioneer in systematic decarbonization efforts, aiming to link up various policy initiatives to drive decarbonization across different sectors, including for building construction and operation (Arianna Vitali Roscini et al., 2020; European Academies Science Advisory Council (EASAC), 2021; European Commission, 2019; Rolf Frischknecht et al., 2019a). However, to avoid 'carbon tunnel vision' when defining targets, policies, or strategies it is crucial to identify and resolve potential 'burden-shifting' to other impact categories or life cycle stages through a comprehensive life cycle-based sustainability assessment (LCSA). LCSA approaches have therefor become a fundamental tool in the EU policy making toolbox (Röck et al., 2021; Sala et al., 2016b) to model and understand the wider environmental, social and economic implications of potential decisions. Insights from life cycle modelling of buildings and building stocks are fundamental to achieving the anticipated decline of emissions towards net-zero by mid-century. To make informed decisions in context of buildings, decision makers need comprehensive insights on buildings' environmental impacts across spatiotemporal scales, meaning insights on the distribution of environmental impacts across different spatial elements of buildings as well as across different stages of the building life cycle. However, despite this clear need, models and tools available thus far are limited by lack of data granularity and model resolution in building analysis when applied at higher (macro-)scale levels (Röck et al., 2021). To adequately assess environmental impacts and avoid burden-shifting across spatial and temporal scales, it is hence fundamental to advance data granularity of building level life cycle information. High granularity data inputs are fundamental to enabling improved model resolution and the inclusion of all relevant environmental impact categories and analysis of environmental hotspots at higher scale levels, such as for building stock modelling.

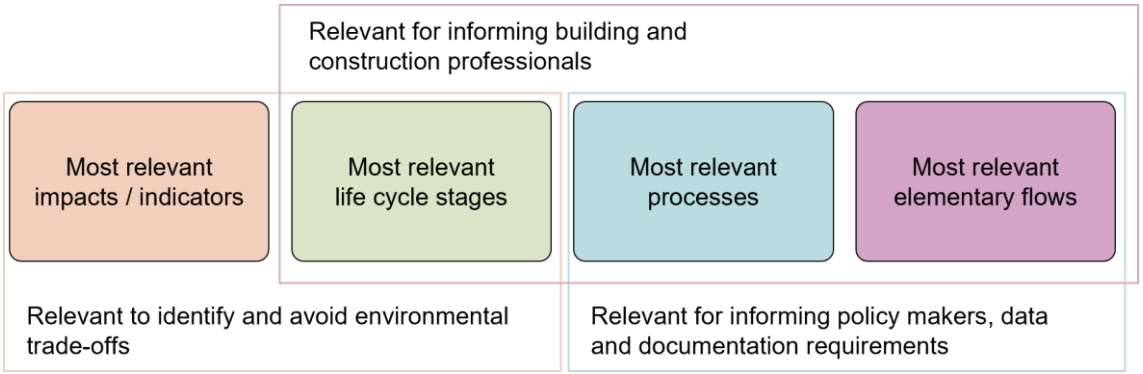


Figure 39: Concept of hotspot analysis for identification of most important aspects relevant for guiding green transition of buildings and construction across Europe (adapted from (James and Galatola, 2015; Spirinckx et al., 2019a)).

An appropriate logic and protocol for systematic hotspot analysis has been proposed by (James and Galatola, 2015) as part of the environmental footprint (EF) initiative for assessment both product environmental footprints (PEF) as well as organization environmental footprints (OEF). Systematic screening and analysis of environmental hotspots, as proposed by (James and Galatola, 2015), means assessing in a clear and reproducible way the most relevant aspects of a product's environmental footprint (EF) with regards to its most relevant indicators, most relevant life cycle stages, most relevant processes as well as most relevant elementary flows – as shown in Figure 39. Each of these perspectives is important and relevant for diverse sets of stakeholders, for example: to identify and avoid environmental trade-offs (most relevant indicators and most relevant life cycle stages); to inform building and construction professionals or construction product manufacturers about hotspots within their building or product (most relevant life cycle stages, most relevant processes, most relevant

elementary flows); as well as to inform policy makers, data and documentation requirements for monitoring and guiding sustainable development of buildings and building stocks (most relevant processes, most relevant elementary flows). Application of the hotspot analysis protocol to buildings has been showcased within the PEF4Buildings project on testing the application of PEF to new buildings (Röck et al., 2018c; Spirinckx et al., 2019a; VITO et al., 2018). However, while proven applicable in principle, there is still a lack of scalable solutions for enabling the wide implementation of such hotspot analyses for buildings in both policy research as well as industry practice. This lack of scalable solutions for environmental hotspot analysis of buildings is linked to the lack of open data models for providing building related life cycle information with high granularity, especially regarding life cycle inventory (LCI) data and life cycle impact assessment (LCIA) results.

The objective of this article is to present the SLiCE building data model, an accessible and open building data model aimed at researchers and industry professionals as well as policy experts, as a basis for implementing systematic screening and analysis of environmental hotspots in building research as well as, eventually, in everyday industry practice. This article presents the conceptualization of the problem within the Space-Time-Indicator Nexus and proposes the SLiCE data model as a potential solution. The added value of SLiCE is validated based on two main use cases of SLiCE data: a) a systematic analysis of environmental hotspots, via a custom-built hotspot analysis tool; and b) a dynamic assessment of climate impacts and carbon uptake, based on SLiCE data of bio-based building elements.

The SLiCE data model and related applications aim to offer open interfaces for researchers and industry professionals for joint elaboration and development, including for links to other models and use cases to advance together towards scalable, high-definition LCA of buildings and building stocks at scale.

6.2. Methods and materials

6.2.1. High-definition life cycle data

Space-Time-Indicator (STI) framework

Life-cycle related information on buildings is interwoven in spatial and temporal dimensions and linked through various environmental, social, and economic indicators. This chapter aims at conceptualizing this nexus of multidimensional interrelations of life cycle information to clarify what information and granularity is available and/or required for different applications and use cases, taking systematic environmental hotspot analysis as an exemplary use case and proof-of-concept.

The Space-Time-Indicator (STI) framework (Figure 40) aims at providing such a conceptual framework and is based on three main dimensions of building life cycle-related information: Space; Time; and Indicators. For all dimensions, a notion of high or low ‘resolution’ is applied to express the granularity and level of definition in modelling and results provision for spatial and temporal information, as well as the comprehensiveness of indicators investigated in a particular analysis. In the present example, the spatial resolution focuses on the analysis of a building for which results can be provided as the sum at building level (level 0); per building element (level -1); per sub-element (work sections, components) (level -2); or per building material (level -3). Higher as well as lower scale levels can be added to this concept, such as the contribution of even smaller entities, such as raw materials, or the aggregation of results for different building clusters (e.g., a national building stock). In terms of temporal resolution, the results of building LCA are often provided as the sum across the whole life cycle (WLC) (A). In the European context, studies usually follow the related standard EN 15978, which suggests the modelling and reporting of results per life cycle stage (LCS) or life cycle module (LCM). Beyond the reporting of life cycle information in predefined categories, the actual point in time for the occurrence of something like GHG emissions, is of interest. The point in time can be specified along various resolutions, such as

categorically per LCS, LCM or more specifically, per its year, month, or day of occurrence, and so on. Enabling the reporting of indicators/impacts on a yearly (or in future quarterly or monthly) basis will be useful and important for corporate Environmental, Social and Governance (ESG) reporting. Looking to building energy modelling, and the emerging role of digital building logbooks, we can further anticipate that both energy- and material-related indicators will become available at daily, or in the case of energy, even hourly resolutions. These and other combinations of spatial and temporal resolution can be applied during life cycle analyses and used for reporting on the third dimension, indicators.

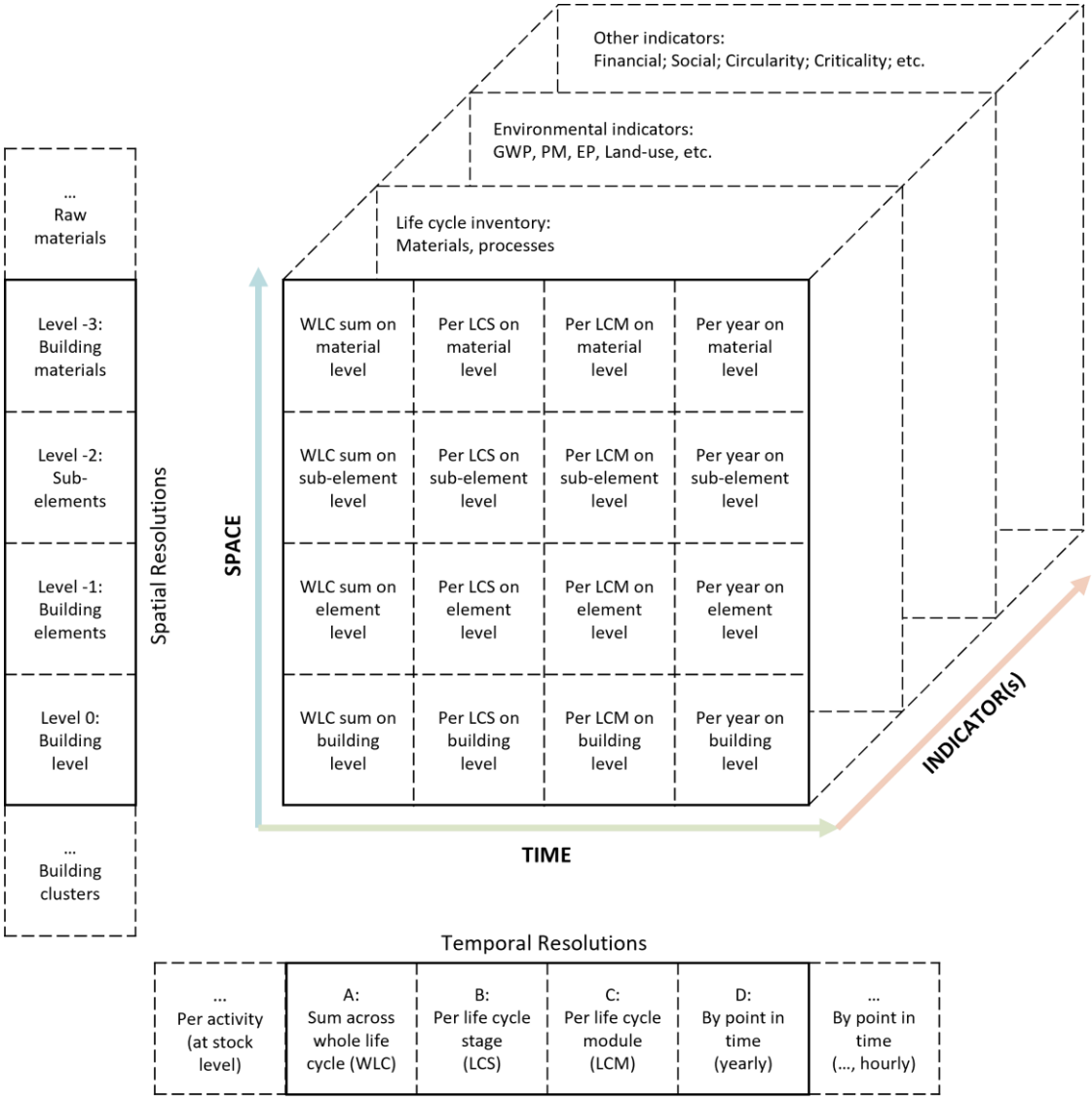


Figure 40: Space-Time-Indicator (STI) framework depicting different spatial and temporal resolutions for life cycle related information, such as life cycle inventory data, environmental and other indicators.

This article focuses on the accessible and high-resolution modelling of life cycle inventory (LCI) data (materials, processes) and (environmental) life cycle indicator results obtained through comprehensive LCA. The STI logic and data model, however, are scalable and flexible regarding consideration of other indicators, such as, financial or social life cycle assessment, circularity, or criticality metrics. The STI framework and the life cycle modelling approach inspired by computational logics applied in Earth and environmental systems modelling (European Commission (EC), 2016; Maes et al., 2020) and geospatial analysis such as the space-time-attribute (STA) concept (Guo et al., 2006; Lundblad and Jern, 2012), data cubes and array programming more generally (Harris et al., 2020; Rew and Davis, 1990). Inspired

also by the struggle towards the application of standardised multi-dimensional data cubes in these domains, the STI framework, and the consecutive proposal of the SLiCE building data model, aim at providing a step towards enabling the development and use of standardised data formats for analysis of life cycle related information based on: bins (i.e., analysis of results for a specific spatial item, at a specific time and for a specific indicators); bin time series (i.e., analysis of a spatial item and indicator(s) across time); time slices (i.e., analysis of results at a specific time regarding the contribution of different spatial items and indicators at that time); or combinations thereof.

Scalable data structures

The following paragraphs provide the background of the data structure logic utilised by the SLiCE data model and the software modules utilised for the implementation presented. The implementation of the SLiCE relies on IPython in Jupyter Notebook (Perez and Granger, 2007) and a variety of modules to support computation (McKinney, 2017), visualization and interactive presentation of the analysis (Yang et al., 2022). A useful concept utilised in this context (e.g., HoloViz HoloViews (HoloViz, 2023)) is the distinction of variables/attributes into 'key' and 'value' dimensions. In this logic, *key dimensions*, refer to indexing dimensions or independent variables/attributes, and *value dimensions* refer to resulting data or dependent variables/attributes. This logic of key and value dimensions is henceforth applied to support explanation of the SLiCE data model.

The SLiCE building data model deploys a blend of 'tall' and 'wide' data logic as a basis for the analysis of hotspots across spatiotemporal scales and other implementations. Figure 41 illustrates the difference of 'wide' and 'tall' data structures by giving an example of either logic in context of building life cycle information, specifically on the GWP for different materials (A-C) contained in different building cases (A-C). The example illustrates how a 'wide' data structure can offer the benefit of presenting building related information in a clear and more human-readable logic of 'one line (row) per case'. However, with the downside of requiring empty fields where a certain attribute (column) is not applicable, thereby causing inefficiency in data storing and unnecessary computational burden during processing. On the other hand, a 'tall' data structure requires multiple rows to express the information per building, using attributes for the relevant dimensions 'Material' and 'GWP' and expressing the information on each separately. This data structure might be less intuitive at first, but allows to specify complex, multi-level information, for example on hierarchical life cycle inventory data and the related indicators. Furthermore, wide data structures can be challenging with regards to distinguishing value information on different granularity levels, such as the GWP at building level as well as at individual material levels. Tall data structures, as illustrated, store information on the finest granularity level available and can then utilise a dynamic aggregation at requested level(s) using readily available computational operations such as Pandas 'groupby', for example. Tall data structures can therefore be considered particularly suitable for storing large amounts of data on strongly diversified items, such as life cycle information on buildings including on material composition, life cycle inventory, and indicators results.

'Wide' **vs.** **'Tall'**

ıdex	Building	Material A - GWP	Material B - GWP	Material C - GWP
0	A	300 kgCO2e	430 kgCO2e	450 kgCO2e
1	B	200 kgCO2e	238 kgCO2e	-
2	C	400 kgCO2e	-	600 kgCO2e

Index	Building	Material	GWP
0	A	A	300 kgCO2e
1	A	B	430 kgCO2e
2	A	C	450 kgCO2e
3	B	A	200 kgCO2e
4	B	B	238 kgCO2e
5	C	A	400 kgCO2e
6	C	C	600 kgCO2e

Figure 41: Illustrative example of 'wide' and 'tall' data structures, both used within the SLiCE data model.

Practical examples of 'wide' data structures in the building context are the data collection template (DCT) of (Röck et al., 2022c, 2020c; Röck and Sørensen, 2022) and the related building datasets presented in chapter 4 (Open database on embodied and whole life carbon of buildings). Practical examples for 'tall' data structures are the hierarchical, multi-level life cycle inventories developed in the context of BIM-based LCA as deployed in the PEF4Buildings project (Röck et al., 2018c). Suitable building life cycle information can be aligned with the SLiCE data model by transformation of selected attributes between 'wide' and 'tall' data, for example using Pandas 'melt' / 'pivot' (Lemenkova, 2020; McKinney, 2017; Stepanek, 2020).

6.2.2. Hotspots analysis protocol

The basis for the environmental hotspot analysis routine and prototype implementation presented here are the EF hotspot analysis protocol developed by (James and Galatola, 2015) and experiences from its application within the PEF4Buildings project (Röck et al., 2018c; Spirinckx et al., 2019a; VITO et al., 2018). A summary of the hotspot analysis methodology (James and Galatola, 2015) and specificities of this implementation is offered in Table 23 and elaborated in the following. In this implementation, the hotspot analysis protocol follows a three-step procedure, which involves identifying the most relevant indicators (e.g., impact categories), temporal hotspots (e.g., life cycle stages), and spatial hotspots (e.g., materials, processes and/or elementary flows):

1. Most relevant indicators: The first step is to identify environmental hotspots based on the most relevant impact categories, which are identified based on the normalised and weighted results. A default list of impact categories has been defined in context of PEF/OEF. However, the method allows adaptation to custom use cases, including a custom list of impact categories and related normalization and weighting factors.
   The hotspot analysis script presented in this article considers: at least three relevant impact categories (where applicable); the most relevant impact categories as all impact categories that cumulatively contribute to at least 80% of the total impact by default, with a variable threshold value, starting from the largest to the smallest contributions. Computation of the percentage contribution of any process or flow is assessed based on absolute values (i.e., the minus sign is ignored) to account for the relevance of any indicator value, even if negative. The presented prototype hotspots tool is flexible with regards to processing assessment results with different impact categories and related custom weighting sets.
2. Temporal hotspots: The second step is to identify temporal hotspots, based on the most relevant life cycle stages. The original method suggests considering all life cycle stages (LCS) that contribute over 80% (before normalisation and weighting) to any of the impact categories. The default life cycle stages should be raw material acquisition and pre-processing, production of the main product, product distribution and storage, use stage scenario (if in scope), and end-of-life (including product/part reuse, recovery/recycling; if in scope).
   This implementation identifies the most relevant life cycle stages based on the normalised and weighted results, in line with the application of the method in the PEF4Buildings study. The most relevant life cycle stages are those which together contribute to at least 80% of any of the most relevant impact categories identified. The current implementation thereby diverts from the original PEF/OEF guidance, which suggests identification of most relevant LCS based on characterised results for each indicators, rather than overall weighted results. It is, however, possible to adapt the script accordingly and utilise equal weighting for individual steps of the analysis in the future. Furthermore, this implementation is based on the life cycle model of building LCA as defined in EN 15978 and supports analysis of cradle to grave life cycle results.
3. Spatial hotspots: The third step is to identify the spatial hotspots, which can be identified at different levels of granularity, such as most relevant processes (or elementary flows), the so-called 'level-1'. In this implementation, the level for contribution analysis can be customised

to define whether as building element (level-1), building sub-elements (e.g., work sections) (level-2), material level (level-3), or any other lower level available in the dataset. Most relevant spatial items (level-1) are then identified for each of the most relevant impact categories identified and for each life cycle stage, with an indication of the most relevant ones. Furthermore, the definition of 'hotspots' by (James and Galatola, 2015) in context of PEF/OEF is: A) Life cycle stages, processes, and elementary flows cumulatively contributing at least 50% to any impact category before normalisation and weighting (from the most contributing in descending order), or B) At least the two most relevant life cycle stages, processes, and at least two elementary flows (minimum 6), with the option to identify additional hotspots.

This implementation offers the possibility to individually select (include or exclude) indicators, temporal items (e.g., life cycle stages), and spatial items (e.g., materials), as appropriate for a particularly study. This also allows to follow the methodology in the PEF4Buildings study, where the levels for which most relevant processes are to be identified are distinguished based on the contribution of the operational stage to life cycle impacts (if >50%, both use stage and whole life cycle excluding use stage are assessed separately).

Table 23: Summary of the hotspot analysis method deployed in this implementation.

Most relevant items	Identification of relevance	Threshold
Indicators (e.g., impact categories)	Based on normalised and weighted results, ideally from a comprehensive set of indicators (e.g., LCA). Options: Using predefined sets or 'equal weighting' (e.g., for already normalised values); Selection of only one or more indicators (e.g., limit to GWP).	The indicators that cumulatively contribute to at least 80% of the total indicator value, by default. Customizable threshold value (0-100%), including option for 'no threshold' (100%).
Temporal items (e.g., life cycle stages) *'Temporal hotspots'*	For each of the most relevant indicators (e.g., impact categories). Options: Equal weighting; Limited indicators selection.	All temporal items (e.g., life cycle stages, point in time) contributing cumulatively more than 80% to any indicator (e.g., impact category), by default. Customizable threshold value (0-100%).
Spatial items (e.g., building materials) *'Spatial hotspots'*	For each indicator (e.g., impact category) and temporal item (e.g., life cycle stage), with indication of the most relevant ones. Option: Custom definition of 'level-1' if multi-dimensional data input available (e.g., SLiCE).	All spatial items (e.g., building materials) contributing cumulatively more than 80% to any indicator (e.g., impact category), by default. Customizable threshold value (0-100%).

6.2.3. Dynamic life cycle assessment

The use of SLiCE data for dynamic impact assessment was tested under supervision of the author within the master thesis of (Vanoverberghe, 2022). The description of methods and materials described in the following are based on this thesis.

The static LCA and dynamic LCA (DLCA) workflows were custom-built and programmed using Anaconda Jupyter Notebooks (Kluyver et al., 2016), iPython (Perez and Granger, 2007) and the Pandas package for data handling (McKinney, 2017, 2011). For the dynamic LCA, a dynamic LCI is computed considering emissions in the year they occur, based on the foreground inventory information provided in the respective SLiCE dataset and static background LCI from Ecoinvent (Wernet et al., 2016). The temporal resolution is one year. The dynamic foreground inventory is combined with a detailed background inventory from the LCA background database. The approach of a SLiCE-based dynamic impact assessment is tested based on the four most important GHGs: CO2, CH4, N2O, CO.

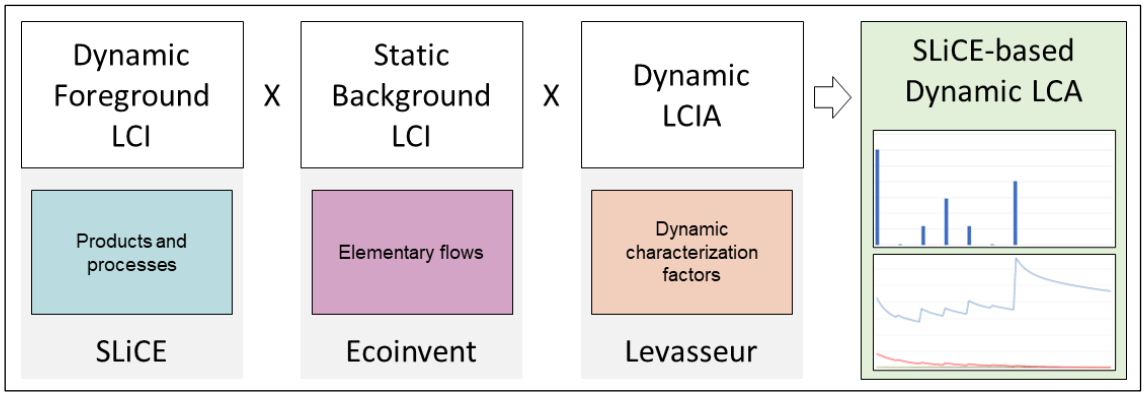


Figure 42: Conceptual steps of SLiCE-based dynamic life cycle assessment. Starting from a SLiCE dataset with temporally explicit, dynamic foreground LCI on products and processes; multiplied by a static background LCI on elementary flows, e.g., from the Ecoinvent database v3.8 (Wernet et al., 2016); and temporally dynamic characterization factors, such as presented by Levasseur et al. (Levasseur et al., 2010a); are combined to achieve a SLiCE-based dynamic LCA.

Dynamic LCI foreground: Products and processes from SLiCE

As a basis for the SLiCE-based dynamic LCA, a SLiCE dataset with temporally explicit, dynamic foreground LCI on products and processes is required. This application requires a SLiCE dataset of a minimum temporal resolution 'STI:D', i.e., disaggregated information on life cycle processes by point in time (year). Furthermore, the spatial resolution of the dataset requires sufficient level of detail to determine the specific activities, products and processes, occurring in a given year. The latter is required to allow a mapping of the foreground LCI with background data on elementary flows related to those activities. In the case of buildings or building elements, this means as SLiCE dataset with information on the specific material and/or energy flows taking place in any given year.

Static LCI background: Elementary flows from Ecoinvent

Furthermore, (static) background LCI is required to obtain information on elementary flows, such as flows of different GHGs. In this example, the LCA background database used is Ecoinvent version 3.8 (Wernet et al., 2016). Ecoinvent records related to the foreground products and processes were used to obtain detailed background inventory data on selected GHG emissions (CO2, CH4, N2O, CO), considering exchanges related to 'fossil', 'from soil or biomass stock', and 'non-fossil', respectively.

Dynamic LCIA: Dynamic characterization factors (CFs)

SLiCE foreground and Ecoinvent background LCI are then multiplied with dynamic characterization factors (CFs) to obtain the global warming impact of the building element as a function of time. By dividing the life cycle into yearly time steps, the dynamic inventory for each greenhouse gas (GHG) is obtained by summing the emissions occurring at each time step. This example applies SLiCE together with the dynamic impact assessment method of Levasseur et al. (Levasseur et al., 2010a). Levasseur et al. introduced a methodology that enables the calculation of the time-dependent impact on global warming (GWI) in a life cycle by incorporating dynamic characterization factors.

(1) $$GWI(t) = \sum_i GWI_i(t) = \sum_i \sum_{j=0}^{t} [g_i]_j \times [DCF_i]_{t-j}$$ (Levasseur et al., 2010a)

(2) $$GWI(t) = \sum_i \sum_{j=0}^{t} [S_i]_j \times [B_i] \times [DCF_i]_{t-j}$$ (Our approach)

As specified in equation (1) (Levasseur et al., 2010a), the calculation of the GWI at a specific time (t) caused by the inventory (g) related to a particular GHG (i) involves multiplying the total emission (dynamic inventory result) at time (t) by the dynamic characterization factor (DCF) at time 0. Additionally, the GWI calculation includes adding the score assigned to the total emission at time (t-1) multiplied by the DCF at time 1, and so on, until finally incorporating the total emission at time 0

multiplied by the DCF at time (t). This calculation captures the increase in radiative forcing at time (t) resulting from discrete GHG emissions throughout the entire life cycle process. The time horizon in this example is 100 years.

The SLiCE-based dynamic LCA expands on this logic, as illustrated in equation (2), by distinguishing the inventory (g) into a dynamic, SLiCE-based foreground inventory (S) providing information on the primary activities occurring across the life cycle, and a static background inventory (B) providing details on biosphere flows (such as GHG emissions) related to the foreground activities.

Further details on the method applied are available in the related master thesis (Vanoverberghe, 2022).

6.2.4. Case study building elements

For testing the hotspot analysis tool and the dynamic impact assessment workflow, respectively, SLiCE datasets have been generated from bio-based building elements developed under the supervision of the author and presented in (Mouton et al., 2023a).

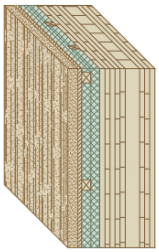
Building element	Work section							Material						
BE figure + name	WS name	Th [cm]	Freq B2.2	Freq B2.3	Freq B4.1	WS unit		Ecoinvent record	M unit	Ratio M/WS	ρ [kg/m³]	Mass [kg/m²]	λ [W/mK]	Scenario C1
 EW01 (48.4 cm) Mass timber + hemp insulation	Cork finish	5.6	0	10	0	m²		Cork slab {RER}| production | Alloc Rec, U	m²	1	200	11.20	0.05	Waste wood
	Bituminised wood fibre board (screwed)	2.2	0	0	0	m²		Fibreboard, soft, bitumised [RER]| production | Alloc Rec, U	m²	1	253.59	5.58	0.05	Wood fibre board
								Chromium steel, screws [RER]| production	pcs	5.56	7800	0.02		Wood fibre board
	Hemp insulation + structure	10	0	0	0	m²		Hemp insulation, packed [RER]| production	m²	0.90	35	3.15	0.04	No C1 impact
								Softwood, untreated timber [BE]| production, MIX	m²	0.10	400	4.00	0.12	No C1 impact
	Thoma H100-W30	30.6	0	0	0	m²		Softwood, untreated prefabricated structural product [BE]| production, MIX	m²	1	400	122.40	0.12	Waste wood

Figure 43: Example of the input hierarchically modeled life cycle inventory by example of EW01 (Mouton et al., 2023a).

In their study, Mouton et al. focused on building elements and conducted various modeling and inventory activities. They defined multiple compositions for each building element type, incorporating bio-based construction techniques. The compositions were adjusted to achieve desired U-values or sound insulation. Variations of these elements were also defined by changing insulation materials. Additional compositions were derived from product catalogs and input from building stakeholders. The inventory modeling process involved categorizing input parameters and scenarios based on the respective levels (work section or material) in the Belgian MMG method (Allacker, 2010; Lam and Trigaux, 2021; Servaes et al., 2013; Trigaux, 2017). Detailed compositions and hierarchically modeled LCIs of specific elements, such as the external wall EW01, were presented. The study utilized existing conventional element options from the MMG database. The detailed inventory data and information on materials used in the respective life cycle inventories are available as supplementary information to that study and were used to generate SLiCE data for testing different use cases of SLiCE.

SLiCE data was generated for selected external wall (EW) elements to enable: showcasing a SLiCE dataset example (section 6.3.1) based on element ‘EW05’; the environmental hotspot analysis tool (section 6.3.2) based on element ‘EW05’; as well as the dynamic modelling of climate impacts and biogenic carbon uptake (section 6.3.3) based on EW ‘MMG09’.

6.3. Results and discussion

6.3.1. SLiCE data model

Conceptual logic of the SLiCE data model

The SliCE data model - illustrated in Figure 44 - deploys a combination of 'wide and 'tall' data structures. The data model logic represents key dimensions expressed in spatial and temporal attributes via a 'tall' data structure and combines it with value dimensions, indicator results, implemented as a 'wide' data structure to allow efficient expansion with further indicators.

Spatial attributes (keys)
Hierarchical building information modelling (element-method)

[…]	Building	Element	Worksection	Construction material/product	[…]
-	Bldg A	Elem A	Wsec A	MatC A	-
-	Bldg A	Elem A	Wsec A	MatC B	-
-	Bldg A	Elem A	Wsec B	MatC A	-
-	Bldg A	Elem A	Wsec B	MatC C	-
-	Bldg A	Elem B	Wsec C	MatC D	-
-	Bldg A	Elem B	Wsec C	MatC E	-
-	Bldg A	Elem B	Wsec A	MatC A	-
-	Bldg A	Elem B	Wsec A	MatC B	-
-	[…]	[…]	[…]	[…]	-

Temporal attributes (keys)
Building life cycle stages/modules and point in time

[…]	Life cycle stage	Life cycle module	Nested module	Point in time (year)	[…]
-	A - Production	A1	-	0	-
-	A - Production	A2	-	0	-
-	A - Production	A3	-	0	-
-	B - Use phase	B6	-	1	-
-	B - Use phase	B6	-	2	-
-	B - Use phase	B6	-	3	-
-	B - Use phase	B4	A1	15	-
-	B - Use phase	B4	A2	15	-
-	B - Use phase	B4	A3	15	-
-	[…]	[…]	[…]	[…]	-

Indicator attributes (values)
LCI amounts and LCIA results

[…]	Material amount	Energy amount	Indicator GWP	Indicator PM	[…]
-	xx kg	-	xx kgCO2e	xx kgPM2,5e	-
-	-	yy kWh	yy kgCO2e	yy kgPM2,5e	-
-	zz kg	zz kWh	zz kgCO2e	zz kgPM2,5e	-
-	[…]	[…]	[…]	[…]	-

Figure 44: SLiCE data logic combining spatial attributes (keys), temporal attributes (keys) and indicator attributes (values) to accommodate scalable, high-definition life cycle information of buildings.

The illustration in Figure 44 indicates that a variety of spatial attributes (key dimensions) can be accommodated within the data model, following a hierarchical building information modelling approach. Examples of hierarchical levels for such spatial information are the levels of building, element, sub-element (or work section), construction material (or construction product). Higher as well

as lower scale spatial levels can be implemented as needed. As mentioned, spatial attributes are represented using a tall data structure. Similarly, temporal attributes (key dimensions) can be implemented at different levels of granularity, such as following EN 15978 and specifying the respective life cycle stages or module an activity occurs in. The example also anticipated the specification of 'nested' life cycle stages, where applicable. Nested modules can occur, for example, for processes related to replacement of building elements, which triggers both production (of the new element) and recycling or end-of-life (for the element being replaced). Furthermore, detailed temporal information on the 'point in time' a process occurs in can be accommodated within the SLiCE data model. When, for example, implemented as the 'year' a process occurs, the point in time can give valuable context into the timing of environmental impacts to support identification of relevant phenomena such as the upfront embodied carbon spike of building material production (occurring in or even before year '0') or the fact that operational emissions are spread out across the various years of a building life cycle. Deploying the SLiCE data model with life cycle information specified by point in time (e.g., 'year') can furthermore enable the implementation of dynamic LCIA, based on changing characterization factors over time. Indicator attributes (value dimensions) are implemented using a 'wide' logic, as mentioned, meaning information is spread out horizontally rather than stacked vertically so that each indicator attribute is represented with an individual column. Note that stacking of (parts of) the indicator attributes can be appropriate, such as for attributes indicating material or energy flows, depending on the implementation and use case.

The SLiCE data model supports provision of high-granularity LCI and LCIA information, and as such can be combined with other relevant information on the building, the object of assessment – including its context and site variables, relevant building design parameters, relevant information on assessment methods, and more – using, for example, the list of attributes proposed in chapter 4 (Open database on embodied and whole life carbon of buildings).

Practical example of a SLiCE dataset

Table 24: SLiCE dataset example based on building element ('EW05 CLT + str blown') from (Mouton et al., 2023a). The table shows different spatial attributes (element, work section, product/process (activity), and techflow), temporal levels (life cycle stage, life cycle module, point in time (year), and activity type), as well as indicator results (LCI amount (techflow), and LCIA results (by example of LCA indicators GWP, PM, EP)). The LCIA totals at the bottom of the table confirm coherence of the high-resolution SLiCE dataset with the results reported in the original study of (Mouton et al., 2023a).

Spatial attributes (keys)				Temporal attributes (keys)				Indicator attributes (values)			
Element	Worksection	Product/Process	Techflow	Life cycle stage	Life cycle module	Point in time	Activity type	LCI amounts	LCIA results		
element_name	*worksection_name*	*activity_name*	*techflow_name*	*LCS_name*	*LCM_code*	*activity_year*	*activity_type*	*techflow_amount*	*indicator_GWP*	*indicator_PM*	*indicator_EP*
EW05 CLT + str blown	Wall - external finish | Cladding	cork (32-80mm)	Cork slab {RER}| produ	A1-3: Product	A1-3	0	Material in	1.12E+01	1.58E+01	1.44E-02	9.87E-03
EW05 CLT + str blown	Wall - external finish | Infrastruc	fibre board + bitumen	Fibreboard, soft, bitum	A1-3: Product	A1-3	0	Material in	5.58E+00	3.88E+00	2.40E-03	2.48E-03
EW05 CLT + str blown	Wall - external finish | Infrastruc	screws	Chromium steel, screw	A1-3: Product	A1-3	0	Material in	1.88E-02	1.36E-01	1.97E-04	8.78E-05
EW05 CLT + str blown	Wall - external finish | Thermal i	blow-in straw	Straw, stand-alone pro	A1-3: Product	A1-3	0	Material in	1.51E+01	1.58E+00	7.21E-04	5.43E-03
EW05 CLT + str blown	Wall - external finish | Thermal i	timber grid	Softwood, untreated tir	A1-3: Product	A1-3	0	Material in	6.40E+00	1.94E+00	6.88E-03	1.77E-03
EW05 CLT + str blown	External wall - loadbearing | Prir	cross laminated timber	CLT, cross laminated tir	A1-3: Product	A1-3	0	Material in	6.59E+01	2.95E+01	8.07E-02	2.62E-02
EW05 CLT + str blown	Wall - external finish | Cladding	cork (32-80mm)	Transport, freight, lorry	A4-5: Constru	A4	0	Transport to sit	1.01E+00	8.73E-02	4.80E-05	4.71E-05
[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]
EW05 CLT + str blown	Wall - external finish | Cladding	cork (32-80mm)	Cork slab {RER}| produ	A4-5: Constru	A5	0	Material loss	5.60E-01	7.89E-01	7.19E-04	4.93E-04
[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]
EW05 CLT + str blown	Wall - external finish | Cladding	cork (32-80mm)	Softwood, laths, dried (	B1-4: Use stag	B2	10	Process	2.20E-03	2.66E-01	9.46E-04	2.44E-04
EW05 CLT + str blown	Wall - external finish | Cladding	cork (32-80mm)	Chromium steel, screw	B1-4: Use stag	B2	10	Process	2.50E-03	1.82E-02	2.63E-05	1.17E-05
EW05 CLT + str blown	Wall - external finish | Cladding	cork (32-80mm)	Softwood, laths, dried (	B1-4: Use stag	B2	20	Process	2.20E-03	2.66E-01	9.46E-04	2.44E-04
EW05 CLT + str blown	Wall - external finish | Cladding	cork (32-80mm)	Chromium steel, screw	B1-4: Use stag	B2	20	Process	2.50E-03	1.82E-02	2.63E-05	1.17E-05
EW05 CLT + str blown	Wall - external finish | Cladding	cork (32-80mm)	Softwood, laths, dried (	B1-4: Use stag	B2	30	Process	2.20E-03	2.66E-01	9.46E-04	2.44E-04
EW05 CLT + str blown	Wall - external finish | Cladding	cork (32-80mm)	Chromium steel, screw	B1-4: Use stag	B2	30	Process	2.50E-03	1.82E-02	2.63E-05	1.17E-05
EW05 CLT + str blown	Wall - external finish | Cladding	cork (32-80mm)	Softwood, laths, dried (	B1-4: Use stag	B2	40	Process	2.20E-03	2.66E-01	9.46E-04	2.44E-04
EW05 CLT + str blown	Wall - external finish | Cladding	cork (32-80mm)	Chromium steel, screw	B1-4: Use stag	B2	40	Process	2.50E-03	1.82E-02	2.63E-05	1.17E-05
EW05 CLT + str blown	Wall - external finish | Cladding	cork (32-80mm)	Softwood, laths, dried (	B1-4: Use stag	B2	50	Process	2.20E-03	2.66E-01	9.46E-04	2.44E-04
EW05 CLT + str blown	Wall - external finish | Cladding	cork (32-80mm)	Chromium steel, screw	B1-4: Use stag	B2	50	Process	2.50E-03	1.82E-02	2.63E-05	1.17E-05
EW05 CLT + str blown	Wall - external finish | Cladding	cork (32-80mm)	Transport, freight, lorry	C1-4: End of li	C2	60	Transport EOL	1.40E+00	2.28E-01	1.08E-04	1.20E-04
EW05 CLT + str blown	Wall - external finish | Infrastruc	fibre board + bitumen	Transport, freight, lorry	C1-4: End of li	C2	60	Transport EOL	1.77E+02	1.14E-01	5.36E-05	6.00E-05
[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]
EW05 CLT + str blown	Wall - external finish | Cladding	cork (32-80mm)	Sorting of waste combu	C1-4: End of li	C3	60	Process	5.60E-01	9.06E-04	5.34E-07	7.04E-07
EW05 CLT + str blown	Wall - external finish | Infrastruc	fibre board + bitumen	Sorting of waste woode	C1-4: End of li	C3	60	Process	4.24E+01	2.73E-04	2.39E-07	3.01E-07
[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]
EW05 CLT + str blown	Wall - external finish | Cladding	cork (32-80mm)	Incineration of waste w	C1-4: End of li	C4	60	Process	1.06E+01	1.02E-01	3.11E-04	5.87E-04
EW05 CLT + str blown	Wall - external finish | Cladding	cork (32-80mm)	Sorting of waste combu	C1-4: End of li	C4	60	Process	1.06E+01	1.72E-02	1.01E-05	1.34E-05
[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]
								TOTAL	60.25	0.12	0.05

Table 24 shows an example SLiCE dataset, generated from the SLiCE building LCA tool presented in chapter 7 (SLiCE building LCA: A model for life cycle analysis of buildings across scales), which

elaborates on the implementation of the SLiCE data model for the generation of LCA data on buildings across of buildings across scales. The sample dataset shows the element EW05. In full, it consists of approximately 200 rows representing various activities corresponding to the modeled life cycle of this element, spanning a duration of 60 years. The table provides an overview of a typical SLiCE dataset on building element level, showing various spatial attributes such as element, work section, product/process (activity), and techflow. It also includes temporal attributes such as life cycle stage, life cycle module, point in time (year), and activity type. Additionally, the table presents indicator results included in the SLiCE dataset, including LCI amount (techflow) and LCIA results based on LCA indicators such as GWP, PM, and EP. At the bottom of the table, the LCIA totals are displayed, confirming the consistency of the high-resolution SLiCE dataset with the results reported in the original study conducted by (Mouton et al., 2023a).

6.3.2. SLiCE-based hotspot analysis

The SLiCE hotspots tool enables the analysis of environmental hotspots within building assessment results following the SLiCE data model – see Figure 45 for a conceptual overview of the tool, based on snippets of the current prototype of the tool, implemented via JupyterNotebook (Kluyver et al., 2016) and Panel (Yang et al., 2022).

To start, the hotspot analysis script requires some user inputs and settings:

1. First, a SLiCE-compliant dataset as well as a file with weighting factors related to the impact indicators in the dataset have to be specified.
2. Second, the ‘level 0’ attribute object must be specified, which represents the baseline for the analysis and determines the attribute value(s) that can be selected for inclusion in the analysis. Depending on whether one or more items (attribute values) are selected, the results will provide insights on one item and its hotspots or allow for comparison of different items.
3. Third, the indicators to be considered in the hotspot analysis must be selected. These will be normalised and weighted to obtain a common base unit, based on the weighting factors/sets which also must be selected here (if several weighting sets are available, including an option of “equal weighting”). Here it is furthermore possible to unselect indicators or select just one, in which case the consecutive steps of the analysis will only consider the active indicators.
4. Fourth, the temporal attribute is defined, i.e., the attribute based on which the most relevant life cycle stages will be determined. The selection mask allows to select one or many life cycle stages, with all stages selected by default. Here it is possible to focus the analysis on selected life cycle stages, for example, to assess the most relevant indicators, life cycle stages and processes within the building use-phase, or for embodied impacts only.
5. Fifth, the ‘level -1’ attribute is specified, which represents the ‘process’ level in this analysis. The SLiCE tool is flexible with regards to defining ‘level-1’ as any spatial level below the initial ‘level0’ attribute. This means, for example, if ‘level0’ is the ‘building level’, then ‘level-1’ can be ‘building element’, ‘work section’, or ‘material level’, respectively.
6. Sixth, the threshold value for the cumulative impact of ‘most relevant’ items is defined. By default, it is set at 80%, as per the PEF/OEF hotspot analysis protocol, but can be changed as needed.
7. Lastly, when the above settings have been defined (or changed), pushing the ‘Run hotspot analysis’ button will run the analysis and generate (or updated) results tables and plots.

To illustrate the proof-of-concept, the prototype of the SLiCE hotspots tool was tested using sample data. Figure 45 presents the original tables and figures obtained from analysing this data and confirms the feasibility of the concept. The data sample uses impact indicators and weighting sets of the Belgium MMG method (Allacker, 2010; Lam and Trigaux, 2021; Servaes et al., 2013), and has been tested with life cycle inventory data on building elements by (Mouton et al., 2023a) as well as SLiCE datasets of

building level archetypes developed in the 'Supporting a Roadmap for the Reduction of Whole Life Carbon in Buildings'(Le Den et al., 2023). The detailed LCIA results were obtained through an implementation of the SLiCE data model within a comprehensive LCA modelling framework, building on the 'MMG+_KULeuven' model (Allacker, 2010; Trigaux, 2017), the details of which are further elaborated in chapter 7 (SLiCE building LCA: A model for life cycle analysis of buildings across scales).

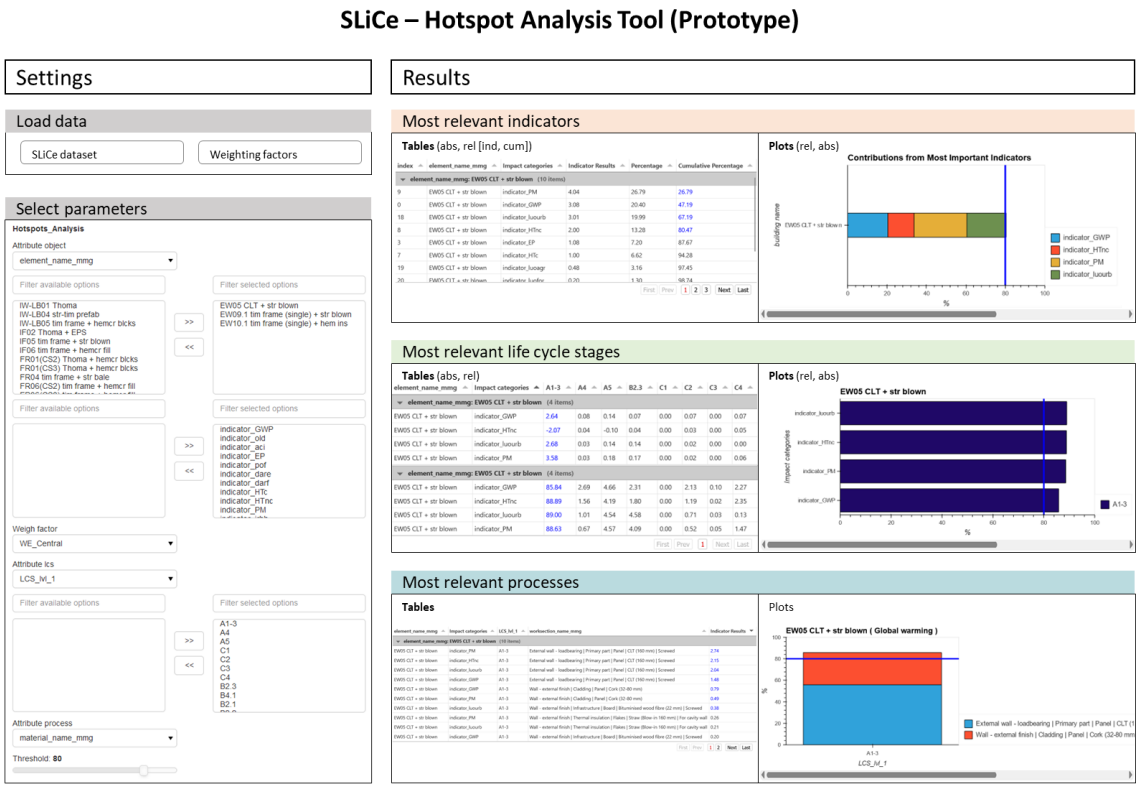


Figure 45: Conceptual dashboard view of the SLiCE hotspot analysis tool, showing elements of the user interface for relevant settings and examples of the generated results of the hotspot analysis, presented as tables and plots.

6.3.3. SLiCE-based dynamic LCA

One of the guiding design principles for developing the SLiCE data model was to provide high-resolution foreground inventory data for dynamic assessment of environmental impacts and potential carbon removals. The feasibility of the SLiCE data model for this purpose has been tested under supervision of the author within the related master thesis (Vanoverberghe, 2022).

Dynamic foreground LCI

The dynamic LCA builds on a SLiCE dataset of the respective building element, as illustrated by the example shown in Table 24, which provides a dynamic foreground LCI with explicit information on the type and timing of activities per year of the life cycle, i.e., a minimum spatial and temporal resolution of STI:D/-3. The SLiCE dataset includes a specification of the key spatial attributes: i.e., activity name (activity_name) and the related techflow (techflow_name), for soft linking to Ecoinvent background data. As well as information on temporal attributes: the life cycle stage (LCS_name) and timing of the activity (activity_year) and type of flow going in/out of the system (activity_type).

Static background LCI

The SLiCE dynamic foreground LCI is combined detailed static background LCI from Ecoinvent by mapping information based on the techflow name. In this example, the background LCI is only used to

obtain data on the four main GHGs in relation to different life cycle stages specified in the foreground LCI, as illustrated in Table 25. Background data on other biosphere flows could be used to dynamically assess other environmental impacts, such as, for example, land use or water scarcity. The present example utilizes a direct mapping of specific background and foreground LCI for providing further information on the specific GHG flows related to different activities in a certain year.

Table 25: Static LCI resulting from the combination of dynamic SLiCE foreground LCI and Ecoinvent background LCI, aggregated by life cycle stages given in the foreground LCI.

Life cycle stages	GHG emissions inventory			
	CO_2 [kg]	**CH_4 [kg]**	**N_2O [kg]**	**CO [kg]**
A1-A3	4.85E+01	8.03E-02	1.58E-03	1.86E-01
A4	2.40E+00	4.00E-03	7.77E-05	9.24E-03
B2	1.04E+00	2.03E-03	1.72E-05	4.04E-03
B4	2.22E+01	4.12E-02	1.42E-03	1.17E-01
C1, C3-4	4.51E+01	3.90E-03	1.97E-04	1.02E-02
Total	**1.19E+02**	**1.32E-01**	**3.29E-03**	**3.27E-01**

Static LCIA results

At first, a static LCIA is conducted to obtain reference results on the global warming potential (GWP) of the building element per square meter (m^2) for a 100-year time horizon. The static LCIA results presented in Table 26 show that carbon dioxide (CO2) has the largest contribution to the GWI, accounting for 96% of the total impact. Methane (CH4) contributes 3%, while the remaining percentage is attributed to nitrous oxide (N2O). The production phase has the greatest impact, representing 41.4% of the total, followed by the end-of-life phase with 36.5%, and replacements with 19.2%.

This approach is useful, as it utilizes the detailed LCI data to explicitly reveal the impact and contribution of different GHG to the total global warming impact of the product system, the case study building element. However, the static LCIA results still lack explicit information on the temporality of those emissions, crucial for understanding in which year they occur and what climate impact is associated with different pulse emissions over time.

Table 26: Static LCIA results for time horizon of 100 years.

Life cycle stages	GHG emissions impact				GWP
	$kgCO_2$	**$kgCH_4$**	**kgN_2O**	**kgCO**	**[$kgCO_2e$]**
A1-A3	4.85E+01	2.25E+00	4.18E-01	1.86E-01	5.13E+01
A4	2.40E+00	1.12E-01	2.06E-02	9.00E-03	2.54E+00
B2	1.04E+00	5.40E-02	4.54E-03	4.01E-03	1.10E+00
B4	2.22E+01	1.16E+00	3.76E-01	1.17E-01	2.38E+01
C1, C3-4	4.51E+01	1.09E-01	5.21E-02	1.00E-02	4.53E+01
Total	**1.19E+02**	**3.68E+00**	**8.71E-01**	**3.26E-01**	**1.24E+02**

Dynamic LCIA results

The combination of a SLiCE-based dynamic foreground inventory and dynamic impact characterization factors allows this analysis of the temporal dynamics of climate impact. Figure 46 displays the dynamic impact of all considered GHGs, obtained by multiplying the LCI (bottom) with the corresponding dynamic characterization factors (DCFs) to obtain dynamic LCIA results (bottom). Th figure shows the dynamic climate impact results for CO_2 (blue), CH_4 (red), N2O (green) and CO (purple). CO_2 emissions,

as expected, have the largest contribution to dynamic climate impact results. Both CO_2 (blue) and CH_4 (red) show the highest peaks occurring during production and construction (year 0) and at the end-of-life (year 60) of the building element. Additional spikes can be seen at years 10, 20, 30, 40, and 50, mainly resulting from the replacement of nails, paint, and larch cladding. Notably, there are minimal emissions of N_2O (green) in the LCI. The patterns observed in the LCI graph (top) are reflected in the dynamic impact curves (bottom), with spikes at the beginning and end of the building element, as well as at intermediate years.

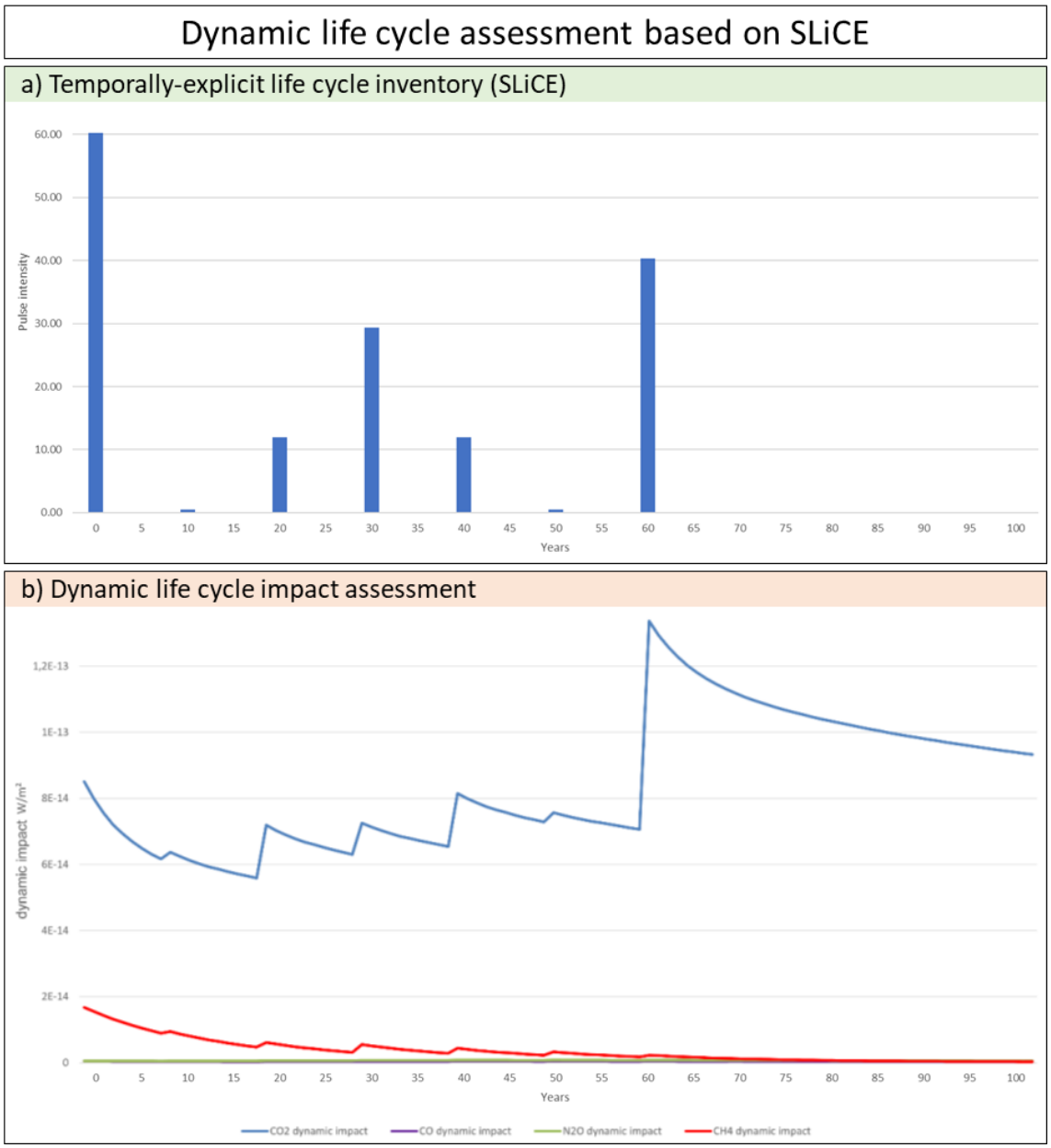


Figure 46: Illustration of dynamic life cycle assessment based on SLiCE showing (a) temporally explicit life cycle inventory (SLiCE) and (b) the resulting dynamic life cycle impact assessment graph. The graphs illustrate the GHG emission pulses (b) related to the activities occurring each year (a). As the specific types of activities in a given differ, so does the related GHG emissions 'pulse', which was computed using Ecoinvent background LCI data. The resulting dynamic climate impact (b) is therefor higher or lower, depending on the type of activity in the life cycle inventory.

This presents the proof-of-concept for using SLiCE for dynamic life cycle impact assessment. The underlying thesis (Vanoverberghe, 2022) applied this method to investigate dynamic climate impact as well as biogenic carbon uptake considering the effects of different scenarios regarding study time

horizon, element service life, as well as forest rotation period and crediting of carbon uptake during harvest, i.e., from previous growth, or during regrowth. The methodology can further be developed to address existing limitations, such as the current cut-off after a predefined time horizon, which can be addressed by applying a 'rolling time horizon' (THr), which extends the study period by THr years beyond the year of the last activity/pulse. It is furthermore possible to distinguish the contribution to dynamic climate impact from different activities in the foreground inventory in a given year as well as cumulative across the time horizon.

6.3.4. Future development

Beyond the presented use cases of SLiCE data for high-granularity data and environmental hotspot analysis of buildings, various further use cases can be conceived in context of integrating LCA in building information modelling across spatiotemporal scales. In the following we present initial thoughts on functional, informational, organizational and technical aspects (Obrecht et al., 2020a) to be further developed:

Functional aspects

Opportunity: Advanced analytics and visualization

SLiCE datasets of a building's life cycle inventory and environmental indicators results offer a variety of opportunities for advanced analytics and visualization, which are yet to be fully explored. The presented use case of the data model for environmental hotspot analysis is only a first prototype which uses basic visualizations. Departing from the SLiCE data logic as a computational foundation, a variety of advanced visualization options can be developed for building LCA to ensure relevant insights are provided for different stakeholders and use cases (Hollberg et al., 2021; Lupton and Allwood, 2017; Resch et al., 2020; Röck et al., 2018a)

Challenge: Resource-intensive inventory modelling

Labour intensive modelling: While SLiCE support the handling of detailed LCI and LCIA data, the bottleneck of time-intensive definition of high-quality inventory data remains. Modular approaches as well as increased automation in life cycle inventory generation can help reduce the resource and labour intensity of this task (Allacker, 2010; Kiss et al., 2019; Röck et al., 2018a). In parallel to developing advanced analytics and visualization capabilities, the processes and workflows for LCI definition have to advance.

Informational aspects

Opportunity: Data enrichment and mappings

The SLiCE data structure and its computational backbone support the enrichment of a SLiCE dataset, for example by mapping onto it classifications from various building element classifications. Examples of such element classifications that can be mapped are national systems such as CI-SfB/BB-SfB (De Troyer, 2008), German DIN276, or Austrian ÖN1801, international industry standards such as UniClass, UniFormat, or transnational reporting requirements such as the Level(s) sustainability reporting framework (Directorate-General for Environment (European Commission), 2021; European Commission, 2017). A similar mapping is possible for information at the other scale levels contained in SLiCE data, such as mapping of material classification systems such as the Eurostat material accounts or conventions used in studies relevant to a particular use case (Baldassarri et al., 2017; Eurostat, 2018; Joint Research Centre (European Commission) et al., 2022). A comprehensive overview of systematic classification systems and the challenges and opportunities of using them in a building LCA context have been presented by (Soust-Verdaguer et al., 2023).

The detailed information on a building's LCI and LCIA offered via SLiCE, can be combined with a detailed description of other attributes of the object of assessment, the building, such as attributes on the building's context and site, relevant building design characteristics, or variables related to assessment methods applied in a particular case study. A proposal for an extensive set of attributes for building description in context of benchmarking whole life carbon is presented in chapter 4 (Open database on embodied and whole life carbon of buildings).

Challenge: Input data availability and granularity

A challenge yet unsolved is the availability and granularity of input data relevant to informing the life cycle modelling of buildings and building stocks. Detailed information on the micro-level, such as the composition of building elements, can often be obtained through reviewing technical documentations or, if needed, surveying on-site (see labour intensive modelling bottleneck). Detailed information on the macro-level, however, is currently limited to statistical data on the regional material and energy flows obtained from multi-regional input-output (MRIO) models. While certainly useful for many applications, the data provided by such models mostly lacks the necessary granularity when it comes to buildings, for which it would be relevant to understand resource flows not just between regions, but between different types of buildings and activities (How much concrete is used for the new construction of single-family houses in a given year?). Extended definition and use of data reporting standards for information relevant to life cycle modelling of both buildings and stocks can hopefully improve this situation in the future. The advancement of corporate sustainability reporting standards, as well as the revamp of platforms such as the Building Stock Observatory (European Commission (EC), 2023)as well as other data collection efforts such as the BuiltHub project (BuiltHub, 2023), offer glimpses of what next steps might look like.

Organizational aspects

Opportunity: Digital Building Logbook

The SLiCE data model is agnostic with regards to the use of prospective, scenario-based information, or information based on as-built or in-use measurements. In practice, a SLiCE dataset could hence be used in a first steps to store both, the initial life cycle assessment results, based on plausible life cycle scenarios. In a second step, and through iterations at various points across the use phase, the initial life cycle data can be replaced with as-built or in-use measurements to represent the actual building condition and performance and update the SLiCE dataset accordingly. In that regard, a SLiCE dataset, storing detailed information on the building life cycle inventory and related environmental impacts, can be one of several modules and an integral part of a digital building logbook or digital twins more broadly (Gómez-Gil et al., 2022a, 2022b; Hunhevicz et al., 2022; Roxin et al., 2022).

Challenge: Stakeholder-specific needs

As different stakeholders have different needs, the features of SLiCE data model and its implementation in different tools will evolve over time. As of today, the SLiCE data model has been developed from a building LCA perspective and the use of high granularity building data within high resolution models of building stock up to macro-scale. The link between building and building stock level is particularly important to support detailed life cycle modelling for testing the effects of building-level decarbonization strategies when upscaled to the macro-level. Data models such as SLiCE are important for ensuring a robust link between building and building stock level that can avoid unnecessary loss of data through aggregation or computational inefficiencies.

Technical aspects

Opportunity: Dynamic impact assessment

The detailed life cycle inventory offered by SLiCE data, if including a specification of flows and processes by 'point in time' (e.g., per year), can further be the basis for modelling dynamic impact characterization, such as for temporally dynamic assessment of climate impacts. A proof-of-concept of such a dynamic characterisation of climate impact in context of bio-based construction materials has been presented by (Vanoverberghe, 2022). Detailed life cycle inventory data provided using the SLiCE data model can furthermore include the specification of related background LCA datasets (e.g., reference to datasets in the Ecoinvent database), in order to enable spatially dynamic assessment, i.e., regionalization of the background data as well as the impact assessment, for example via tools like Brightway (Mutel, 2017; Mutel and Hellweg, 2009; Steubing et al., 2020; Verones et al., 2020)).

Opportunity: High resolution LCA modelling at higher scales

Finally, the potential of SLiCE data to handle high granularity LCI and LCIA in an efficient way, can enable increased model resolution in life cycle assessment at higher scale levels, such as for environmental modelling of building stocks at macro-scale. The modelling of higher scales, beyond the buildings level, can be expected to follow different logics as the building LCA life cycle information model, the ability to map the detailed LCI and LCIA data offered by SLiCE with definitions common in building stock modelling will be useful. SLiCE results per life cycle stage can, for example, be mapped with different building stock level activities, such as new building construction (considering results in life cycle stages A1 to A5), to obtain insights into the upfront impacts or emissions of such activities from a bottom-up perspective.

6.4. Conclusion

In response to the need of policy and decision makers to understand (environmental) hotspots along the life cycle of buildings, this chapter presents the SLiCE building data model as a basis for scalable life cycle engineering and analysis of buildings across spatiotemporal dimensions.

The hitherto unresolved challenge of providing and processing high granularity building life cycle information to support the needs of policy and decision makers is conceptualised within the space-time-indicator (STI) framework as a means of communicating the availability and requirements for building life cycle information regarding diverse indicators at different levels of granularity along spatial and temporal dimensions. The SLiCE data model is introduced, and its data structure explained, as well as a first use case presented by implementing a systematic protocol for the analysis of (environmental) hotspots within building life cycle information. The proof-of-concept for using SLiCE data for hotspot analysis data model is implemented within a functional prototype for hotspot analysis. Furthermore, an exemplary use case of SLiCE for dynamic LCA is presented based on the combination of dynamic LCI data from SLiCE and Ecoinvent and the use of dynamic characterization factors from literature. Both applications are implemented utilizing IPython Jupyter Notebooks and interactive UI elements.

The SLiCE data model, the SLiCE hotspot analysis tool prototype, as well as the SLiCE-based dynamic impact assessment model are henceforth available for implementation within future building LCA workflows and tools, such as, for example, for high-definition assessment of buildings across spatiotemporal scales.



7. SLiCE BUILDING LCA: A MODEL FOR LIFE CYCLE ANALYSIS OF BUILDINGS ACROSS SCALES

Bibliographic data

Title	SLiCE building LCA model - Implementation for high-definition life cycle assessment of buildings across spatiotemporal scales
Authors	Martin Röck, KU Leuven (BE)
	Karen Allacker, KU Leuven (BE)

Highlights

- Policy and decision makers involved in governing, procuring, designing and operating building stock developments, require robust insights from life cycle-based modelling of climate and environmental impacts of buildings and building stocks to inform decision making.
- Even though substantial efforts have been made to develop ever more capable computational methods for the environmental modelling of buildings and building stocks, decision makers are still faced with a trade-off between policy-relevance of higher-scale modelling and limitations in data granularity and model resolution at those higher scale-levels.
- This chapter presents an implementation of the SLiCE data model within a building LCA modelling framework for building LCA across spatiotemporal dimensions – the SLiCE building analysis ecosystem.
- This SLiCE implementation offers high-resolution modelling at higher scale levels while maintaining high granularity and model resolution.
- Application examples showcase the potential of this model to support high-definition building analysis at different scale levels, showing examples from micro-scale (building elements), over meso-scale (building archetypes), up until the macro-scale (transnational building stocks).

Author contributions

Martin Röck: Conceptualization; methodology; data curation and visualization; writing – original draft; writing – review and editing; project administration.

Karen Allacker: Methodology; writing – review and editing; supervision; project administration.

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Data and code availability

The SLiCE building data model is deliberately open source and details on the model and its further use are presented in the original chapter 6 (The SLiCE building data model for hotspot analysis). In the present chapter, the SLiCE data model is implemented to establish a building LCA framework using modelling logics and calculation algorithms of the MMG+_KULeuven building LCA tool, which is closed source. The authors are exploring the potential to open-source parts of the presented SLiCE building LCA model not covered by pre-existing IPR, where feasible.

The following chapter presents a draft manuscript for submission to a peer-reviewed journal.

Abstract

The decarbonization of buildings and building stocks is gaining increasing attention among researchers, policy makers, and hence real estate people and building design professionals. However, modelling effective strategies for reducing emissions of building stocks considering the full life cycle of buildings still represents a challenge. Existing computational methods for studying climate and environmental impacts of building stocks at scale, show limitations regarding the level of detail applied for modelling environmental impacts across spatiotemporal dimensions.

This article presents an implementation of the SLiCE building data model for high-definition life cycle assessment of buildings across spatiotemporal scales, the SLiCE building LCA model. The article presents the computational foundation as well as practical applications of the framework: dynamic modelling of climate impacts and bio-based material's biogenic carbon uptake; comparative spatiotemporal analysis of environmental impacts of bio-based and conventional building elements; the upscaling of high-resolution building archetype results for assessing the baseline of life-cycle-related GHG emissions of the European building stock; as well as the analysis of decarbonization scenarios when applying different carbon reduction strategies.

The presented assessment model enables the scalable life cycle modelling of buildings across spatiotemporal dimensions and shows the proof-of-concept through several application examples. The future development of the model can incorporate additional indicators (financial, social, environmental); further streamlining of the archetype and scenario modelling interfaces; as well as the link to other modelling frameworks and application to further use cases.

7.1. Introduction

Background and problem

Policy and decision makers involved in management, procurement, design and operation of buildings need robust evidence from life cycle-based modelling of climate and environmental impacts of buildings and building stocks to inform decision making. However, in the current situation, there is a persistent and problematic trade-off between policy-relevance and resolution – see Figure 47.

More specifically, as the systematic literature review and analysis of Röck et al. (Röck et al., 2021) identified, there is a particular lack of building stock models with comprehensive assessment scope and a high level of detail at higher (macro-)scale levels, such as the regional and national as well as the transnational level. The integrated review has shown that current research on environmental modelling of building stocks varies substantially in terms of its spatiotemporal scope, with published studies reaching from portfolio and urban scale (meso-scale) up to national and transnational (macro-scale) and that studies are conducting (mostly prospective) evaluations with timeframes ranging from one or a few years up to 200. The assessment of existing building stock modelling methodologies by (Röck et al., 2021) furthermore identified helpful information on how to model material- and energy-related effects, including methodological approaches and data sources for inventory definition. However, it has become apparent that the number of environmental indicators covered by existing studies showed to be rather limited, with most studies focusing mostly on GHG-related indicators. Although considerable efforts have been made to develop ever increasingly powerful computational methods for the environmental modelling of buildings and building stocks, decision makers are still faced with a trade-off between policy-relevance on one hand, and data granularity and model resolution on the other hand, as illustrated in Figure 47. This is especially concerning for the policy-relevant modelling of macro-scale building stocks (such as on country or regional level up to transnational/EU-level) but also the case for meso-scale building stocks (such as larger building asset portfolios or urban/rural agglomerations), the insights from which are important to inform local governance as well as, increasingly, all decision makers responsible for managing building portfolios and commercial real estate.

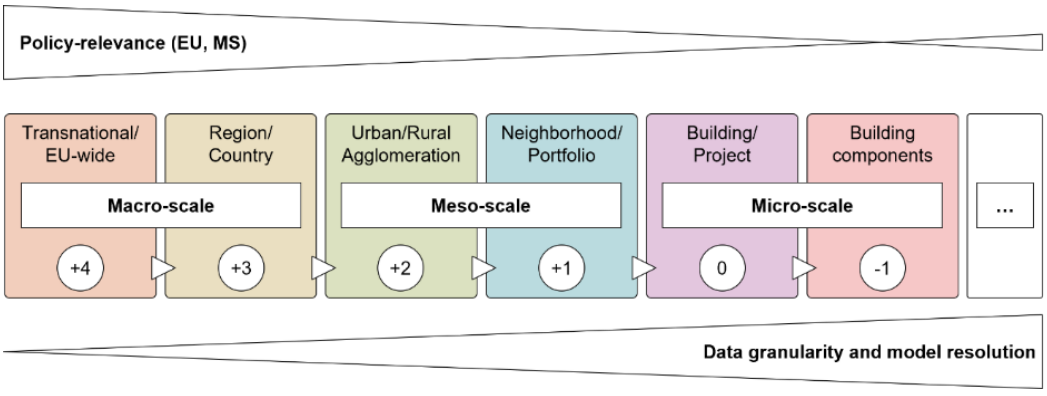

Figure 47: Prevailing trade-off between policy-relevance and data granularity and model resolution across spatial levels (Own figure, adapted from (Allacker et al., 2019))

It follows that there is a need for comprehensive, high resolution building models that support analysis across spatiotemporal scales to provide the robust and relevant insights required by decision makers who influence the procurement, design, construction, operation and management of buildings at scale. In this chapter, SLiCE is implemented within an LCA modelling framework for scalable life cycle modelling of buildings across spatiotemporal dimensions – the SLiCE building LCA model.

Goals for scalable life cycle assessment of buildings

With SLiCE, we utilise an open data model for scalable, high-definition life cycle engineering and analysis of buildings across spatiotemporal dimensions and hereby show an implementation of the data model at scale within the SLiCE building LCA framework, building on KU Leuven's MMG building LCA tool ('MMG+_KULeuven')(Allacker, 2010; Lam and Trigaux, 2021; Servaes et al., 2013; Trigaux, 2017). This SLiCE implementation aims at offering an LCA framework for high-resolution modelling also at higher scale levels, i.e., for environmental life cycle modelling across micro- and meso- as well as at macro-scale, such as for building portfolios and trans/national building stocks.

Among the main design goals of this SLiCE implementation are the objectives to:

- Develop a scalable framework for modelling high-resolution life cycle inventories which maintains the high level-of-detail of assessment results across spatiotemporal dimensions, from micro to macro-scale.
- Advance spatiotemporal resolution of foreground inventory, with regards to adding information on the temporality of processes (such as the life cycle stages as well as the point in time, e.g., the year, these occur in) as well as their spatial allocation within the building system (such as hotspots within element, work sections, materials).
- Link detailed information on energy and material flows and associated impacts from a building LCA perspective with modelling of the building stock at higher scales, using the element method and a standardised life cycle model in line with latest standards and requirements.
- Elaborate on the tried-and-tested MMG life cycle analysis method for environmental profiling of building elements and buildings, as a robust basis for assessment of life cycle environmental impacts and financial cost.
- Enable assessment of a comprehensive set of environmental impact indicators, as a starting point for future extension with other attributes and indicators, such as for costing, circularity, or criticality aspects.
- Provide an extendable, modular codebase and provide in-depth analytics and customizable visualizations leveraging modern computational opportunities, building on Python and SQL backbone.

The original, spreadsheet-based MMG model, while constantly improved and updated, largely exhausted the capabilities of what is feasible within its computational framework and scale levels beyond the meso-scale (i.e., neighbourhoods or urban agglomerations) are no longer feasible due to computational limits. Besides enabling detailed modelling of hierarchical inventories and consideration of expansive life cycle information, the MMG model lost important relevant information due to the need for aggregation of intermediate results to save computational cost. The goal of further scaling the model while maintaining or even expanding spatial and temporal resolution required a transformation of the MMG model into a scalable life cycle modelling framework for building analysis based on the SLiCE data model. A potentially helpful analogy for understanding how the SLiCE implementation advances the original MMG model, could be to consider SLiCE and MMG for life cycle modelling of buildings like 'unit processes' and 'system processes' in general life cycle (inventory) modelling in the well-known Ecoinvent database. This comparison aims to capture the benefit of high-resolution, multi-dimensional modelling and non-aggregated data (unit processes / SLiCE) for comprehensible life cycle modelling and in-depth analysis of life cycle hotspots.

7.2. The SLiCE building LCA model

7.2.1. Advances of SLiCE

The SLiCE building LCA and its advances compared to the original MMG+_KULeuven model are explained in the following. The main advances of SLiCE over MMG are: 1) Improved data structure of the input tables and more efficient computation; 2) Addition of information on mass and energy flows to the output results; 3) Addition of temporal information, i.e., year of the flow, in the output results; 4) Increased level of detail of the output results at all levels – specified down to underlying Technosphere flows and description of relevant attributes of each flow.

The SLiCE building LCA framework was developed in parallel in Visual Basic (VBA)/Excel and in Python/SQL. The parallel development was useful for several reasons, including that it enabled: 1) Development and testing in Visual Basics to be done faster as less complex translations were required, 2) To keep the model available in Excel and make use of the existing spreadsheet based MMG+_KULeuven model interfaces, and 3) To provide a Visual Basic version of SLiCE as a functional blueprint and basis for the development of the Python/SQL version of the latest SLiCE model.

The inputs for the temporal aspects of the model were already programmed in the original MMG+_KULeuven version, where results were retrieved by customised Excel equations (VBA). However, the information had been aggregated and years of Technosphere flow occurrences were not used (only the number of occurrences), as this would have unreasonably increased size of the Excel files. With some modifications, the functions could be integrated into the new Visual Basic script and Python/SQL models. This improvement is of great importance for building LCAs, because emissions and resource extractions in the future may have different consequences to the environment than those occurring in the present, making information on the timing of mass and energy flows and related environmental impacts ever more important. Moreover, other uses can be modelled utilizing this detailed spatiotemporal information, such as biogenic carbon fixation of wood or other bio-based materials. Here, it is important to know how long the fixed carbon is stored as this will influence carbon fluxes over time.

SLiCE enables the use of different classification schemes for classifying information, e.g., on materials or building elements. In addition to the specific internal logic for naming and categorization of items such as material or element definitions, the current version of SLiCE is applying several external classification schemes to support structured data analysis and improve interfaces with other modelling domains, such as: a) Material classification according to the multi-level Eurostat material categories for Material Flow Analysis (MFA) and environmental-economic accounts (Eurostat, 2018), as well as according to the logic used in the recent European Commission Joint Research Centre (JRC) study on background data collection and LCA for construction and demolition waste (CDW) management (Joint Research Centre (European Commission) et al., 2022); b) Building element classification according to the international SfB system, in particular the Belgian adaptation of the scheme (BB-SfB) (De Troyer, 2008; European Commission (EC), 1976); as well as an element classification in accordance with the European Commission's Level(s) Sustainability Reporting Framework (European Commission, 2017).

Table 27 presents a summary of the main table structures for input and output results in the Excel equations and Visual Basics versions of the MMG+_KULeuven model - the Python/SQL version has a different database structure but follows similar principles.

Table 27: Summary of main input and output data in original MMG+_KULeuven spreadsheet and SLiCE (VBA version).

Inventory level	Type	Original MMG+_KULeuven	SLiCE (VBA version)
Work-sections	Input tables	Combined table of work sections and materials in rows and parameters in columns	Separate tables for work sections and materials: - work section in rows and parameters in columns - work section and material combinations in rows and parameters in columns
	Output results	Work sections and materials in rows and indicator results per life cycle stage in columns	Work sections, material/activity, life cycle stage (levels 1 and 2), reference flow of work section, flow unit, density (for materials), mass/amount per reference flow, type of material/activity (material in/out/loss, process, or transport to site/to EOL), Technosphere flow name in rows and indicator results in columns
Elements	Input tables	Combined table of elements in rows and parameters in columns	Separate tables for elements and work sections: - Elements in rows and parameters in columns - Elements and work section combinations in rows and parameters in columns
	Output results	Definition of elements and work sections in rows and indicator results per life cycle stage in columns	Elements, work sections, material/activity, life cycle stage (levels 1, 2 and 3), reference flow of element, work section unit, flow unit, density (for materials), mass/amount per reference flow of element and of work section, type of material/activity (material in/out/loss, process, or transport to site/to EOL), Technosphere flow name, and year of the flow in rows and indicator results in columns
Buildings	Input tables	Tables in same spreadsheet for: - Buildings in rows and layout/element variants and parameters in columns - Layout variants in rows and parameters in columns - Element variants in rows and parameters in columns	Similar structure but individual data tables stored in the database for various definitions of: - Building variants: Combinations of layout and element variants - Layout variants: Definition of building and element quantity - Element variants: Definition of building element types
	Output results	Buildings/elements in rows and indicator results per life cycle stage in columns	Building, elements, work sections, material/activity, life cycle stage (levels 1, 2 and 3), reference flow of building, element, work section unit, flow unit, density (for materials), mass/amount per reference flow of building, element and of work section, type of material/activity (material in/out/loss, process, or transport to site/to EOL), Technosphere flow name, useful floor area, and year of the flow in rows and indicator results in columns

7.2.2. SLiCE environment

The computational environment of SLiCE (Figure 48) is structured along three types of objects related to: user interfaces; scripts (for data computation or visualization), as well as data inputs or outputs.

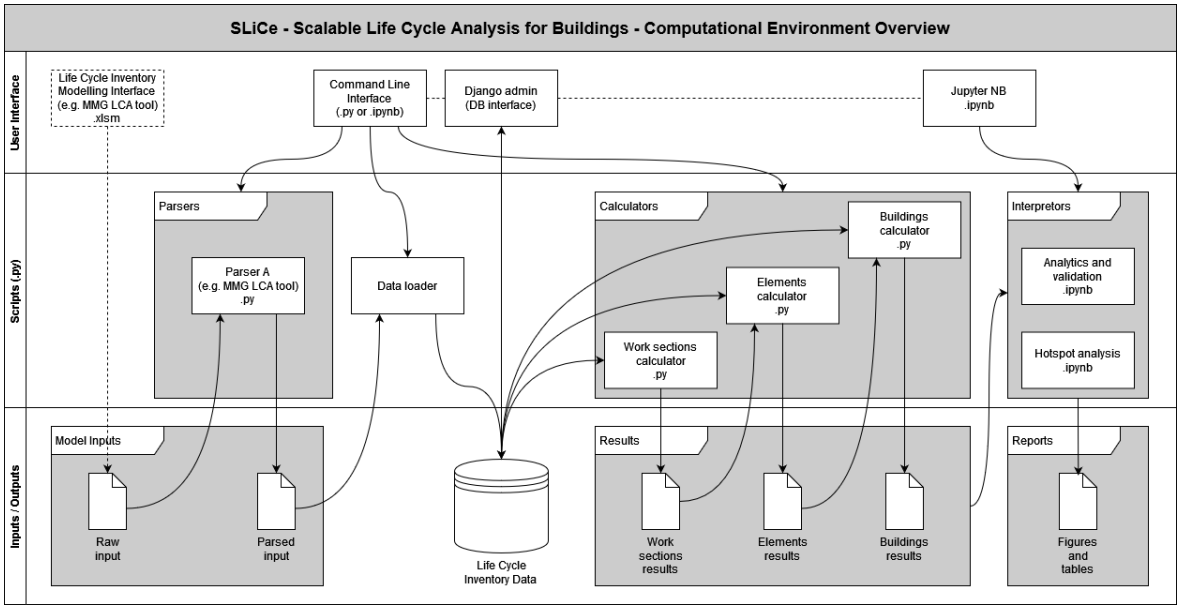

Figure 48: SLiCE computational environment overview.

User interfaces: user interfaces provide various ways to interact with exposed parts of the code. The main user interfaces utilised by the SLiCE framework are:

- Command line interface (CLI), as a type of interface which allows users to run exposed commands using a command line which, depending on the operating system, can also be called a console or a terminal. SLiCE CLI allows to: parse input data, load parsed data to a database and run calculations. The same functionalities accessible through the CLI can be – and are to some degree already – embedded in a Jupyter Notebook (see below).
- Django admin is a web interface built to support CRUD (Create, Remove, Update, Delete) operations on the project database and other custom actions. It is built on top of the Django web framework which provides features like authentication or internationalization (i18n).
- Jupyter Notebooks are web based interactive text editors integrated with a Python interpreter. Notebooks are composed of cells which can either contain descriptive text (using markdown language) or executable code (in this case, following the python syntax). The integration with the programming language allows Jupyter Notebook to import any part of the project and execute it in the python cell.

Scripts: scripts within the SLiCE framework are usually Python-based packages and modules separating distinctive components of the model, such as:

- Parsers are python scripts intended to transform any compatible input data, e.g., MMG+_KULeuven LCA model spreadsheets data, into standardised format expected by the SLiCE data loader.
- Data loader is the script that reads standardised inputs from a given path and saves them in the relational database. Data loader input must meet the standardised data formats in order to be processed, which for external inputs will usually require a specific parser. In future, a dedicated modelling interface for the definition of life cycle inventory data in line with the data loader requirements will be established to enable streamlined modelling and more direct interaction with the database.
- Calculators include the scripts for obtaining environmental impacts based on the inventory data stored in the database and processing them to calculate assessment results, such as conducting an environmental life cycle impact assessment (LCIA). There are four levels for which environmental impacts can be obtained: materials, work sections, elements, and buildings.

Results from lower levels are required to perform calculations on higher levels. Results from each level can be utilised for further analysis at higher scale levels as well as direct analysis and generation of reports at the given level.

- Interpreters include scripts for specific steps of the interpretation such as for analytics and validation of assessment results; systematic analysis of environmental hotspots; as well as for overall results visualization and reporting, using packages such as Matplotlib or HoloViz.

Inputs and outputs: inputs and outputs are any resources used in the project as data sources or outputs, in particular: raw input data to parsers; standardised data processed by the data loader; (intermediate) calculation results; assessment reports; and at the core, a relational database storing the informational building blocks of the other steps.

7.2.3. SLiCE modelling logic

The SLiCE building LCA model offers high-definition inventory modelling and impact analysis across spatial and temporal dimensions based on a logic of highly parametrised hierarchical modelling of spatial information and a modular approach to the specification of temporal life cycle information at different spatial levels. Figure 49 presents an overview of the hierarchical logic of spatial inventory modelling in SLiCE. Figure 50 shows the temporal life cycle information modules and their specification at different spatial levels. This particular logic is taken over from the Belgian MMG method, which was again based on the logics proposed in the SuFiQuaD project (Allacker, 2010).

Internal inputs are the starting point for inventory modelling in MMG/SLiCE. Internal input definitions can be describing building materials or processes and are directly related to one or more external inputs (i.e., background inventory data from dedicated LCA databases such as Ecoinvent). The definition of internal inputs requires specification of ratios to translate between differing units and to specify the amounts of external inputs (i.e., tech-flows) within a certain material or process. The specification further comprises information on Lambda and R-values or the compressive strength of materials, as well as other relevant thermophysical properties, where applicable. Already at the internal input level, temporal life cycle information is specified with regards to material production (A1-3). If the internal input is a material definition, life cycle scenarios are also defined for transport (A4) and construction and installation processes (A5) as well as for deconstruction (C1), processing (C2) and end-of-life treatment (C3, C4) through the assignment of material and waste categories and the associated separately configurable scenario definitions.

Work sections, the next higher spatial inventory level, build on (new or previously defined) internal input definitions via an ‘n:n’ relationship, meaning that a specific work section can have several internal inputs and a specific internal input can be used in several different work sections. The work section definition includes specification of ratios to define the amount of internal inputs per unit of work section, such as the material thickness which then enable calculation of attributes like the U-value of a chapter. Furthermore, life cycle information related to cleaning and maintenance (B2) as well as replacement (B4) is specified, considering the possible interrelations of different materials (layers, parts) within a work section. The B2 and B4 life cycle scenario definitions require the specification of frequency and hence determine the number of occurrences across the reference study period.

Elements, similar to the previous levels, are defined via an n:n relation with work sections. Specification again includes ratios to translate between potentially different units and to specify the amount of work section(s) per unit of element. The element level provides all information required to determine the transmission heat loss through a build-up and hence allows for an element-level assessment of operational energy use (B6) and related impacts. The element definition is further relevant for the optional model-based estimation of building-level operational energy use.

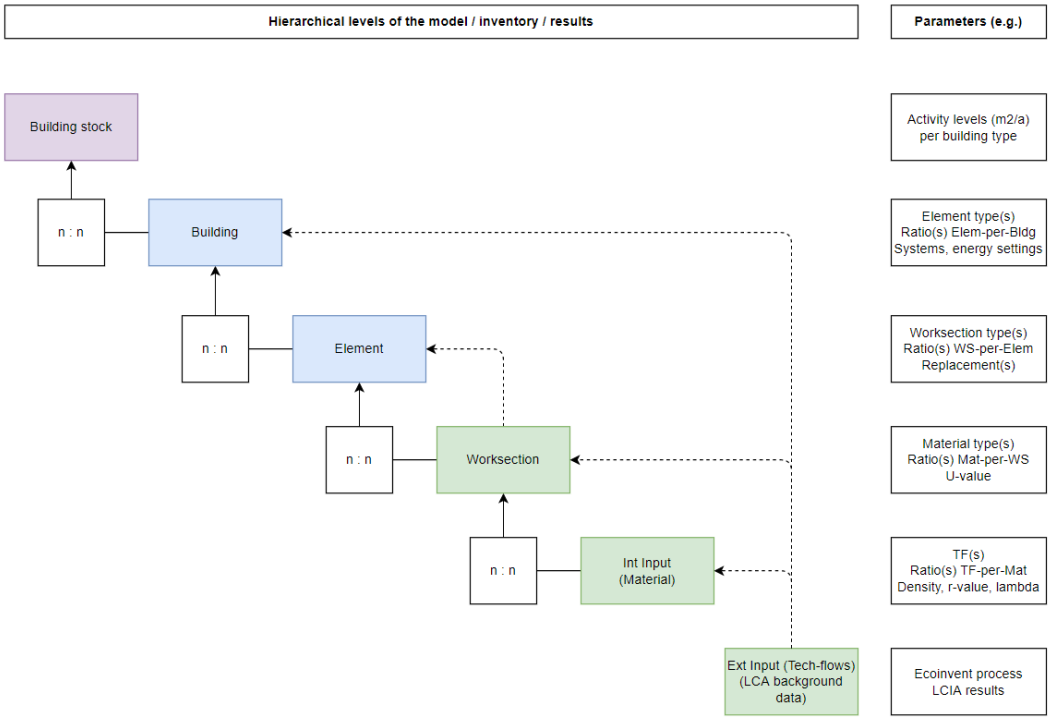

Figure 49: Hierarchical logic of spatial inventory modelling in SLiCE and exemplary parameters defined at each level.

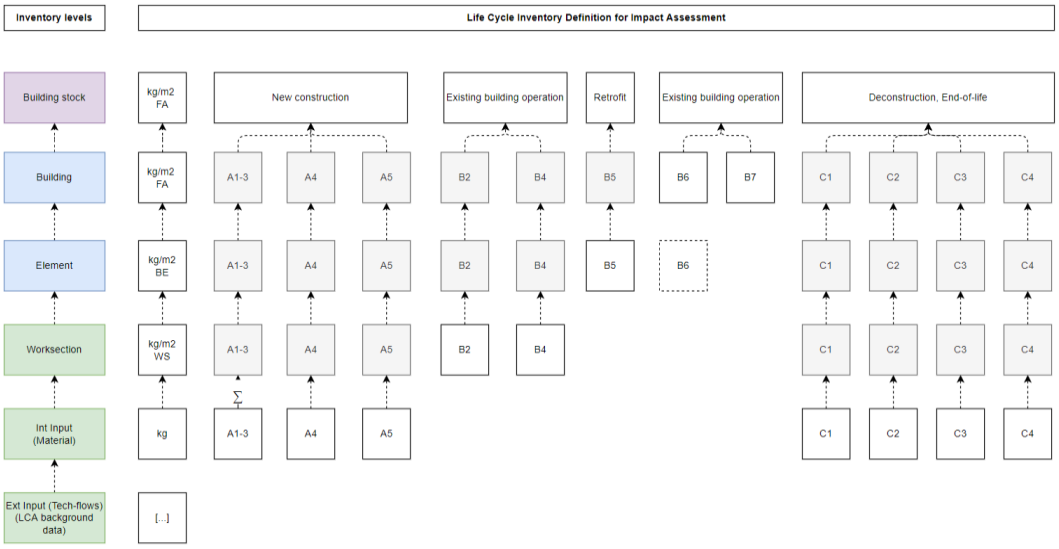

Figure 50: Temporal life cycle information modules and their definition and assignment at different spatial inventory levels.

Building level is the baseline level for SLiCE based analyses, the 'level 0' for most analyses. Diverging from the logic at previous scale levels, a building definition is comprised of three main parts: a) A building layout definition, which specifies relevant attributes around the buildings type of use, it's basic geometry indicators and most importantly the amounts of different building element classes in the layout, such as the m² of external wall, or number of doors; b) A building element variant definition, which selects specific building element types, as specified at the lower inventory level, for mapping onto the amounts specified in the layout definition; c) A technical systems and climate context definition which includes the definition of elements comprising the technical building system, general information on system efficiencies, as well as the method and inputs for calculating operational energy use for heating and cooling, respectively, as well as operational water use.

Building stock level: Higher scale inventory levels, such as the modelling of building portfolios or building stocks at macro-scale, usually have established perspectives different from that of building LCA. Hence, an upscaling to level +1 or higher involves a mapping of the building level definitions of life cycle inventory and subsequent assessment results with relevant building stock level activities (Table 28). Relevant building stock level activities that can be represented this way are, for example, existing building operation, existing building retrofit, new building construction, or deconstruction and end-of-life processing. Dedicated building archetypes are required to adequately represent the building level data for these different activities, i.e., different building models will be established for representing new building construction (NEW), existing buildings (EXB) and their respective refurbishment (REF). Building stock life cycle emissions are connected to the following building stock activities: construction, renovation, and demolition (LCA modules A *Production and Construction*, B5 *Planned refurbishment* and C *Deconstruction and demolition*). The emissions are calculated per floor area. The floor area affected by these activities is determined by the rates of construction, renovation, and demolition. The emissions are then upscaled based on floor area undergoing these activities. As these are immediate emissions, these are fully accounted for when the specific building activity occurs.

The mapping of building level results for dedicated life cycle stages, combined with activity data at the building stock levels, expressed as the amount of floor area as the respective multiplication factor, provides a consistent bottom-up approach for the modelling of building related impacts from micro to macro scale.

Table 28: Mapping logic for upscaling of building level results to macro-scale based on building stock activities

Building level: Life cycle stages		**Building stock level: Activities in year X**			
Building stock activities (top) and corresponding building archetypes (bottom)		Existing building operation	Building refurbishment and energy retrofit	Building deconstruction, end-of-life	New building construction
		Existing buildings archetypes (EXB)	Refurbishments archetypes (REF)	Existing buildings archetypes (EXB)	New buildings archetypes (NEW)
Production stage	A1-A3	No	(Nested in B5)	No	Yes
Transport to site	A4	No	(Nested in B5)	No	Yes
Construction and installation process	A5	No	(Nested in B5)	No	Yes
Use	B1	-	-	-	-
Cleaning, maintenance	B2	Yes: annual amount	No	No	Yes: annual amount
Repair	B3	-	-	-	-
Replacement	B4	Yes: annual amount*	No	No	Yes: annual amount
Planned refurbishment	B5	No	Yes	No	No
Operational energy use	B6	Yes: annual amount	Yes: annual amount	No	Yes: annual amount
Operational water use	B7	-	-	-	-
Deconstruction, demolition	C1	No	(Nested in B5)	Yes	No
Waste transport	C2	No	(Nested in B5)	Yes	No
Waste processing	C3	No	(Nested in B5)	Yes	No
Waste disposal	C4	No	(Nested in B5)	Yes	No
Beyond system boundary	D	-	-	-	-

While the modelling up to building level is well established, advancing on the tried and tested MMG+_KULeuven model, the step of upscaling to building stocks at different levels is prototypical thus far and will see further development. Aspects to elaborate are increasing flexibility in the activity mapping, an advance building stock turnover model which can include explicit assumptions on the probable service life of buildings.

7.2.4. SLiCE inventory database

Database schema

Figure 51 illustrates the comprehensive database schema of the SLiCE life cycle inventory database specifically designed to handle the diverse and interconnected data required for building-level life cycle assessments. The schema reveals the intricate structure and organization of various data tables within the SLiCE database, enabling effective management and analysis of building-related information. SLiCE currently uses a simple SQLite database which stores data in files located in the project directory.

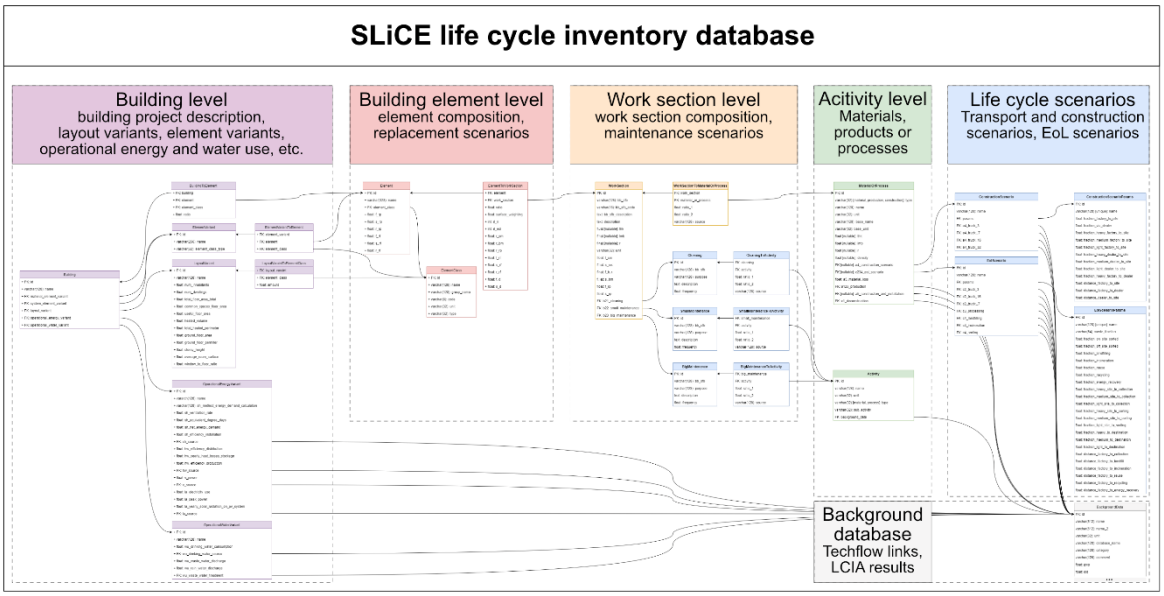

Figure 51: SLiCE life cycle inventory database schema, showing the different data tables present in the SLiCE database to manage information on building level (such as building project description, definitions for layout variants, element variants, operational energy and water use); building element level (with information on element compositions, replacement scenarios); work section level (definitions of work section composition, maintenance scenarios); activity level (material, products or process definitions); as well as life cycle scenario definitions (related to transport, construction process, or end-of-life (EoL) processing); and the background database (with links to tech flow datasets and pre-calculated LCIA results). To save space, the schema of the background database has been cut-off which omits the remaining environmental indicators.

At the building level, the database incorporates essential data tables that encompass crucial aspects such as building project descriptions, layout variants, element variants, and operational energy and water usage. These tables serve as repositories for detailed information about the specific characteristics and attributes of each building (archetype) in the model. Moving down to the building element level, the schema captures vital data on element compositions and replacement scenarios. This information is required for evaluating the environmental impacts associated with different building elements over their life cycles. Additionally, the work section level definitions provide valuable insights into the composition of work sections and maintenance scenarios, which further contribute to a comprehensive understanding of the building's life cycle. The activity level data tables capture intricate details regarding material, product, and process definitions, providing a granular view of the various components and activities involved in the building's life cycle. This level of detail enhances the accuracy and precision of the life cycle assessment results. Furthermore, the schema includes specific life cycle scenario definitions related to transport, construction processes, and end-of-life (EoL) processing. These definitions facilitate the modelling and analysis of different scenarios, enabling the evaluation of alternative strategies and interventions to improve the sustainability performance of buildings. Lastly, the background database is an integral part of the schema, establishing links to techflow datasets and pre-calculated life cycle impact assessment (LCIA) results. This integration enables efficient access to

relevant data sources and facilitates the calculation of LCIA indicators based on the specific life cycle scenarios defined in the database. The SLiCE life cycle inventory database schema presented in Figure 51 exemplifies the meticulous organization and management of data required for comprehensive, high-definition building LCA. By capturing various attributes, relationships, and data types, this schema provides a robust foundation for conducting accurate and insightful analyses of the environmental impacts associated with building materials, components, and processes as well as for further upscaling such information using the SLiCE building data model.

Django interface

The database is managed through a Django interface (Django Software Foundation, 2023; Holovaty and Kaplan-Moss, 2009), intended to provide basic web interface to the project's database and allow to perform CRUD (Create, Read, Update, Delete) operations on collected data. The web page is generated by the Django web framework using its 'admin' application.

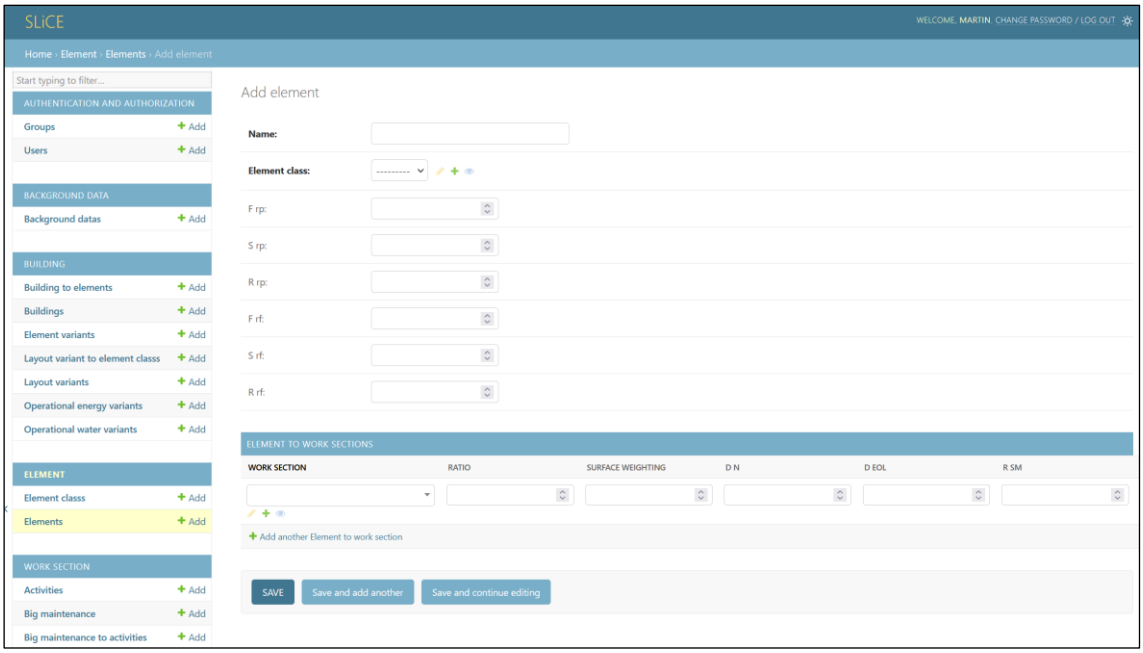

Figure 52: Screenshot from the Django admin interface of the SLiCE life cycle inventory database. The screenshot offers a glimpse into the different data tables contained in the database (as specified in the database schema), and the authentication and authorization functionality for managing groups and users. Django admin enables to perform CRUD (Create, Read, Update, Delete) operations on collected data. As an example of the Create functionality, the screenshot shows the interface for adding a new element through the specification of element name, element class (via selection of class options from a linked table), the frequencies for replacement of that element and the composition of the element based on the selection of one or more work sections (from linked data tables), respective ratios, and life cycle scenarios.

Figure 52 illustrates the SLiCE Django admin interface, showcasing various data tables that form an integral part of the database schema, as specified in the database schema diagram (Figure 51). Additionally, the screenshot illustrates the authentication and authorization functionality, enabling the management of user groups and individual user permissions, thereby ensuring secure access to the database. The Django admin interface is highly customizable and has been tailored to suit the specific requirements of the SLiCE project. The screenshot reveals a range of useful features, including custom list views, search bars, filtering panels, autocomplete lookup fields, and inline components. These features enhance the usability of the interface and facilitate efficient navigation and data retrieval. The interface supports the creation of new elements within the database, as depicted in the screenshot. Through the Create functionality, users can add additional items, such as new building element definitions, based on essential details such as the element name, element class (selected from a linked

table providing class options), and frequencies for element replacement. Furthermore, the composition of the element can be specified by selecting one or more work sections from linked data tables, along with respective ratios. The life cycle scenarios associated with the element can also be defined, allowing for a comprehensive representation of the element's life cycle. In practice, however, the addition of new items is more efficient when done in an automated way by loading respective data directly via the data loader (Figure 48). The Django admin interface offers powerful capabilities within the SLiCE life cycle inventory database management system. With its user-friendly design and customizable features, this interface empowers users to efficiently interact with the database, perform CRUD operations on collected data, and manage the various attributes and relationships captured within the system.

7.2.5. SLiCE impact calculations

High level data flow

Figure 52 illustrates the high-level data flow applied to all SLiCE calculation algorithms. This high-level data flow ensures a systematic and consistent approach to calculations across all algorithms within SLiCE. By leveraging the SLiCE database and employing Pandas dataframes, the calculation scripts efficiently process the data, enabling the generation of comprehensive output files for subsequent analysis and interpretation.

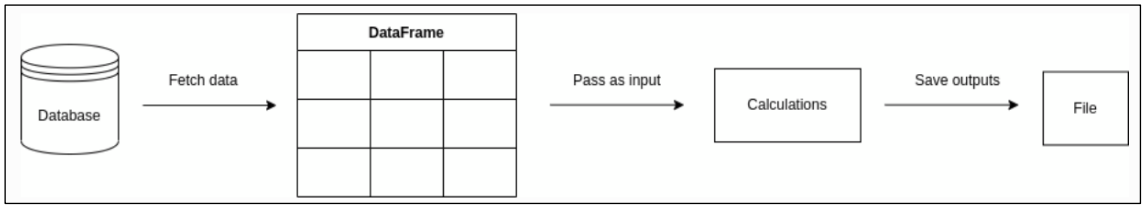

Figure 53: High level data flow applied to all SLiCE calculation algorithms. Data are fetched from the SLiCE life cycle inventory database using the format of Pandas data frames. These are passed as an input to the calculation scripts, which process the inputs from different, linked data tables present in the database and save outputs in one or more files.

Figure 52 illustrates the overall process of data flow in SLiCE, starting from the SLiCE life cycle inventory database. Data is fetched from the database in the form of Pandas dataframes, a popular data manipulation tool. These dataframes serve as input to the calculation scripts, which perform various computations using the interconnected data tables stored in the database. After processing the data, the calculation scripts generate output files in either '.csv' or 'parquet' format. These output files can be further utilized for postprocessing, analysis, and visualization purposes. The calculations in SLiCE are conducted in a bottom-up manner, sequentially computing life cycle inventory (LCI) and life cycle impact assessment (LCIA) results for work sections, elements, and buildings.

Life cycle inventory calculations

The basis for the spatiotemporal life cycle inventory model is a detailed, hierarchically structured bill of quantities for the building. This inventory is defined by linking the different spatial inventory levels via ratios that define the amount of lower level items within higher level items (i.e. X kg concrete (material level) per unit (e.g. 1 m²) of concrete wall (work section level)), including a separate unit conversion, where required. Additional information is input on physical and thermal properties of materials, work section, and elements, respectively, to enable a coherent mass-conversion as well as simulation of energy performance (e.g., u-value, transmission heat losses).

- Ratio 1 – (‘ratio_1’) – unit conversion between spatial inventory levels, e.g., convert techflow [m3] into material [kg], value is ‘1’ if unit already consistent.
- Ratio 2 – (‘ratio_2’) – amount of the item within the higher spatial level, e.g., amount of material [kg] within 1 unit of work section [m^2].

- Density – (‘density_kg_m3’) – density of a material (kg per m3), to calculate a consistent mass-based material quantity output at work section, element and building levels.

Following the original implementation of the element method in the MMG+_KULeuven tool (Allacker, 2010), computation of the spatial life cycle inventory follows a general logic expressed in equation (1). As illustrated, each item (I) at a particular spatial inventory level (i) is defined as the sum of all items at the respective lower inventory level (L), multiplied by the amount ratio (a) of that lower-level item within the main item, adjusted by a specific unit conversion ratio (u), if needed. If no scaling of the amount or conversion of units is intended, both ratios (a, u) can also be defined as ‘1’.

(1) $$I_i = \sum_{n=1}^{\infty} a_L * (L * u_L)$$ (Allacker, 2010)

Material stocks and flows

At any given point in time (t), indicated by parameter 'activity_year') the logic for assessing the material stock is expressed in equation (2). The material stock (S) at a certain time (t) is the sum of material inputs (I), during initial building production or input during replacement, minus the construction material loss (L), occurring during initial building production or replacement, and potential material outflows (O), from replacement or at end of life of the building, that occurred until time (t).

(2) $$S_t = I_t - L_t - O_t$$

Calculation of the flows is based on the sum of materials affected by different activities along the life cycle. Only those activities labelled as ‘materials’ (as opposed to ‘processes’) are considered and labelled in indicator ‘activity_in_out’ as illustrated in Table 29.

Table 29: Assignment of activity type (in/out) based on flows is based on the life cycle stage (main, nested) an activity occurs in, combined with the type of activity (material or process).. Only those activities labelled as ‘materials’ (as opposed to ‘processes’) are considered and assigned the ‘material in’, ‘material out’, or ‘material loss’ label, depending on the life cycle module they related to.

Stage (Main)	**Substage** (Nested 1)	**Sub-substage** (Nested 2)	**Activity Material/Process**	**Activity In/Out**
A1-3	-	-	**Material**	**Material in**
A4	-	-	Process	Transport to site
	-	-	Process	Process
A5	A1-3	-	**Material**	**Material loss**
	A4	-	Process	Transport to site
	C2	-	Process	Transport to EOL
	C3	-	Process	Process
	C4	-	Process	Process
B2	-	-	Process	Process
B4	A1-3	-	**Material**	**Material in**
	A4	-	Process	Transport to site
		-	Process	Process
	A5	A1-3	**Material**	**Material loss**
		A4	Process	Transport to site
		C2	Process	Transport to EOL
		C3	Process	Process
		C4	Process	Process
	C1	-	**Material**	**Material out**
	C2	-	Process	Transport to EOL
	C3	-	Process	Process
	C4	-	Process	Process
C1	-	-	**Material**	**Material out**
C2	-	-	Process	Transport to EOL
C3	-	-	Process	Process
C4	-	-	Process	Process

Life cycle impact assessment

The current version of SLiCE uses a data table of materials and processes as part of the SLiCE life cycle database which contains LCIA results from impact assessments using the specified Ecoinvent datasets, calculated in SimaPro. This data table (techflows) can be updated with results from other background datasets or the application of other impact assessment methods. However, this step currently requires changes to the underlying codebase in order to adapt the calculation scripts and enable the use of different inidicators. Future versions of SLiCE will seek to apply a more direct and dynamic link to enable the application of different impact assessment methods within the SLiCE python environment.

7.2.6. Working with SLiCE

Conducting an LCA with SLiCE follows the general logic of LCA as outlined in Table 30. Based on the initial definition of goal and scope of the study, the specification of the object of assessment and modelling of foreground LCI are conducted, e.g., via MMG+_KULeuven model spreadsheet inputs. foreground LCI is then processed through a dedicated parser script and loaded to the central Life Cycle Inventory Database (LCI-DB) through the data loader script for storing the inventory in preconfigured data table formats. Different calculator scripts can be called to then conduct the life cycle impact assessment (LCIA) at one or more spatial levels, with assessment results provided as comprehensive data table exports. Currently, internal input data (Int input) are at the level of materials and processes with links to the related Ecoinvent data and pre-assessed LCIA results (per kg, kWh, etc.) stored in the data tables as an input to the modelling of other spatial inventory levels. The results can be analysed and interpreted through different interpreter scripts to assess and communicate the model outcomes as well iteratively refine the previous steps, if needed.

Table 30: Exemplary steps of SLiCE building analysis by example of an environmental life cycle assessment.

Step	Description (examples)
Goal and scope	• Define the purpose of the study, such as: Comparative elements LCA; building level hotspot analysis; building stock scenario analysis. • Define level(s) of analysis from work section to building cluster level. • Define specific and/or representative buildings/elements and LCA background data use (e.g., Ecoinvent).
Life cycle inventory (LCI)	• Establish detailed baseline inventory (e.g., based on a building's bill-of-quantity) via the element method applying parametric modelling and iterations. • Expand modelling with life cycle information for the various life cycle stages within scope (e.g., based on representative life cycle scenarios).
Life Cycle Impact Assessment (LCIA)	• Calculate the life cycle impact assessment via linked LCA background data. • Utilise the ability to expand the static LCA towards a dynamic assessment of temporal/spatial items and impact characterization, if appropriate.
Results and interpretation	• Use analytics and validation scripts to review and revise and elaborate on detailed LCI (background), if appropriate. Generate insights using, e.g., environmental hotspot analysis across spatial and temporal dimensions to identify most relevant indicators / life cycle stages / processes. • Analyse the temporal distribution of impacts across the reference study period. • Use the visualization and reporting script to inform results reporting.

Additional documentation for the SLiCE building LCA model is developed in a private GitLab repository. The related GitLab page is built with Sphinx (Sphinx, 2023) and serves as a centralized resource for sharing data, code, and documentation related to the implementation of the SLiCE building LCA tool in Python.

7.3. Practical applications and future development

7.3.1. Overview of practical applications

A selection of practical application examples for SLiCE is illustrated in Figure 54 and described in the following. Details on data flow and interfaces with other models are illustrated in Figure 55.

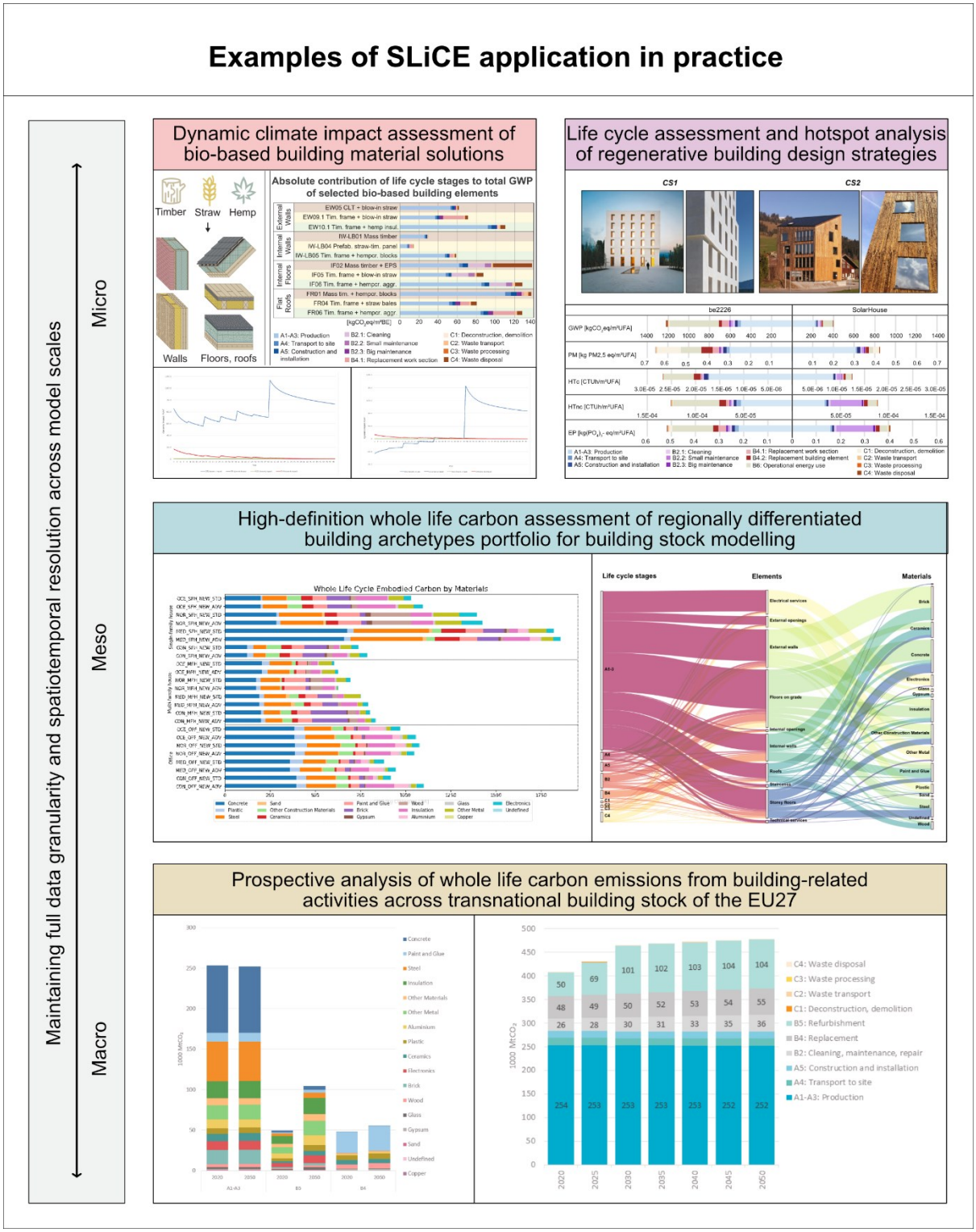

Figure 54: Examples of practical applications of the SLiCE model (figures partly showing mock results, including visualization examples from (Mouton et al., 2023a, 2023b; Vanoverberghe, 2022)).

Dynamic climate impact assessment of bio-based building material solutions

The bio-based building elements established in (Mouton et al., 2023a) were used to run an early version of the SLiCE building LCA model to generate high-definition early version of the SLiCE building LCA model was used to generate high-definition foreground LCI data for the explorative analysis of dynamic climate impacts in (Vanoverberghe, 2022), as presented in more detail in chapter 6. The temporally explicit SLiCE foreground inventories, together with background data from Ecoinvent 3.8, were utilised to dynamically assess climate impacts based on four relevant GHGs: CO_2, CO, CH_4, and N_2O. The dynamic climate impact was estimated based on the temporally explicit SLiCE foreground LCI in combination with background LCI data on the four main GHGs obtained from the related Ecoinvent datasets, and the subsequent multiplication of the amount of the GHG pulse at a given point in time (year) with the dynamic characterization factor values from (Levasseur et al., 2010a). Based on these inputs, the yet to be published study investigated the influence of: Static versus dynamic impact assessment; the time horizon applied in the dynamic approach (50/100/500 years), as well as; variations of the reference study period and service life of the building element and its components, respectively.

Life cycle assessment and hotspot analysis of bio-based design strategies

SLiCE was used to translate the building life cycle assessment of the case studies investigated by (Mouton et al., 2023b). While the original article presented results of a semi-automated hotspot analysis of process-contributions limited to contributions at the element level, the inventory data from (Mouton et al., 2023b) was used to generate the SLiCE sample data used for testing the hotspot analysis tool presented in chapter 6 (The SLiCE building data model for hotspot analysis). The interactive hotspot analysis tool in chapter 6 enables further flexibility in the selection of (environmental) indicators and related weighting sets, as well as supports adaptable analysis of life cycle- and process-contributions across different temporal and spatial scales of the inventory model, respectively.

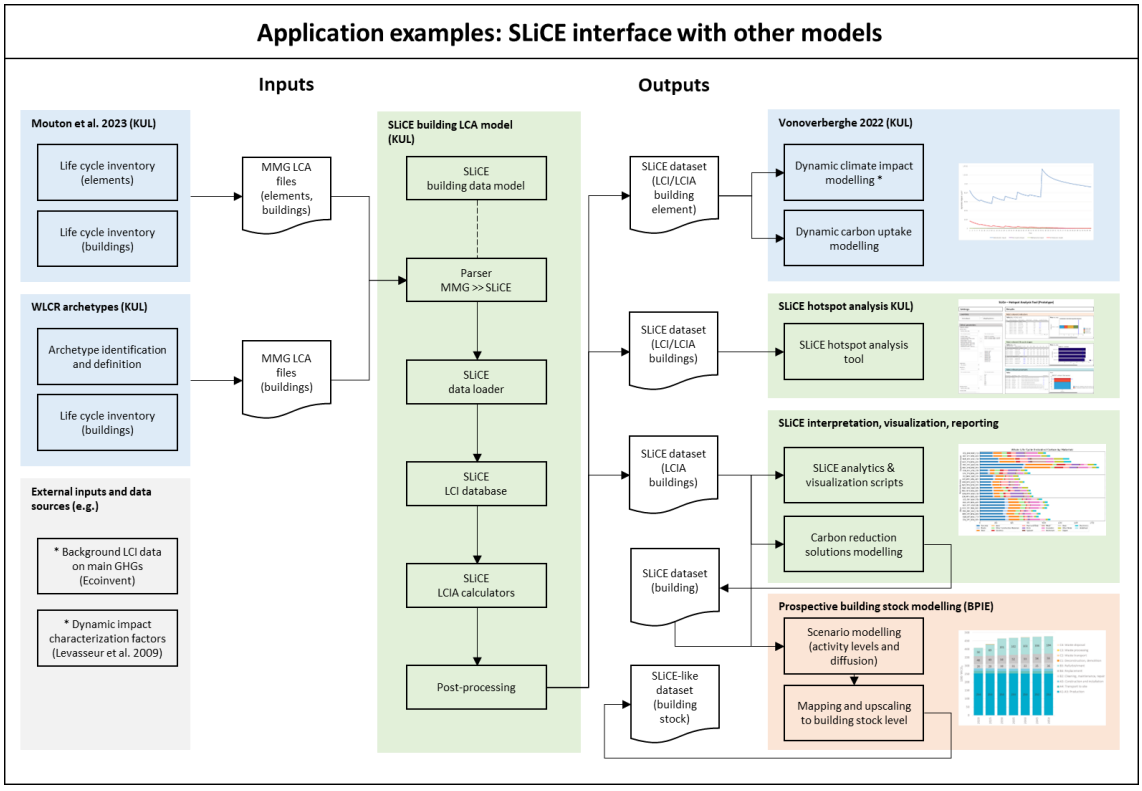

Figure 55: Elaboration on SLiCE interface with other models in application examples.

High-definition whole life carbon modelling of building archetypes

Within policy-informing research for the European Commission's DG ENV on 'Supporting a Roadmap for the Reduction of Whole Life Carbon in Buildings'(Le Den et al., 2023), a portfolio of 60 archetypes was defined and modelled to represent typical building types, construction periods, energy performance levels and construction material use for buildings across four European regions. Application of a SLiCE building LCA model prototype enabled detailed analyses of the whole life carbon hotspots by providing specific insights into the timing of emissions per life cycle stages and per year as well as detailed information on the contribution of elements, work sections and materials at all levels of the building archetype analysis.

Prospective analysis of whole life carbon emissions at transnational scale

The primary context for the development and application of the SLiCE building LCA model, thus far, is the study for supporting the development of a roadmap for decarbonization of buildings in the EU (Le Den et al., 2023). The following section presents insights into the application of SLiCE within this study, mainly for the high-resolution modelling and adaptation of archetype building for representing the baseline building stock as well as the quantified carbon reduction potentials from different strategies. The following section builds on excerpts from the final public project deliverable with emphasis on and including elaborations regarding the use of SLiCE within the project.

7.3.2. SLiCE-based building stock modelling

The study for supporting the development of a roadmap for decarbonization of buildings in the EU (Le Den et al., 2023) aimed to provide a comprehensive analysis of the baseline and projected WLC emissions for EU buildings under different scenarios. The study evaluates a range of solutions to reduce operational and embodied carbon footprints, encompassing measures to address building demand ('avoid'), improvements in material production and efficiency ('improve'), and the promotion of alternative building materials ('shift').

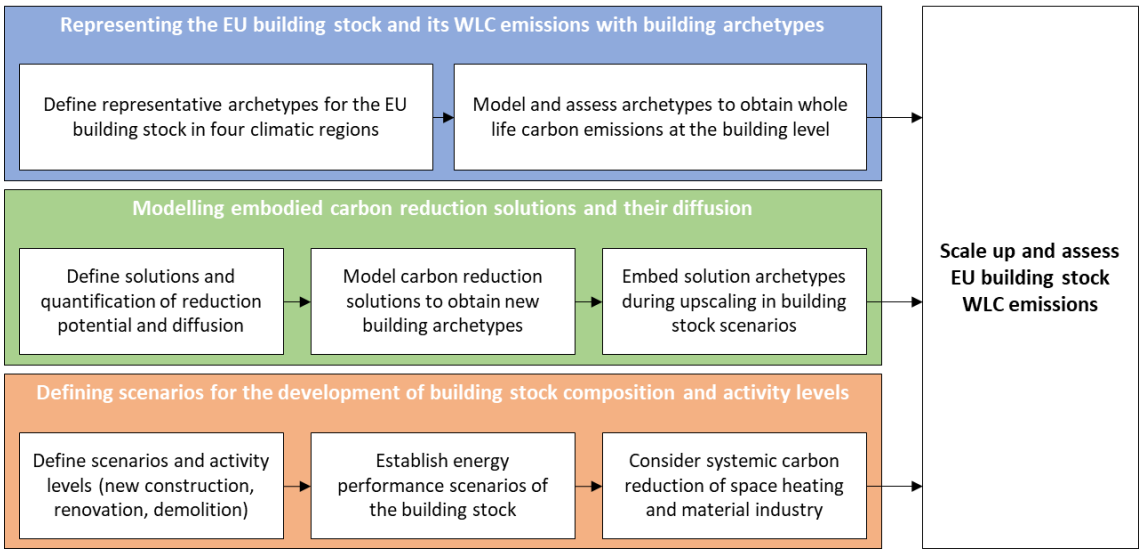

Figure 56: Conceptual overview of the three main steps in the modelling conducted in the study for supporting the development of a roadmap for the decarbonization of buildings in the EU (Le Den et al., 2023). Starting from: 1) the representation of the EU building stock and its WLC emissions through the definition, modelling and assessment of representative building archetypes; to 2) the modelling of embodied carbon reduction solutions and their diffusion, based on a modification of the baseline archetypes; and 3) the definition of scenarios for the development of building stock composition and building stock activity levels, modelled by upscaling the different archetypes to assess the WLC emissions of the EU stock.

The modelling follows an integrated approach that combines three key steps, as illustrated in Figure 56: Firstly, representative building archetypes are utilized to assess the lifecycle impacts of both new and existing buildings across the EU. Secondly, embodied carbon reduction solutions quantify the potential and implementation timeline for measures targeting new construction avoidance, enhanced building design, and the adoption of low-carbon materials. Lastly, building stock modelling integrates the previous components with macro-economic decarbonization trends to quantify emissions and outline pathway scenarios from 2020 to 2050.

SLiCE-based archetype modelling

As a foundation in the study supporting the development of a roadmap for reducing whole life carbon of buildings in the EU (Le Den et al., 2023), high-definition SLiCE building data were generated by the author and colleagues and used to scale up results to building stock level via custom scripts developed with project partners at the Building Performance Institute Europe (BPIE). Building stock level results were first modelling for the baseline year 2020 for the four European regions, showing WLC emissions of the different building stock activities: building use, new construction, refurbishment, and demolition/end-of-life. The study team scaled up building-level emissions to the entire EU building stock by employing representative building archetypes assessed using the SLiCE building LCA tool and considering stock-level activities such as new construction, renovation, and demolition. Building archetypes are virtual representations of different types of buildings within a building stock that share similar characteristics. Figure 57 provides an overview of the aspects considered in the definition of the representative archetypes. The definition of archetypes is based on statistical analysis of the building stock, considering the diversity in age, size, construction practices, installed equipment, appliances, behavioural patterns, and emission profiles across Europe.

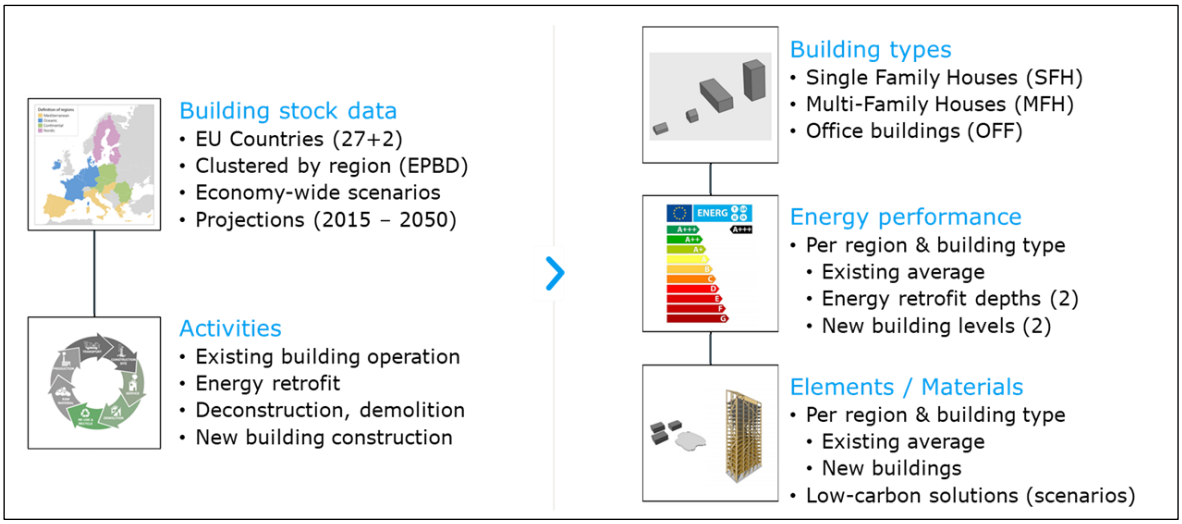

Figure 57: Overview of aspects considered for definition of representative archetypes in (Le Den et al., 2023). Based on statistical data of the EU building stock (EU countries 27+2), clustered into four climatic regions (in line with the EPBD regions), archetypes have been defined for representing different building stock activities (such as existing building operation, retrofit of existing buildings, deconstruction and demolition of existing buildings, as well as new building construction). Dedicated archetypes have been defined, modelled, and assessed for three building types (single family houses, multi-family houses and office buildings), considering different energy performance levels as well as different building elements and material composition, representative to the respective building archetype and region.

The study utilizes three representative archetypes: single-family homes (SFH), multi-family houses (MFH), and offices (OFF). These archetypes are tailored to four distinct climatic regions defined in the recast of the EU's Energy Performance of Buildings Directive (EPBD): Oceanic, Mediterranean, Continental, and Nordic. A total of 60 archetypes were developed to represent existing buildings,

various retrofit options, and different new building variants specific to each of the four regions. The selection of representative archetypes was based on statistical analysis of building stock composition and characterization, using data from EU projects Ambience (AmBIENCe, 2023) and Hotmaps (Hotmaps, 2023). The archetypes were defined in detail using data from TABULA/EPISCOPE (TABULA, 2023; TABULA and EPISCOPE, 2023), which provides national building typologies representing the residential building stock. The building archetype inventories were modelled using the SLiCE/MMG building LCA tools developed by KU Leuven, as described in chapters 6 and 7.

SLiCE-based building stock scenarios

Carbon reduction solutions (CRS)

Table 31: Overview of carbon reduction solutions (CRS) considered in the study (Le Den et al., 2023). CRS are defined by their unique code and name, and implemented considering the specific CRS application scope (i.e., type of building use, stock activity, building element class, material class, and life cycle stage a solution applies to), as well as the CRS implementation factors (i.e., the carbon reduction potential (CRS reduction factor) at the defined CRS level, and the CRS diffusion potential (i.e., potential market share)).

CRS description		CRS application scope						CRS implementation factors	
CRS code	CRS name	Building use	Stock activity	Building element class	Material class	Life cycle stage	CRS level	CRS reduction factor	CRS diffusion factor
3a	Re-use bricks	*	['NEW', 'REF']	*	['Brick']	['A1-3']	Material	0.99	0.29
3b	Re-use steel	*	['NEW', 'REF']	*	['Steel']	['A1-3']	Material	0.40	0.29
6a	Light construction: Concrete	*	['NEW', 'REF']	['Floors on grade', 'Foundations', 'External walls', 'Internal walls', 'Storey floors', 'Roofs']	['Concrete', 'Brick']	*	Building	0.20	0.85
6b	Light construction: Steel	*	['NEW', 'REF']	['Floors on grade', 'Foundations', 'External walls', 'Internal walls', 'Storey floors', 'Roofs']	['Steel']	*	Building	0.15	0.13
7a	Industry by-products instead of clinker in cement	*	['NEW', 'REF']	*	['Concrete']	*	Material	0.45	0.15
7b	Alternative cementitious materials instead of cement in concrete	*	['NEW', 'REF']	*	['Concrete']	*	Material	0.41	0.03
7c	Use recycled concrete and other by-products for new concrete	*	['NEW', 'REF']	*	['Concrete']	*	Material	0.08	0.09
7d	Reduce concrete demand by use of void formers in concrete slabs	*	['NEW', 'REF']	['Floors on grade', 'Storey floors', 'Roofs']	['Concrete']	*	Work section	0.34	0.03
7e	Use carbon cured concrete	*	['NEW', 'REF']	*	['Concrete']	['A1-3']	Work section	0.04	0.00
11a	Use recycled steel in steel production	*	['NEW', 'REF']	['Floors on grade', 'Foundations', 'External walls', 'Internal walls', 'Storey floors', 'Staircases', 'Roofs']	['Steel']	['A1-3']	Material	0.85	0.35
11b	Use recycled glass	*	['NEW', 'REF']	['External openings']	['Glass']	['A1-3']	Material	0.30	0.35
12a	Use renewable energy in cement production	*	['NEW', 'REF']	*	['Concrete']	['A1-3']	Material	0.30	0.50
12b	Use renewable energy in steel production and other metals	*	['NEW', 'REF']	*	['Steel']	['A1-3']	Material	0.90	0.70
12c	Use renewable energy in glass production	*	['NEW', 'REF']	['External openings']	['Glass']	['A1-3']	Material	0.70	0.50
13a	Implement carbon capture in cement production	*	['NEW', 'REF']	*	['Concrete']	['A1-3']	Material	0.90	0.64
13b	Implement carbon capture in steel production	*	['NEW', 'REF']	['Floors on grade', 'Foundations', 'External walls', 'Internal walls', 'Storey floors', 'Staircases', 'Roofs']	['Steel']	['A1-3']	Material	0.70	0.64
13c	Implement carbon capture in glass production	*	['NEW', 'REF']	['External openings']	['Glass']	['A1-3']	Material	0.85	0.09
9a	Full timber construction	['SFH']	['NEW']	['External walls', 'Internal walls', 'Storey floors', 'Roofs']	['Concrete', 'Brick', 'Steel']	*	Building	0.20	0.03
9b	Hybrid (concrete + timber) structures in new construction	['MFH', 'OFF']	['NEW']	['External walls', 'Internal walls', 'Storey floors', 'Roofs']	['Concrete', 'Brick', 'Steel']	*	Building	0.35	0.10
10a	Use other bio-based materials (insulation)	*	['NEW']	*	['Insulation']	*	Work section	0.25	0.75
10b	Use other bio-based materials (full ext. walls)	['SFH', 'MFH']	['NEW']	['External walls']	*	*	Work section	0.75	0.50

* = applies to all items, no filtering

Within the study, the author and colleagues defined different embodied carbon reduction solutions as practical measures implemented by market actors with direct GHG emission reduction impacts achieved by reduced material demand, carbon intensity or waste generation. The scope of embodied carbon reduction solutions is focused on solutions on a building project level. These solutions relate to sufficiency in building demand (avoid), material efficiency through improved design or improved means of production (improve), and shifting to the use of alternative, low-carbon material solutions (shift). Table 31 offers an overview of the full list of solutions modelled. Identification, categorisation, and quantification of the GHG reduction impacts are supported by a comprehensive literature review that includes academic publications, reports of international organisations, government publications, as well as industry roadmaps. This evidence was compared across sources and validated through

interviews with experts. Still, in some cases, limited data availability meant that a quantification of potential future diffusion had to be assumed relying on comparable sectors or technologies.

Upscaling and scenario modelling

SLiCE building archetype data were used for prospective analysis of business-as-usual projections as well as investigation of different decarbonization scenarios. The prospective scenario analysis involved the application of various carbon reduction strategies (CRS) and the modelling of their effects on both building (archetype) level and building stock level. CRS impacts (i.e., embodied carbon reductions) on construction product, component (work section or element) and building level were incorporated based on the primary SLiCE data through custom scripts for identifying and adapting the data records to model effects of a given CRS (e.g., the effects of using of low carbon concrete in walls and floors of new residential buildings). To this end, detailed spatiotemporal inventory and assessment data from the SLiCE model of the initial baseline archetypes were used to apply the strategies and model their relative reduction potential at different spatial levels and for different life cycle stages - see relevant spatial and temporal attributes in the SLiCE data example illustrated in Table 24. Implementation of the CRS considers the CRS definitions, application scope and implementation factors presented in Table 31.

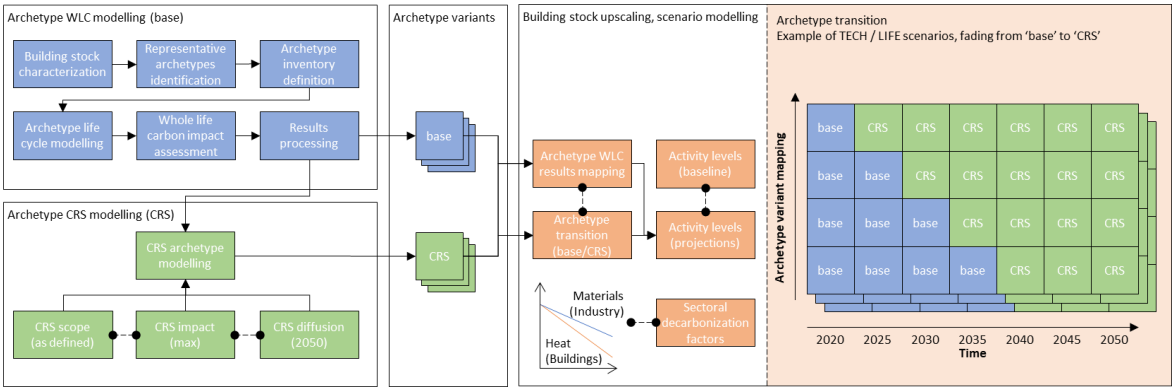

Figure 58: Modelling steps and data flow of the SLiCE-based building stock modelling scenario analysis in (Le Den et al., 2023). Representative baseline archetypes are derived from building stock characterization, identification of representative building groups (archetypes), definition of archetype inventory and related life cycle information, to enable the life cycle impact assessment (focusing on whole life carbon (global warming potential, GWP)). Results are processed and used to represent the baseline archetypes ('base') in the upscaling and scenario modelling, as well as the basis for modelling the carbon reduction strategies (CRS), considering the CRS scope (e.g., building types, building elements, materials affected by a strategy), the strategy impact (i.e., the maximum reduction potential of the strategy within the given scope), as well as the strategy diffusion (i.e., potential for uptake of the strategy at the EU scale as ratio of market share).

As illustrated in Figure 58, both SLiCE data on both base and CRS archetype variants are used for upscaling, based on a mapping of building-level data with building stock-level activities, as previously presented in Table 28. The scenario analysis considers different activity level projections (e.g., new construction rates), different compositions of the building stock (change in the fraction of base vs. CRS archetypes within the (new) stock), as well as general sectoral decarbonization factors for energy and industry. The main decarbonization scenario in the study (TECH-Build and LIFE-Build), both consider a gradual shift from base archetypes to CRS archetypes by 2040, i.e., an uptake of all carbon reduction strategies modelled in the study by that year. In addition, the LIFE-Build scenario implements different 'avoid' strategies, such as sufficiency principles and their potential to reduce demand for (new) construction activity. On building stock level, CRS relating to changes in building stock activities (e.g., changes to refurbishment rates, new construction rates, etc.) were incorporated during upscaling and scenario modelling by BPIE experts. The building stock composition and development under different scenarios was modelled based on data from the economy-wide EUcalc model (EUcalc, 2023). Adaptations were made to building stock activity levels to align the respective scenarios, such as

changes to the rates of new construction, renovation, and demolition rates, as well as estimated future diffusion of standard/advanced energy performance levels and energy use for building operation.

SLiCE building archetype results

A primary outcome of the SLiCE-based building stock modelling are the high-definition results on the whole life carbon impact of different representative building archetypes, which enable the analysis of total embodied climate impact, as well as the detailed investigation of temporal aspects, such as a distinction of embodied carbon occurring in different life cycle stages, or spatial aspects, such as contribution of different building elements or construction materials. These can be visualized per-case, as presented in the following figures by example of the 'new construction' archetypes, as well as analysed using statistical methods to understand the distribution of values, common trends and ranges.

Temporal analysis: Contribution of life cycle stages

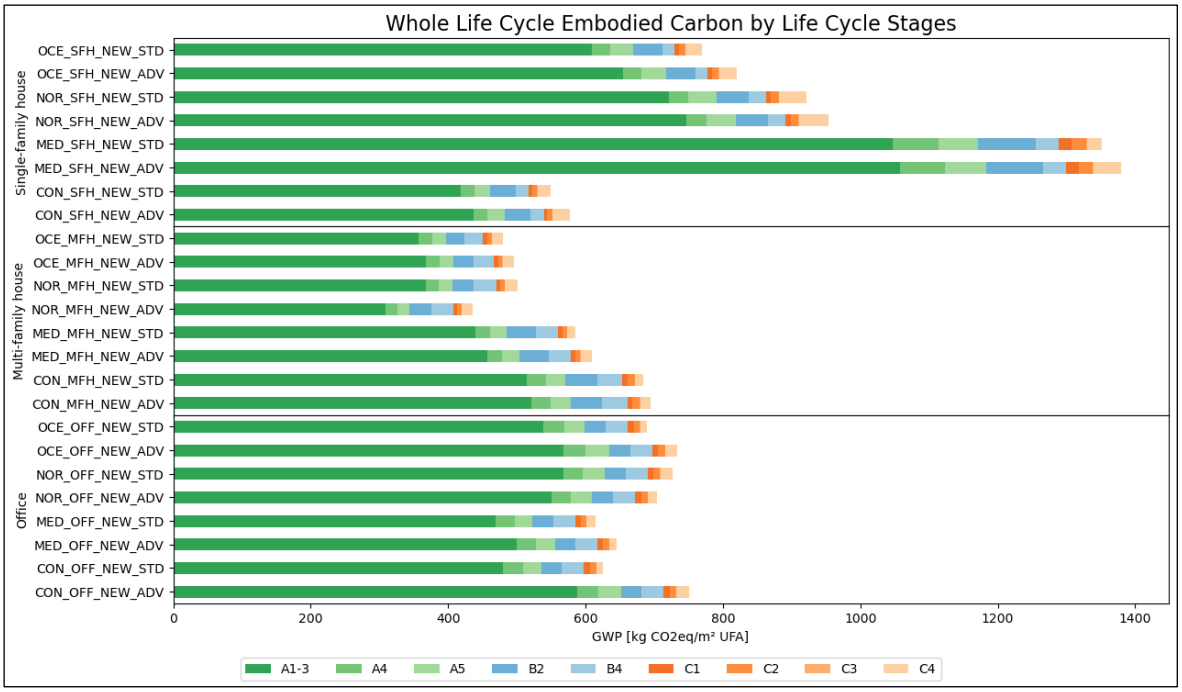

Figure 59: Embodied whole life carbon of new construction building archetypes by life cycle stage, showing results for global warming potential, GWP (Le Den et al., 2023).

Figure 59 presents the analysis of embodied WLC results of the baseline building archetypes, showing contributions from different lifecycle stages. It shows that upfront embodied carbon emissions – i.e., product stage (A1-3), transport to building site (A4) and the construction and installation process (A5) – account for more than 8/10 of embodied WLC, highlighting the immediate climate impact of new building activity. On average, upfront embodied carbon emissions account for 84% of embodied WLC (79% to 87%). The product stage (A1-3) is the most important individual life cycle stage as it accounts for an average of 76% - more than 3/4 - of whole life embodied carbon emissions (71% to 80% for individual new buildings archetypes). An average 4% of embodied WLC is contributed by Transport to site (A4) (3% to 5%), and the construction-installation process (A5) (4% to 5%), respectively. Building use-related embodied carbon occurring from maintenance (B2) and replacement (B4) accounts for 10% (7% to 14%) of embodied WLC, on average. The individual contribution to embodied WLC from maintenance (B2) is 6% (4% to 7%) and 4% (2% to 7%) from replacement (B4), respectively. Only about 5% (4% to 7%) of embodied WLC occur during end-of-life (C1, C2, C3, C4). Within this stage, an average of 3% of embodied WLC emissions occur during disposal (C4) (1% to 5%), while 2% or

less of embodied WLC are related to each of deconstruction and demolition (C1) (1%), transportation to end-of-life (C2) (1% to 2%), or waste processing (C3) (<1%), respectively.

Spatial analysis: Contribution of building elements

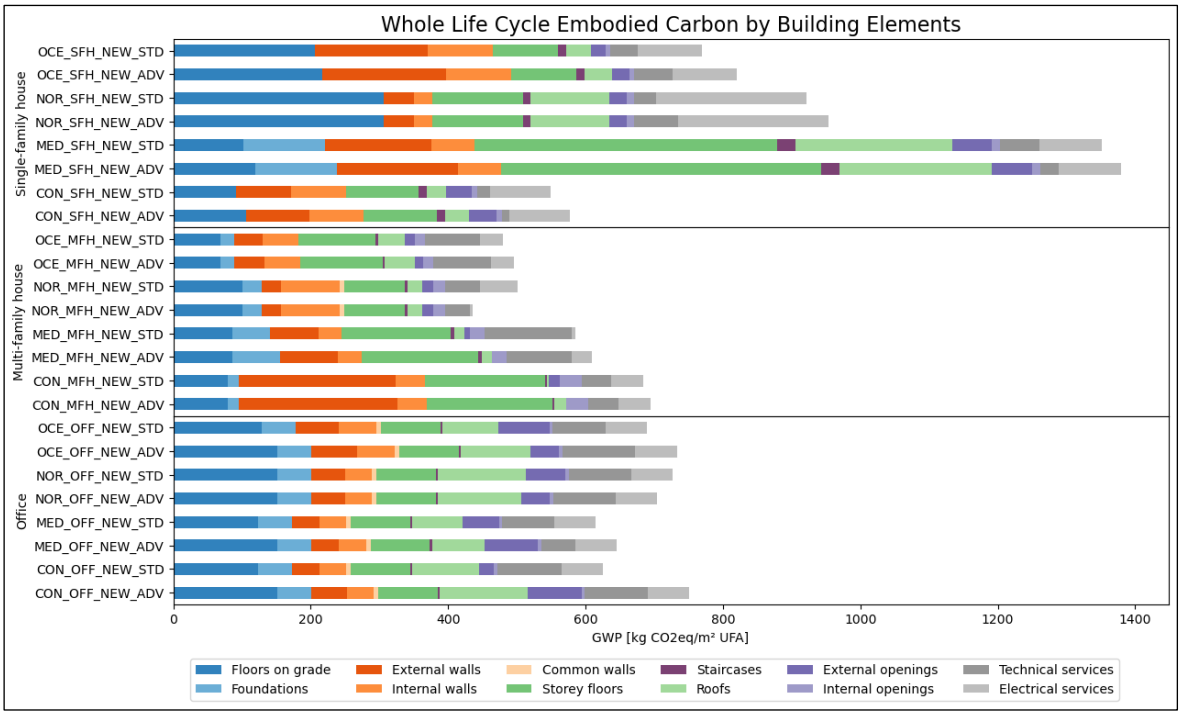

Figure 60: Embodied whole life carbon of new construction building archetypes by building elements, showing results for global warming potential, GWP (Le Den et al., 2023).

Spatial analysis: Contribution of construction materials

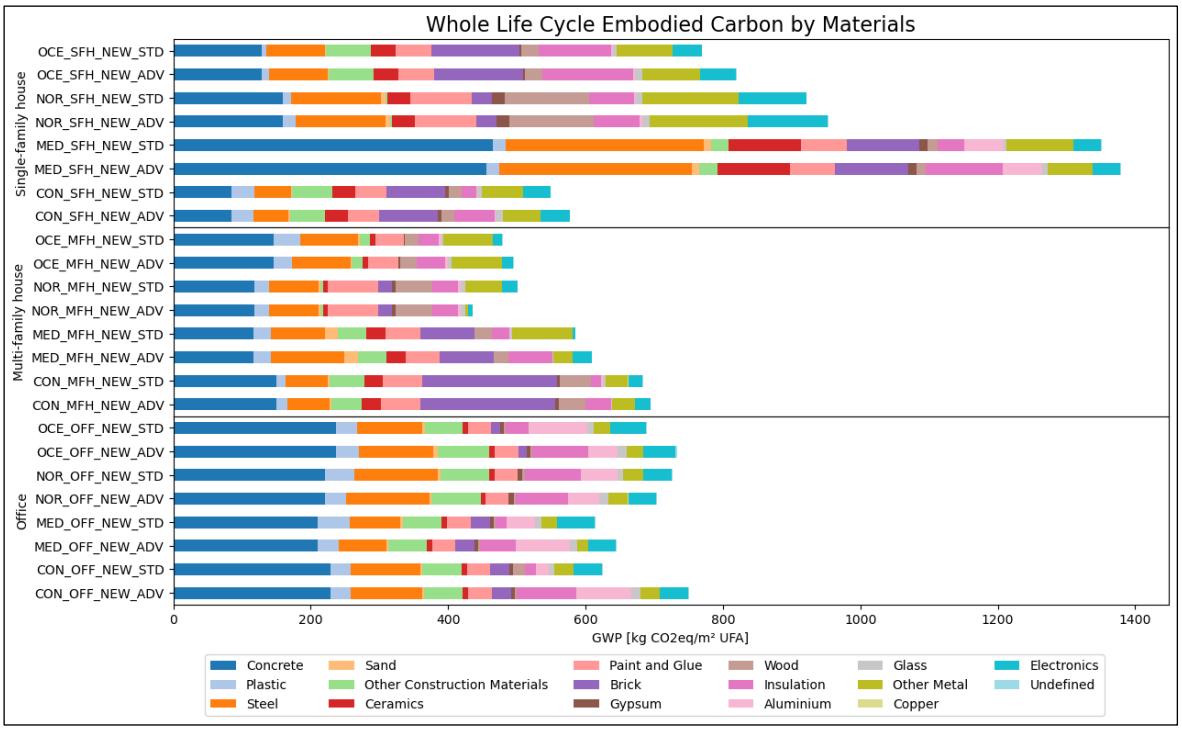

Figure 61: Embodied whole life carbon of new construction building archetypes by construction materials, showing results for global warming potential, GWP (Le Den et al., 2023).

Figure 60 presents the analysis of embodied WLC results of the baseline building archetypes, focusing on contributions from different building elements. The most important building element sections, on average, are floors on grade (19%) and foundations (5%), storey floors (19%) and roofs (10%), and external walls (12%) and external openings (5%), which together account for more than 2/3 of embodied WLC, on average. Another 10% are, on average, related to technical services, and electrical services, respectively. This is followed by internal elements such as internal walls (8%), internal openings (doors) (2%), or staircases (1%). However, the contribution of different building elements varies strongly across different building types and regions, as both building geometry as well as regional construction culture and materials influence the distribution of embodied carbon in buildings regarding both their spatial and temporal distribution. To enable a more generalized presentation of the results, the building element classes presented in the figure are assigned during SLiCE post-processing, based on a mapping of the SLiCE-internal element classification (which follows the BB-SfB system).

Figure 61 presents the embodied WLC results of the baseline building archetypes, focusing on contributions from different construction materials. It shows that most embodied carbon stems from the structural materials concrete, steel, and bricks. The individual contribution of these and other materials varies across the archetypes, as even more than the previous analysis of building element contribution, it is affected by aspects specific to the local context and site, such as local construction culture and material requirements.

The illustrated material categories are assigned during post-processing based on material groups utilized by the JRC report on background data collection on material construction and demolition waste (Joint Research Centre (European Commission) et al., 2022), and their mapping onto the more detailed but less harmonized material definitions used by SLiCE internally. SLiCE enables the application of custom mappings to group the information according to different classification systems for building elements or construction materials, as proposed by the author and colleagues in (Soust-Verdaguer et al., 2023).

A combination of the above aspects can furthermore enable investigation of spatiotemporal hotspots, such as embodied carbon emissions from different life cycle stages and for different building elements.

SLiCE-based building stock results

In the following, selected outputs from the upscaling to EU building stock and analysis of the business-as-usual (BAU) scenario are presented to illustrate the potentials of SLiCE-based building stock modelling. The upscaling involves a mapping of the building level definitions of life cycle inventory and subsequent assessment results with relevant building stock level activities, as previously presented in Table 28. The BAU scenario utilizes only baseline archetypes, no carbon reduction solutions are applied, other than the general sectoral decarbonization factors of energy and (material) industry sector.

Projected WLC emissions of building stock activities

Figure 62 presents the projected development of whole life carbon (WLC) emissions under a business-as-usual (BAU) scenario. In this scenario, WLC emissions are projected to be reduce by 32% in 2050 (compared to the baseline of 2020) driven by operational emission reductions. The reduction of about 440 $MtCO_2e$ is relevant as it is being projected against a 40% increase of the building stock floor area. The 44% savings in use phase operational carbon (470 $MtCO_2e$) are due to renovations, but also space heating decarbonisation, mainly fuel switch in space heating. In parallel, embodied emissions are expected to increase slightly over time due to the embodied carbon cost of increased renovation rates and despite industrial decarbonisation. While gains in operational efficiency and carbon savings are higher than the surge of embodied carbon so that whole life carbon emissions are expected to decrease steadily over the coming decades, the current rate of progress will not achieve the net-zero target.

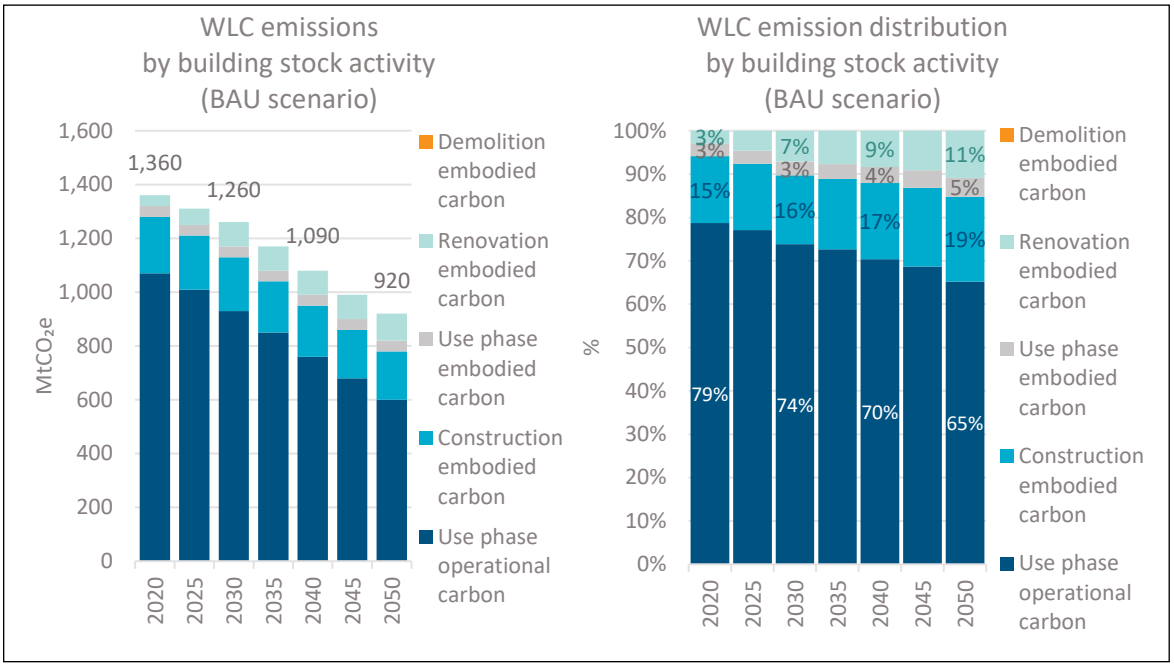

Figure 62: Whole life carbon emissions (left) and emission distribution (right) by building stock activity under the BAU scenario. Results based on upscaled of the SLiCE building archetype results, considering the BAU building stock activity scenario (Le Den et al., 2023).

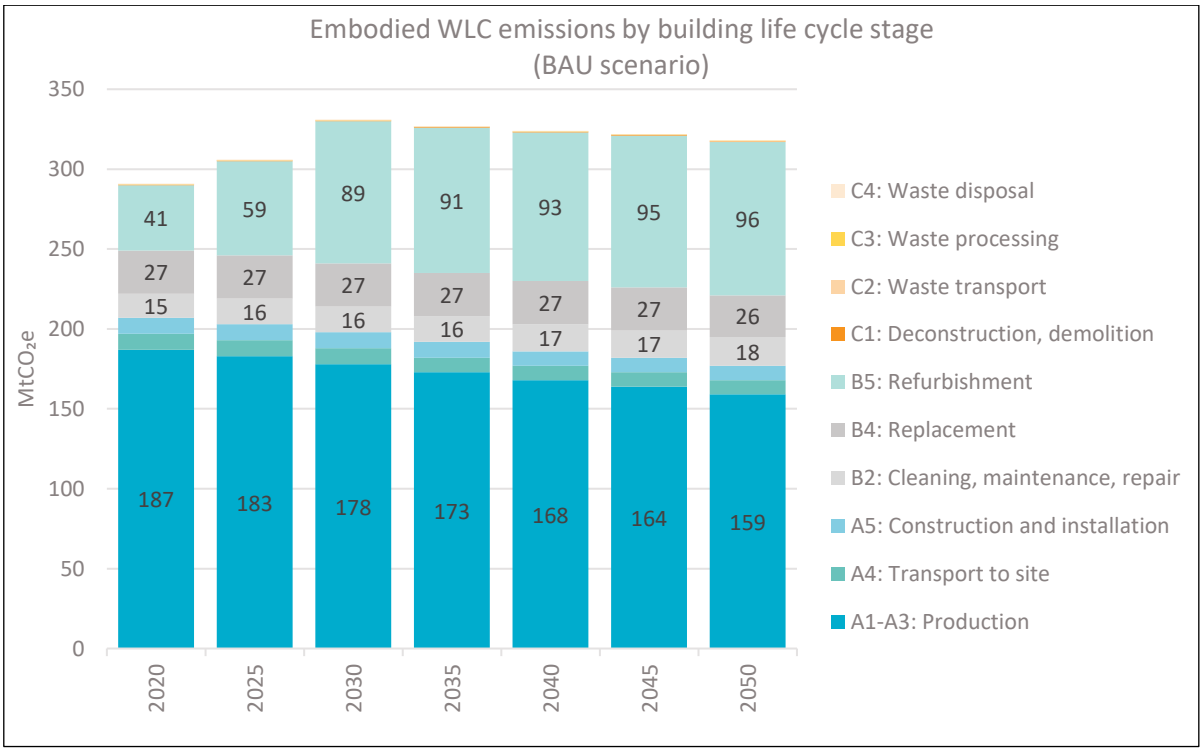

Figure 63: Building stock embodied whole life carbon emissions by building life cycle stages in the BAU scenario (Le Den et al., 2023).

Temporal analysis: Contribution of life cycle stages

Just like the building archetype level analysis, we can investigate the embodied whole life carbon at the building stock level. Embodied WLC emissions over the next 30 years, as illustrated in Figure 63, the BAU scenario shows that upfront emissions (A1-5) related to new constructions are decreasing due to industrial decarbonization of key material supply chains. The use phase embodied carbon (B2

maintenance, B4 replacement) increases marginally and concomitantly with the overall increase of the building stock floor area. On the flip side, renovation-related embodied emissions (B5) double from about 40 to 89 $MtCO_2e$ in the short period between 2020 and 2030, which is in line with the assumptions that the renovation rate will increase towards 2030. From then on, the renovation rate remains at 2% but relative to a growing building stock which means that renovation embodied carbon emissions will continue growing slowly but steadily towards 2050. Emissions related to demolition are nearly insignificant.

Spatial analysis: Contribution of construction materials

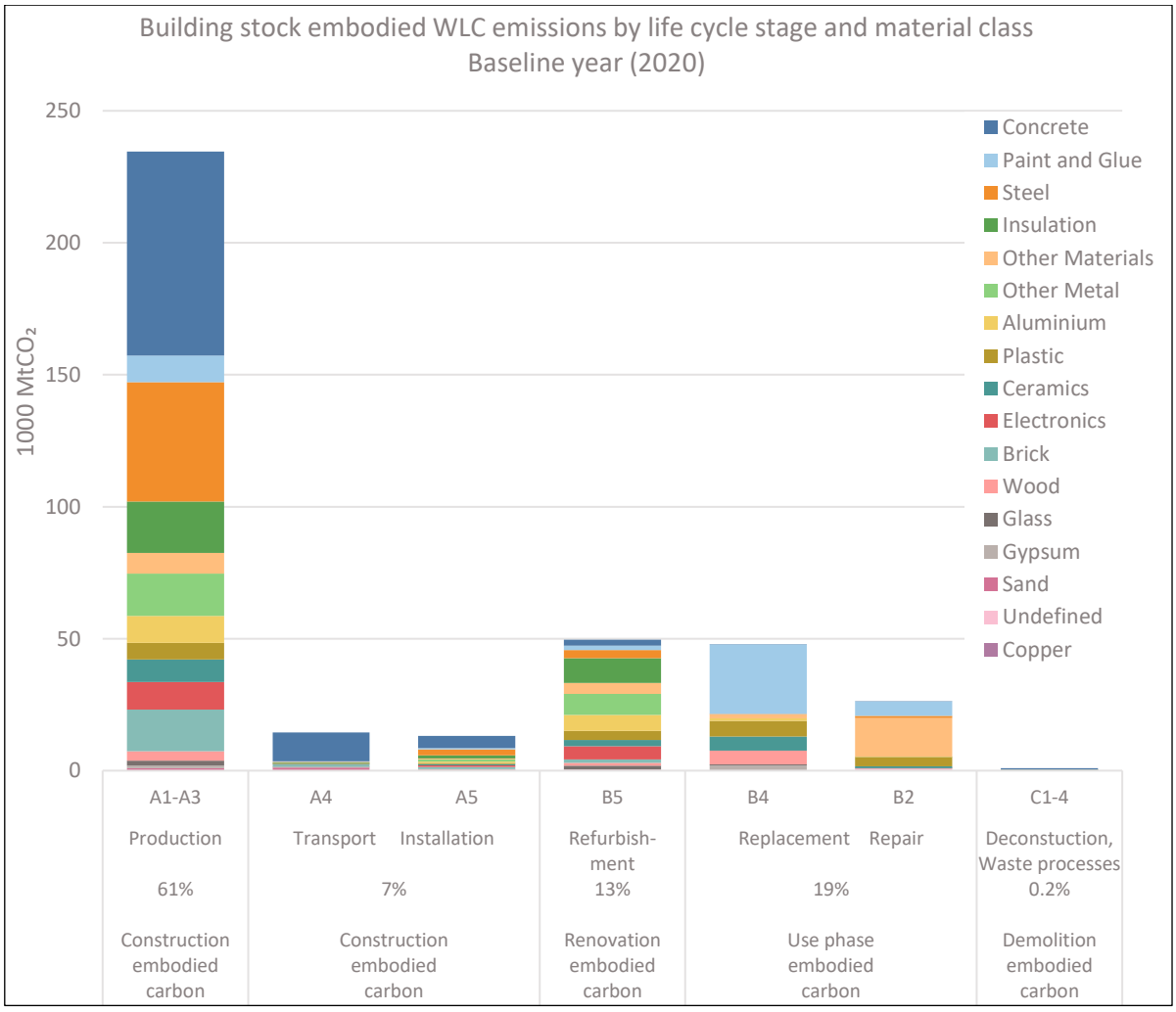

Figure 64: Building stock embodied WLC emissions ($MtCO_2e$) in the baseline year 2020 by material class and building life cycle stages (Le Den et al., 2023).

Figure 64 present the analysis of embodied WLC emission by differentiating different life cycle stages and construction materials. Materials used in the construction and renovation of buildings are dominating the embodied emissions at stock level. However, materials also represent a massive emission reduction potential from material efficiency strategies or the use of low-carbon and recycled materials. Transitioning to a future of low-carbon built environment requires a better understanding of the material build-up of the stock, carbon hotspots and of the strategies that take a whole building life cycle and systems-thinking approach. The embodied WLC emissions per material class, shown in the following figures have been developed through the upscaling of individual buildings life cycle emissions to the stock level. These represent the embodied carbon impacts arising from the construction, renovation (refurbishment), demolition and use of buildings. According to the analysis, construction

(A1-3, A4-5) is the most significant source of embodied emissions within the building life cycle with manufacturing of concrete, steel and insulation being responsible for over half of these emissions. In the baseline year of 2020, most embodied carbon, representing 61%, (235 $MtCO_2e$) of the building stock's total embodied emissions, has been released during the production of materials while only adding 1.4% new construction floor area to the building stock. Another 7% were emitted for the transport and installation of materials linked to the construction of new buildings. Renovation activities in 2020 affected about 1% of the floor area and were responsible for about 13% or 50 $MtCO_2e$ of embodied carbon. Given that repair (B2) and replacement (B4) activities are ongoing and are spread across almost the entire floor area (98%) of the building stock, they make up a remarkably large volume of emissions (19%, 28 $MtCO_2e$) which is more than the renovation related embodied carbon (13%). Among the materials relevant for replacement and maintenance (B4), paint and glue are surprising carbon hotspots. Demolition (life cycle stages C1-C4) affect only 0.1% of the floor area and thereby its associated embodied carbon emission is only marginal (0.2% of the total embodied emissions).

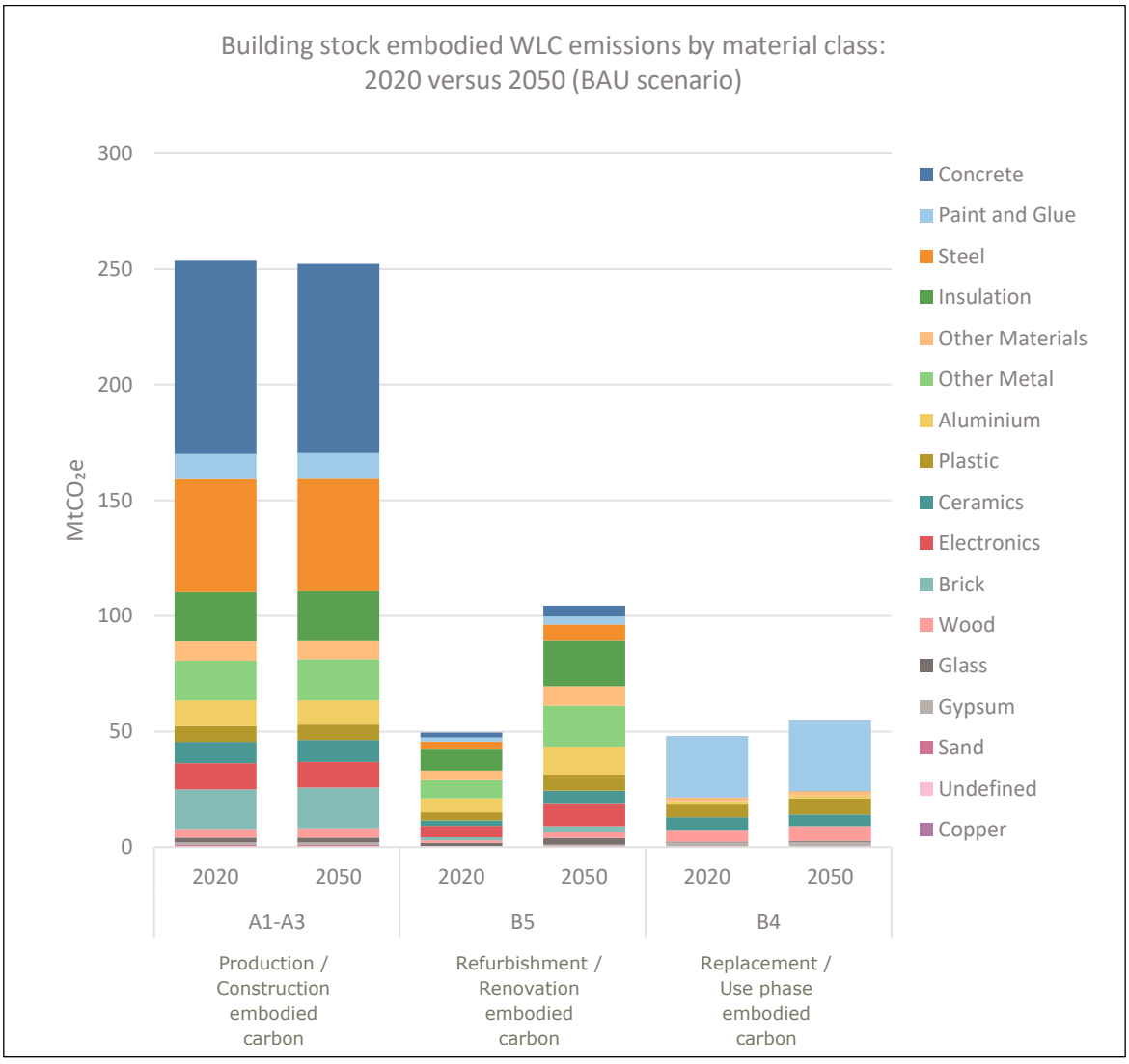

Figure 65: Building stock embodied emissions ($MtCO_2e$) in 2020 by material and building life cycle stages, decreasing by total amount of embodied emissions (Le Den et al., 2023).

Figure 64 illustrates the projected evolution of the largest contributions of material embodied emissions between 2020 and 2050 side-by-side. This business-as-usual scenario does not assume any carbon reduction measures related to the design of the building or the substitution of materials beyond the

general decarbonisation of the energy system and the energy delivered to industry processes that produce/manufacture construction and renovation relevant products. Embodied carbon reduction solutions are modelled separately in the TECH-Build and LIFE-Build decarbonisation scenarios. Under business-as-usual, the renovation embodied emissions (B5 Refurbishment) will more than double (111% increase) and reach 104 $MtCO_2e$ by 2050 due to the projected increase of renovation activities. The annual construction activity remains constant which implies that construction related material embodied emissions (A1-A3 production of construction products) will decrease slightly from 254 $MtCO_2e$ to 252 $MtCO_2e$ which is due to the decarbonisation of the industry for relevant building materials.

Figure 65 compares the material emissions associated with different lifecycle stages in both 2020 and 2050. While the sectoral decarbonization in a BAU scenario reduces the carbon intensity per material unity, the increase in construction activity in this scenario evens out this reduction, showing similar levels of embodied carbon from material production in both 2020 and 2050. However, the figure illustrates the increase of the renovation emissions between 2020 and 2050 due to the assumed increase in building renovation rates under a BAU scenario, considering already enacted policies such as the renovation wave.

As an intermediate conclusion, the SLiCE-based building stock analysis in this study enabled the modelling and assessment of detailed building archetype level results, considering temporal and spatial contributions, as well as modelling of different carbon reduction solutions and the upscaling to building stock level under different scenarios. The presented example results of the BAU scenario illustrate the potential for SLiCE-based building stock analysis to offer detailed results at building stock level, including on the contribution of different building stock activities, life cycle stages, buildings, elements, or even construction materials.

7.3.3. Future development

This implementation of the SLiCE data model for high-resolution building LCA is a starting point towards a wider ecosystem of SLiCE implementation and tools. Future development of the SLiCE building LCA ecosystem will seek to advance internal workflows as well as link to other open tools. The following aspects are currently under development or being considered as next steps.

Expert user interfaces

The SLiCe building LCA framework currently deploys different user interfaces, ranging from a basic command line interface for calling certain scripts and functionalities, over raw Python scripts as well as IPython Jupyter Notebooks for iterative data exploration and interpretation, to a preconfigured UI for managing the SQL database via Django Admin. Future development will seek to further improve user interfaces for foreground inventory modelling with particular attention to parametric generation of archetype variants using the existing modules of elements variants and layout variants. Furthermore, scripts for interpretation will be elaborated to advance analysis and visualization capabilities.

Update and extension of indicators

The current version of the SLiCe building LCA model deploys a complete set of building LCA indicators, however, it does not yet fulfil the latest methodological standard EN 15978+A2. An update of the indicator sets, including related impact assessment methods, is therefor currently under way. In addition, future development will investigate the inclusion of financial indicators for life cycle costing. The MMG+_KULeuven tool already provided such functionality for financial life cycle costing and can serve as an inspiration for the implementation of to-be-updated costing data for different contexts.

Dynamic life cycle assessment at scale

Building on the experiences from the presented implementation of SLiCE for dynamic climate impact assessment (presented in more detail in chapter 6), future development will explore an automated link with the Ecoinvent database and its background LCI data. The link of SLiCE building LCA with open tools like Brightway 2 (Mutel, 2017; Steubing et al., 2020) is considered particularly promising. Temporal as well as spatial dynamics of both foreground and background life cycle inventory as well as life cycle impact assessment will be elaborated. Spatial dynamics in foreground inventory are already considered in archetype-based building stock modelling and will be further elaborated with automated differentiation of background LCA, i.e., regionalization of Ecoinvent datasets applied in different geographies. Furthermore, spatial dynamics regarding the regionalization of impact assessment, based on the spatial distribution of material and energy processes will be explored.

Biogenic carbon accounting

The current workflows for consideration of (biogenic) carbon uptakes will be elaborated and further integrated into the SLiCE building LCA model. Possibly elaborating on the method applied in (Vanoverberghe, 2022) presented in in more detail in chapter 6, the consideration of different re-growth rates of different bio-based construction materials will be implemented. In addition, the carbon removal potential from different strategies (beyond bio-based materials) will be investigated for advanced scenario modelling in future studies.

Building stock turnover model

The current version of the SLiCE building LCA model depends on an activity-based upscaling for the modelling beyond building scale. Future development will build on and elaborate the current workflow towards an integrated building stock turnover modelling. A link with the well-established MESSAGEix model (Huppmann et al., 2019) and the related building stock turnover model (STURM) are currently investigated. Links with other models and frameworks, such as the ODYM-RECC framework (Pauliuk et al., 2021; Pauliuk and Heeren, 2020), are also being explored.

7.4. Summary and outlook

Decision makers involved in management, procurement and design of large building stocks or portfolios face a problematic trade-off between increasing relevance for strategic decision making and decreasing data granularity and model resolution when modelling macro-level life-cycle information.

The Space-Time-Indicator framework proposed in this paper conceptualises the problem and presents solutions that enable high-resolution analysis of both spatial and temporal information as well as relevant key performance indicators such as environmental impacts, or financial cost. The SLiCE model for scalable life cycle analysis of buildings presented herein, provides an extensible data solution for high-resolution modelling from the micro- to the macro-scale and enables the high-level analysis of KPIs as well as detailed analysis of hotspots in life cycle information across spatial and temporal dimensions. SLiCE enables consistent data structures, more efficient data storing, easier creation, removal, updating, and deletion of data. Most importantly, SLiCe support the generation of more detailed spatial and temporal life cycle information, including for diverse indicator results, detailed information on nested life cycle stages, as well as explicit timing of process and flows (per year), indication of mass flows (in/out), and linkage with background datasets on Technosphere flows (Ecoinvent) for retrieving further information in the future. This enables more detailed analysis, easier troubleshooting, and the provision of key information on the environmental performance of buildings even at higher scale levels.

Practical application examples showcase the potential of SLiCE for modelling comprehensive life cycle assessments, such as for bio-based building element solutions, the whole life carbon modelling of representative building archetypes, or SLiCe data use for scenario analysis of the EU building stock. Future development of SLiCE will include elaborating the modelling user interfaces as well as analytics to fully leverage current SLiCE outputs, advancing the interface to models at higher scales to improve building stock turnover and scenario modelling, as well as exploring links to models and sources that can support a dynamic modelling of carbon reduction and removal potentials in future studies.



8. DISCUSSION AND OUTLOOK

8.1. Synthesis

The following paragraphs provide a synthesis of the research presented in previous chapters of the doctoral thesis in context of the research questions (RQs) with further discussion in the next chapters.

Understanding the role of embodied carbon in the life cycle of buildings (RQ1)

Historical trend and state of embodied versus operational GHG emissions of buildings

Chapter 2 (The relevance of embodied carbon in the life cycle of new buildings) presents the results of a systematic review and meta-analysis aimed at identifying and analysing GHG emissions in the building life cycle. The analysis was based on the systematic review of more than 650 individual building LCA studies, with a final sample of 269 cases fit for evaluation. The results (Figure 10) illustrate that the reduction in life cycle related GHG emissions is a global trend for buildings that have adopted new energy performance standards for building operation. At the same time, the contribution of embodied GHG emissions increases up to and beyond a ratio of 1:1 (embodied to operational) when we consider a 50-year reference study period. More specifically: While the average share of embodied GHG emissions from buildings following current energy performance regulations is approximately 20–25% of life cycle GHG emissions, this figure escalates to 45–50% for highly energy-efficient buildings and surpasses 90% in extreme cases.

Whole life carbon trade-off between operational and embodied GHG emissions

Chapter 2 also investigates the total life cycle GHG emissions of European residential buildings in the sample over the amount of embodied GHG emissions and in relation to life cycle climate targets from the Swiss SIA 2040 (Figure 12). The analysis clearly shows that most of the buildings do not meet the target values. This is the case independent of the building energy standard. For all energy performance categories, i.e., existing standards for new standard and new advanced buildings, only a few cases meet the benchmark. Considering the buildings that do meet the target, it is observed that it is not necessarily the buildings with new standards that have a better chance of meeting the targets. This raises the question of the adequacy of building standards, focusing on operational energy efficiency, compared to the targets that need to be achieved to stay at a global temperature increase of 'well below 2°C'. The analysis shows that target values related exclusively to the operational phase are not sufficient for reducing life cycle GHG emissions. It is therefore necessary to develop and implement benchmarks addressing operational and embodied GHG emissions, i.e., whole life carbon, and overall environmental life cycle performance to put buildings on track for ambitious and effective climate mitigation scenarios.

Temporal distribution of whole life carbon of buildings in context of the climate crisis

Chapter 2 finally shows that the relevance of embodied GHG emissions further increases when investigating their temporal distribution along the life cycle and in context of the need for effective mitigation action to address climate change (Figure 13). The analysis reveals that even when anticipating future reductions in GHG emissions from building material production and operation, the initial 'carbon spike' from the production of building materials and systems dominates the climate mitigation timeframe, with a break-even of upfront embodied and operational emissions occurring only after 35 years or more. The initial investment of GHG emissions embodied in the investigated 'New advanced' buildings is hence the single most important aspect in the timeframe relevant for effective decarbonisation action. The analysis highlights the need to address and further reduce the life cycle related GHG emissions of buildings by optimizing embodied emission investments for new construction and promoting 'carbon-effective' investments for the refurbishment of existing buildings.

Towards whole life carbon benchmarks for new buildings across Europe

Chapter 3 (Towards benchmarking embodied carbon of buildings in Europe) deepens the investigation of the whole life embodied carbon baseline for new buildings across Europe based on LCA data cases obtained for five European countries: Belgium, Denmark, Finland, France and the Netherlands – which together provided a total of 769 cases for informing the embodied carbon analysis.

The baseline for whole life cycle embodied carbon emissions (Figure 16) ranges from around 400 to 800 $kgCO_2e/m^2$ with a mean value of around 550 $kgCO_2e/m^2$ for residential buildings, and from about 100 to 1200 $kgCO_2e/m^2$ for non-residential buildings, with a mean value of 450 $kgCO_2e/m^2$. The analysis of embodied carbon emissions per capita (Figure 17) shows for residential buildings a mean value of around 32 t CO_2e/cap, with values ranging from 5 to almost 60 t CO_2e/cap. For non-residential buildings values range from about 2 to 35 t CO_2e/cap, mean value is around 14 t CO_2e/cap. Conclusions regarding which building subtype has the highest embodied carbon emission intensity change when using a per-capita perspective over the established per-m^2 metric. Such is the case for multi-family houses, which have higher per-m^2 values than single family houses but display lowest values of all residential building types in a per-capita perspective, due to higher occupational density compared to single family houses. The analysis of different structural systems and materials (Figure 18) further indicates, for example, that frame structures do not necessarily lead to lower average embodied carbon emissions compared to massive structure. Cases where wood is used as the main structural material led to the lowest values for the respective type of structural system in both massive and frame systems. The average values are 100 to 200 $kgCO_2e/m^2$ lower than for other material options for massive and frame cases, respectively.

Distribution of embodied carbon emissions across space and time

Chapter 3, beyond investigating the embodied carbon baseline range for different building types and structural systems, presents the investigation of embodied carbon across spatial and temporal dimensions. Analysis of the spatial dimension, i.e., the contribution of different building parts (Figure 20), reveals that the main contributors to whole life cycle embodied carbon emissions, on average, are technical services (e.g. heating, cooling, domestic hot water and sewage systems) and structural elements (e.g. structural frame, walls, floors), with a mean value of around 190 $kgCO_2e/m^2$ (ranging from 170 to 230 $kgCO_2e/m^2$) and 170 $kgCO_2e/m^2$ (ranging from 100 to 320 $kgCO_2e/m^2$), respectively. Interior elements (e.g., partition walls, floor and wall finish) also contribute significantly, with a mean value of about 150 $kgCO_2e/m^2$ (ranging from 30 to 250 $kgCO_2e/m^2$). The investigation of the temporal dimension, i.e., the contribution of the different life cycle stages (Figure 19), shows that the largest contributions of embodied carbon emissions occur in the production stage (A1-3), with mean values of about 300 $kgCO_2e/m^2$ (56% of whole life cycle embodied carbon emissions), ranging from about 70 to 520 $kgCO_2e/m^2$. The second largest proportion of embodied GHG emissions occurs during the use phase (B1-4), mean values of about 120 $kgCO_2e/m^2$ (22%), which represents the total of emissions from cleaning, maintenance, and replacement activities taking place over a 50-year reference study period.

Understanding metrics and methods required to support climate policy (RQ2)

Data availability for assessing whole life carbon of buildings across Europe

Informed by the analyses and insights outlined above, the investigation of the state and need of whole life embodied carbon of buildings (RQ1) revealed several important next steps for both sustainable construction research and environmental policy related to the building sector. A major finding of Chapter 3 is the need to improve the availability of whole life carbon building data (Figure 15) as well as to enable meaningful differentiation of building samples and related benchmark values by further elaborating reporting requirements and data collection schemes. The inclusion of more information on

relevant aspects and attributes for understanding and interpretation of assessment results is required. Relevant attributes must address, for example, comprehensive descriptions of the building, including detailed information on building geometry (floor area (gross/net), building footprint, number of floors/height) as well as information on building location and context (climate zone, seismic zone, urban/rural), furthermore; information on buildings material inventory, as well as; detailed carbon emission results by building parts and life cycle stages. A long list of more than 300 relevant attributes and their priority for future data collection is proposed based on the experiences from these analyses provided in chapter 4 (Open database on embodied and whole life carbon of buildings). It proposes the consideration of attributes (Figure 23) related to: Metadata; Context and site; Building design; Assessment method; Inventory data; Indicator results. Attributes are furthermore structured in subgroups, such as: General; Geometry; Energy; Materials; Carbon; Analytics. The data published with this descriptor offers the largest open compilation of data on whole life carbon emissions, energy use and material intensity of buildings published to date and offers a unique data source towards benchmarking whole life carbon, energy use and material intensity. Another major conclusion of Chapter 3 is the need to improve the availability of building data at scale and enhance the representativeness of data samples considering the building stock in respective countries, e.g., based on statistical data on the characteristics of building stocks and new construction activities. Environmental modelling of building stocks can provide useful insights as to which criteria to apply for building stock characterisation and definition of representative samples as the foundation for robust benchmarking of whole life carbon for buildings.

Modelling environmental impacts of building stocks, spatial and temporal dynamics

To develop and identify effective policies to reduce building related GHG emissions and other environmental impacts, not only the modelling and assessment of individual buildings but also a move to the system level are required, taking into account the characteristics and dynamics of building stocks at scale. Chapter 5 (Policy objectives and the state of building stock models) presents an integrated review of both the latest scientific literature on environmental modelling of building stocks as well as an analysis of relevant EU policy initiatives related to buildings and building stock development. Based on the assessment of 104 scientific papers, the study shortlisted and analysed 22 environmental building stock modelling approaches in depth. The analysis shows that existing studies vary in terms of their spatiotemporal scope (Figure 32), with studies ranging from the portfolio and urban scales up to the national and transnational scales and conducting prospective analyses with a timeframe from one or a few years up to 200 years. The LCA methodology of existing models was analysed in terms of life cycle scenarios, impact assessment methods and environmental indicators (Figure 35, Figure 36). An expanded definition of building stock modelling was proposed (Figure 37) based on six basic modules for the environmental assessment of building stocks: i) building stock characterization; ii) material modelling; iii) energy modelling; iv) life cycle impact assessment; v) building stock aggregation; and vi) visualization and reporting. The application of this typology allowed the categorization of existing methodological approaches for building stock modelling (Figure 38) and the discussion of individual characteristics, strengths, and weaknesses (Table 20). This analysis of existing building stock models provided relevant insights in terms of modelling material- and energy-related impacts across the whole life cycle of buildings and revealed research gaps, such as a lack of studies featuring both comprehensive scope and high level of detail. It was further found that few studies thus far investigated the environmental implications of new construction activity that will take place in the coming decades across Europe. Furthermore, the environmental indicators covered in existing studies are very limited, with most studies focusing exclusively on GHG-related indicators. To fully comprehend environmental impacts and avoid burden shifting, it is recommended that all impact categories listed in recent CEN standards for environmental impact assessment of buildings should be considered. Environmental

hotspot analyses at the level of building clusters and individual buildings are scarcely found at all in current models, with a complete lack of examples providing such analyses at the level of detail suggested in recent EU-related documents such as the EF guidelines. The analysis further reveals a total lack of studies investigating how to monitor and actively guide EU building stock development in alignment with environmental targets and identified this as an important area for future research.

EU policy objectives for building stock development and suitability of existing models

Chapter 5 and the findings of the integrated review of building stock models and EU policy objectives, illuminates the strengths and limitations of existing building stock modelling approaches as well as the potential of such modelling and the required directions for future development to provide effective policy support. To analyse EU policy objectives related to buildings and construction, various relevant policy documents issued by the European Commission (EC) in recent years were systematically reviewed (see chapter 5.3.1). The five policy objectives related to EU building stock development and building construction and operations (Figure 31) were identified and summarised, namely the need for: 1.) Improvements to energy efficiency; 2) Increases in renewable energy; 3) Circularity and low-carbon material uptake; 4) Climate change adaptation and resilience; 5) Monitoring of environmental performance. The analysis of existing building stock models revealed that numerous studies investigate scenarios related to the objective of energy efficiency improvement as well as an increase in renewable energy. Several studies investigated circularity and low-carbon material uptake. Three studies specifically investigated the increased use of bio-based materials, two of which cover transnational (EU-28) and national building stocks in the European context. Scenarios regarding the intensity and speed of implementation of measures for adaptation and resilience were found for building stocks at transnational, national and urban scales. However, only two studies investigate the environmental implications of the evolution of building typologies regarding density (e.g., floor area per person), based primarily on assumptions of a continued increase in this metric. No studies were identified that specifically address the policy objective of monitoring environmental impacts. This was found to represent a major research gap, as EU policy makers will require comprehensive monitoring to guide the development of building stocks within environmental limits.

Towards a comprehensive LCA model for buildings and building stock analysis (RQ3)

Information needs for comprehensive analysis of environmental hotspots

Building on the findings from investigating life cycle modelling for buildings at scale (RQ2), chapter 6 (The SLiCE building data model for hotspot analysis) further investigates the specific information needs for supporting policy and decision maker (Figure 39). The challenge is conceptualised within the proposed Space-Time-Indicator (STI) framework as a means of communicating the availability and requirement for building life cycle information regarding diverse indicators at different levels of granularity along spatial and temporal dimensions. The STI framework (Figure 40) aims at providing a conceptual framework for understanding information needs for building life cycle modelling across spatiotemporal scales. The framework is based on three main dimensions of building life cycle-related information: Space; Time; and Indicators. For all dimensions, a notion of high or low ‘resolution’ is applied to express the granularity and level of definition in modelling and results provision for spatial and temporal information, as well as the comprehensiveness of indicators investigated in a particular analysis. In the present example, the spatial resolution focuses on the analysis of a building for which results can be provided as the sum at building level (level 0); per building element (level -1); per sub-element (work sections, components) (level -2); or per building material (level -3). The conceptual framework can be extended by higher as well as lower scale levels, such as the need for information on the contribution of even smaller entities, such as raw materials, or the need for insights at higher levels such as meso- or macro-level building clusters (e.g., national or transnational building stocks). In terms

of temporal resolution, the reporting of life cycle information in predefined categories along existing standards, is extended by the need for information about the actual point in time of the occurrence of something like GHG emissions. Enabling the reporting of detailed indicator/impact results in high spatial as well as temporal granularity, such as a yearly (or in future quarterly or monthly) basis, is considered an essential step towards incorporating advanced assessment and monitoring of environmental, social and governance (ESG) performance.

Scalable building data model for advanced analysis of environmental hotspots

Based on the conceptual STI framework, chapter 6 elaborates the practical implementation and introduces the proposal of an open building data model for scalable life cycle engineering and analysis (SLiCE). The SLiCE data model is introduced, and its data structure explained, as well as a first use case presented by implementing a systematic protocol for the analysis of (environmental) hotspots (Table 23) based on detailed building life cycle information. The SLiCE data model (Figure 44) is primarily aimed at enabling the use of high-granularity LCI and LCIA data for building life cycle analysis across scales. It deploys a combination of 'wide and 'tall' data structures (Figure 41). The data model logic represents key dimensions of spatial and temporal attributes via a 'tall' data structure and combines it with value dimensions, indicator results, implemented as a 'wide' data structure to enable efficient expansion of indicator sets. A variety of spatial attributes (key dimensions) can be accommodated within the data model, following a hierarchical building information modelling approach. Besides supporting the implementation of previously discussed attributes on spatial (elements, sub-elements, materials) and temporal aspects (life cycle stages according to standards), the SLiCE data model proposes and anticipates the specification of 'nested' life cycle stages, where applicable, as well as detailed temporal information on the 'point in time' a process occurs in. Deploying the SLiCE data model for managing life cycle information on this increased level of granularity can, for example, support the in-depth modelling of life cycle related impacts at higher scale levels (such as the macro-level building stock), or enable implementation of dynamic LCIA based on changing characterization factors over time. The proof-of-concept for using SLiCE data for hotspot analysis data model is implemented within a prototypical tool for hotspot analysis, utilizing IPython Jupyter Notebooks and interactive UI elements (Figure 45).

High-definition life cycle assessment across spatial and temporal dimensions

As a final step of the SLiCE proposal, chapter 7 (SLiCE building LCA: A model for life cycle analysis of buildings across scales) presents the SLiCE building LCA model, an implementation of the SLiCE building data model for high-definition life cycle assessment of buildings across spatiotemporal scales, building on KU Leuven's MMG building LCA tool ('MMG+_KULeuven'). The chapter presents the computational foundation of the novel SLiCe building LCA model and showcases some existing practical applications. The SLiCE building LCA model addresses the prevailing trade-off between policy-relevance and data granularity and model resolution for building modelling at the macro scale (Figure 47) by offering an LCA framework for high-resolution modelling also at higher scale levels, i.e., for environmental life cycle modelling across micro- and meso- as well as at macro-scale. The SLiCE building LCA model offers high-definition inventory modelling and impact analysis across spatial and temporal dimensions based on a logic of highly parametrised hierarchical modelling of spatial information (Figure 49) and a modular approach to the specification of temporal life cycle information at different spatial levels (Figure 50), deploying a complete set of environmental indicators. The computational environment of SLiCE is presented (Figure 48) and further description provided on its three main types of objects: user interfaces; scripts (for data computation or visualization), as well as data inputs or outputs. Furthermore, practical guidance for working with SLiCE building LCA along the well-known iterative steps of (building) LCA is offered (Table 30). Finally, several application

examples of the SLiCe building model are presented (Figure 54), including the use of SLiCE-based building LCA data for dynamic modelling of climate impacts and bio-based material's biogenic carbon uptake; a comparative spatiotemporal analysis of environmental impacts and hotspots of bio-based and conventional building elements; as well as the upscaling of high-granularity building archetype data for assessing the life-cycle-related GHG emissions of the European building stock, including scenarios considering the influence of different carbon reduction strategies at scale.

8.2. Scientific and practical relevance

The scientific relevance of this research is manifold, with some aspects being particularly noteworthy.

Embodied whole life carbon data, analysis and benchmarking

The building level investigation and meta-analyses on the role of embodied carbon across the building life cycle (chapter 2) and the cross-European data collection towards benchmarking of embodied carbon (chapter 3) provided relevant insights into the importance of embodied carbon, as well as regarding availability of embodied carbon data, and provide learnings from data collection and analysis important for informing future benchmarking efforts. The scientific relevance of this research is underlined by the attention and uptake the research has received, for example indicated by the number of citations. The research presented in chapter 2 (Röck et al., 2020b), published in early 2020, has thus far received hundreds of citations and was awarded the highly cited research award of the *Applied Energy* journal in 2022. The data descriptor presented in chapter 4 provides not only an extensive list of relevant attributes to consider for whole life carbon benchmark analysis, but also presents the largest open dataset on whole life carbon, energy and material use of buildings to date. This open dataset is expected to be valuable for research applications in context of MFA, I/O and LCA modelling, but also offers a valuable data source for benchmarking whole life carbon, energy use and material intensity of buildings to inform policy and decision making for the decarbonization of building construction and operation.

New models for scalable life cycle assessment of buildings

The scientific and practical relevance of the building and building stock related research presented in chapters 5 (The SLiCE building data model for hotspot analysis) and 6 (SLiCE building LCA: A model for life cycle analysis of buildings across scales) builds on the findings of the integrated review of methods and policy objectives presented in chapter 4 (Policy objectives and the state of building stock models). The integrated review of policy objectives and existing building stock models (Röck et al., 2021), was successfully taken up by its intended audience, European policy makers, and helped specify the needs for policy-informing research for the European Commission (EC) on the whole life carbon modelling of the European building stock. The methodological developments towards scalable building data models for high-granularity life cycle information, presented in chapters 6 and 7, took place alongside policy-informing research contracted by the European Commission and have thus been closely aligned with the practical needs of policy makers to advance scientific methods for the environmental modelling of building stocks at transnational scale. Beyond the immediate relevance of the study results, the modelling approaches presented in chapters 6 and 7 represent significant advancements in the field of building LCA. 1) The SLiCE building LCA model, through its combination of detailed foreground inventory data on the annual material and energy flows along the life cycle of buildings, provides detailed information useful for directly assessing energy use and material intensity, as well as for using that detailed data for life cycle impact assessment to obtain for high granularity results on environmental impacts including hotspots and potential trade-offs across space and time. In that regard, the thesis present several relevant use cases of SLiCE data, including SLiCE-based analysis of environmental hotspots and presentation of a related tool, SLiCE-based dynamic assessment of climate impacts considering the temporal decay dynamics of GHG emissions, as well as SLiCE-based

building stock modelling, including the analysis and specific modelling of different carbon reduction strategies and the upscaling of results for prospective scenario analysis at the level of the European building stock.

Immediate relevance for policy makers and practitioners

The research is furthermore of high practical relevance as both policy makers as well as industry professionals are seeking data and metrics to inform assessment and benchmarking of whole life carbon of buildings. The research and data published alongside this thesis is hence valuable to inform a nuanced and constructive debate towards decarbonization action for the building sector. The practical relevance of the research is furthermore emphasized by the contexts it was conducted in. The research took place in context of several contracted research projects for the EC, aimed at testing relevant methods in the building context (PEF4Buildings, Level(s)) or to inform the latest policy development for decarbonization of building construction and operation (Whole life carbon roadmap), as well as for philanthropic funders eager to support development of data and methods, as well as capacity building across EU member states to enable stakeholders across the value chain to implement and lead on strong decarbonization action. While not immediately apparent to the reader, the research presented in this thesis and the projects it was conducted in, have been largely acquired in consecutive steps, each project building on the findings and success of the previous works. For example, the research underlying chapter 2 (The relevance of embodied carbon in the life cycle of new buildings)(Röck et al., 2020b) and chapter 5 (Policy objectives and the state of building stock models)(Röck et al., 2021) has been picked up, cited in and informed project tenders issued by the European Commission and philanthropic funders. Follow-up research and funding acquisition was hence supported by previous investigation and experience on relevant aspects. Beyond citations, anecdotal evidence suggests that the works are regularly referenced in discussions of and with different stakeholder groups, from construction industry to commercial real estate, from building design professionals to users and inhabitants, as well as in public debate around the topic of whole life carbon emissions and the relevance of reducing embodied carbon of new buildings. As the need for corporate sustainability reporting and compliance with climate targets is increasing, the research presented offers relevant insights on timely topics of public interest.

Table 32: Topics covered in different chapters of this thesis.

	Chapter					
Topics	**2**	**3**	**4**	**5**	**6**	**7**
Contexts						
Climate targets	X			(X)	(X)	(X)
Benchmarking	X	X	X		(X)	(X)
Sustainability reporting		(X)	(X)		X	(X)
Policy making	(X)	X		X	X	X
Scales						
Buildings	X	X	X		X	X
Building stocks				X	(X)	(X)
Indicators						
Whole life carbon	X	X	X		X	X
Life cycle assessment				X	X	X
Material and energy flows		X	X	X	X	X

Table 32 provides an illustrative overview of topics addressed in different chapters of this thesis, based on the contexts, spatial scales, and indicators investigated. An elaboration on the scientific and practical relevance of selected aspects is presented in the following.

8.3. Critical appraisal

Reflections on embodied whole life carbon benchmark comparison

An obvious goal of benchmarking embodied whole life carbon of buildings is to check carbon performance of individual projects against specific life cycle carbon targets for buildings. Benchmarks and targets can be defined in different ways – e.g., using a carbon budget-based, top-down approach, bottom-up case study-informed definition, internal benchmarking against a baseline value, or other references - as elaborated by the author and colleagues in (Habert et al., 2020a). A critical reflection of the benchmark comparison presented in chapter 2 (The relevance of embodied carbon in the life cycle of new buildings) has been presented by the author and colleagues in (Röck et al., 2020a). Selected aspects of this conference paper are presented in the following.

Therein, first, general targets for the carbon performance of buildings are formulated. The estimation of maximum climate impacts of buildings, in other words the GHG emissions budget still available, is typically based on the capacity of the Earth ecosystem, in the long-term, and a share of the global GHG emissions budget allocated to the building sector for transition towards 'net-zero' in the intermediate term – often following the so-called 'grandfathering approach', which bases the budget allocation on previous share of a sector or activity (Habert et al., 2020a). However, while this is a globally uniform goal, it still must be pursued and achieved with specific means in the respective contexts. Hence, the specific solutions are affected by not only climate zones and economic areas but also building types and use scenarios. The long-term environmental targets have to be based on the capacity of the ecosystem following, e.g., the 'planetary boundaries' approach and its application for defining environmental budgets for the built environment, which showed the need to rethink current building practice fundamentally (Andersen et al., 2019; Brejnrod et al., 2017). So far, apart from very general formulations in the direction of 'climate-neutral buildings', there have been hardly any quantitative requirements for a GHG emissions budget that can be interpreted as a design goal or legal requirement.

In a simplified calculation, for limiting global warming to 1.5 degrees, reducing GHG emissions to 1 ton of CO_2e per capita and year can be an intermediate target for taking us on a path towards 'netzero'. Table 33 shows the estimated GHG emission budgets across the life cycle of residential buildings, expressed as CO_2e per living area (or net floor area) and year, i.e., CO_2e /m^2_{NFA}/a. It assumes that around 30% of all GHG emissions are used for construction and operation of residential buildings. Furthermore, it is assumed that, based on existing sample projects, buildings can – and will have to be – designed in such a way that they achieve 'zero' or 'net-zero' GHG emission performance in operation. In this context, a 'near-zero' can be interpreted with 1-2 $kgCO_2e/m^2_{NFA}/a$. Assuming 'net-zero' or 'near-zero' operational GHG emissions means that the GHG emissions budget becomes (almost) entirely allocated for embodied GHG emissions. Hence, this budget is available for building construction and repair, including the replacement of structural parts and building services systems in the life cycle, as well as the deconstruction, recycling, and other end-of-life processes. As shown in Table 33, assuming a budget of 300 $kgCO_2e/cap/a$, a building service life of (at least) 50 years, and an average living space of 30 m^2/person as appropriate, the available budget in the building design context is approx. 10 $kgCO_2e/m^2/a$. This is an estimate target values for a transition period, within which budgets are used to develop 'buildings' towards 'net-zero' GHG emissions across the life cycle.

Table 33: Estimated design target for residential buildings (construction and operation) [CO_2e/m^2*a] (Röck et al., 2020a)

Floor area per capita [m^2/cap]	Carbon budget for residential buildings (embodied and operational carbon) [$kgCO_2e$/cap/a]						
	600	**500**	**400**	**300**	**200**	**100**	**0**
60	**10.00**	8.30	6.70	5.00	3.30	1.70	0.00
50	12.00	**10.00**	8.00	6.00	4.00	2.00	0.00
40	15.00	12.50	**10.00**	7.50	5.00	2.50	0.00
30	20.00	16.70	13.30	**10.00**	6.70	3.30	0.00
20	30.00	25.00	20.00	15.00	**10.00**	5.00	0.00
10	60.00	50.00	40.00	30.00	20.00	**10.00**	0.00

Chapter 2 presents an analysis of global embodied carbon trends based on average values, as well as an investigation of building cases in relation to the Swiss SIA 2040 benchmarks for the life cycle-related GHG emissions of buildings (Figure 12).

As acknowledged by the authors and colleagues at the 71st LCA forum dedicated to environmental benchmarks for buildings (Rolf Frischknecht et al., 2019b), benchmarking and meaningful benchmark comparison can only be applied in the context of specific calculation methods and databases and should therefore be applied within a consistent (national) framework. Although the SIA 2040 benchmark values, too, adhere to a specific method and to specific background data and should therefore preferably be used for buildings planned in Switzerland, we consider it useful to work with it, as it gives a specific example of life cycle related benchmarks already applied in design practice. Furthermore, the general target values presented earlier – rough estimates, yet globally valid under the specified boundary conditions – are surprisingly close to the more advanced calculations of life cycle related target values specified in the Swiss SIA 2040 guideline (SIA, 2017): The SIA benchmarks are 2 $kgCO_2e/m^2/a$ for building operation and 9 $kgCO_2e/m^2/a$ for construction and maintenance over a reference study period of 60 years. Hence, the total design target, i.e., for building construction and operation, is 11 kg $CO2eq/m^2/a$.

However, applying such (or any) benchmarks to the studies in this meta-analysis requires the consideration of the vast differences amongst the cases, which exist in databases, calculation rules, energy supply situation, as well as political and socio-cultural context, among others. This raises the crucial question: How and under what conditions case studies in our sample reach these target values?

Drivers of embodied whole life carbon values

Building on the analysis presented in chapter 2 (The relevance of embodied carbon in the life cycle of new buildings) and the reflections on target setting in the previous section, this section presents the critical investigation of what makes the 'best cases' meet the benchmark - again following the argumentation presented in (Röck et al., 2020).

An in-depth analysis of said cases was conducted based on extended data extraction, focusing on studies' scope and building design-related features. Whilst a strong influence from the scope of a building LCA study, e.g., the completeness in terms of life cycle stages and building elements included, is obvious, standards hardly require a minimum scope but rather ask for transparency in reporting of the chosen scope and method. This fact leads to the challenge of having to account for said differences when comparing building LCA results reported in studies, even for largely similar buildings. Besides building LCA studies' scope, past research has shown various features influencing the results, amongst them i) the type of building and its use (Hossain and Ng, 2018; Säynäjoki et al., 2017a); ii) site-specific properties (e.g., country, climatic zone, seismic zone) (Cobîrzan et al., 2017; Ng et al., 2016); iii) the

energy performance standard (Chastas et al., 2016; Koezjakov et al., 2018); iv) construction method (choice of main building materials (e.g., for structural system, envelope, internal walls) (De Wolf et al., 2016, 2014; Säynäjoki et al., 2017a); and v) the size and shape of the building (e.g., floor area, number of stories, general shape) (Säynäjoki et al., 2017a; Kathrina Simonen et al., 2017). The in-depth analysis hence included all of these aspects, aiming to reveal whether the case study buildings show low GHG emission values because of 'good' design choices (e.g., related to building shape, construction materials, energy efficiency, etc.) or because of 'bad' LCA practice, e.g., a tiered and incomplete product system (missing potentially relevant building parts).

The extended data extraction and in-depth analysis was conducted on those cases of residential buildings that met the SIA benchmark, i.e., analysing 28 residential building cases from six papers. Already within this limited number studies analysed in-depth, a number of challenges and important data gaps became evident. Large data gaps were identified for features related to 'Building design decisions', where crucial information on both 'geometry' (e.g., general description of shape, volume, envelope area, window/wall ratio) as well as building 'performance' (e.g., number of user/occupants, energy provision, sources and distribution, u-values) had not been reported in the respective building LCA studies. It was shown in previous LCA studies that parameters such as, e.g., building geometry or u-values of the building envelope influence environmental performance of a building and should hence be documented as key features of building LCA studies. The following analysis focuses on the influence of selected features on embodied GHG emissions.

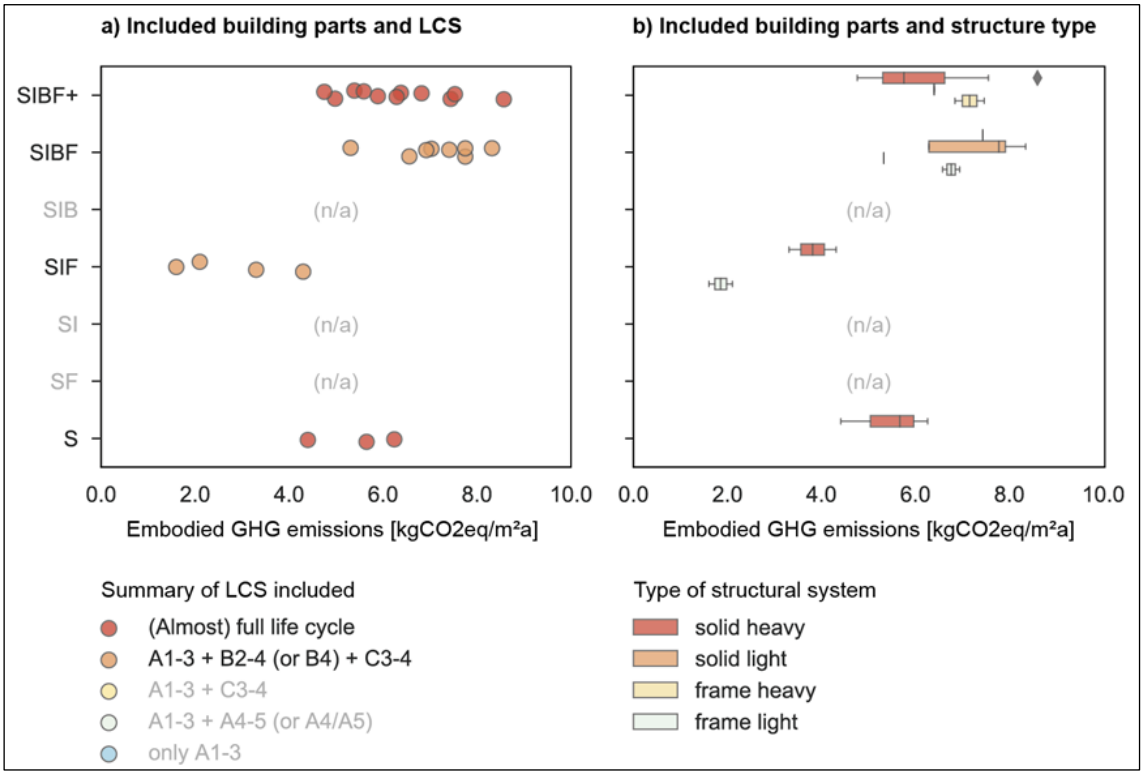

Figure 66: Analysis of the influence from features related to LCA methodology and building design decisions based on 28 residential building cases, plotting embodied GHG emissions (a) by the scope of life cycle inventories (building parts included, and life cycle stages covered), (b) by building parts included for assessment and type of structural system. (Röck et al., 2020)

Amongst the most crucial aspects of LCA studies is the definition of the scope, system boundaries and respective life cycle inventories. To understand the influence of these methodological decisions on the results in terms of embodied GHG emissions, we analysed the scope regarding building parts and life cycle stages included in the "best cases". For building parts, abbreviations describe the parts included

in the respective study: (S) structure; (F) foundation; (I) internal elements; (B) building services; (+) other elements (beyond conventional system boundary definitions). The definition of building life cycle stages (LCS) follows the EN 15978 standard. The type of structural system groups different structural systems and main construction materials: solid heavy (mass brick or concrete), solid light (mass timber), frame heavy (skeleton concrete or steel), frame light (skeleton timber).

As shown in Figure 66.a, plotting cases' embodied GHG emissions based on the building parts included and life cycle stages covered in the assessment suggests that with the increasing 'completeness' of the inventory, also the related embodied GHG emissions are increasing. Following the same structure, i.e. plotting embodied GHG emissions based on building parts included for assessment, additional analysis was conducted on the building design related drivers, namely of type and material of the structural system, see Figure 66.b. When compared to the increase trend in embodied GHG emissions associated to the inventory's level of detail, the type (and main material) of the structural system seem to play a secondary role in the results. The current data suggests that wood structures generally perform better than concrete structures, but there are cases where massive wood shows higher embodied GHG emissions than concrete frame and massive brick structures. In these cases, LCA methodology features seem to dominate the observed results and trends.

The analysis of the influence of different assessment scopes, i.e., life cycle stages and building parts considered, informed the data collection in subsequent analyses and is further elaborated and quantified in chapter 3 (Towards benchmarking embodied carbon of buildings in Europe) for cases collected in that chapter in the European context. In conclusion, (Röck et al., 2022a, 2020a) call for improving the quantity and quality as well as standardisation in reporting of building LCA studies to further enable the use of machine learning, e.g., for estimating environmental performance based on a limited number of key features. Further, in-depth analysis of a larger number of studies should be conducted to allow application of more sophisticated quantitative assessment methods, e.g., for dimensionality reduction, and a solid identification of the dominant drivers and relevant patterns behind a diverse set of building LCA studies. Improving the quantity and quality as well as standardization in reporting of building LCA studies could further enable the use of machine learning, e.g., for estimating environmental performance based on a limited number of key features. A basic requirement for this to happen, are clear methodological guidelines and standardized minimum documentation requirements including a list of key features to be documented for *every* building LCA study. Recommendations and proposals on how to respond to this requirement are presented through the extended list of attributes presented in chapter 4 (Open database on embodied and whole life carbon of buildings) and the building LCA data model proposed in chapter 6 (The SLiCE building data model for hotspot analysis and dynamic assessment).

Indicative decarbonization pathway for embodied whole life carbon

Building on the insights generated through the analyses presented in chapter 2 (The relevance of embodied carbon in the life cycle of new buildings) and the critical reflections presented in the previous sections, another conference paper has been put forward by the author and colleagues (Röck et al., 2022a). The contributions reflects on the analysis presented in chapter 3 (Towards benchmarking embodied carbon of buildings in Europe) as well as the discussion in other tasks of the underlying project including the need and struggle for definition of budget-based targets for buildings (Horup et al., 2022). The paper reflects on the baseline and analysis and uses to values as the basis for showcasing the proposal of a simple approach for the definition of indicative decarbonization targets for embodied carbon based on the 'carbon law' (Rockström et al., 2017). Against the backdrop of increasing efforts to understand and reduce whole life cycle carbon of buildings, (Röck et al., 2022a) combines three perspectives to investigate the role of embodied carbon up until today and into the future, by examining:

1) the historic development of embodied carbon; 2) the current baseline for embodied carbon; and 3) an indicative pathway for embodied carbon reduction. The analysis of this third aspect is presented in the following.

The *carbon law* approach stems from the 2017 article "A roadmap for rapid decarbonization", published in the renowned journal Science (Rockström et al., 2017). Therein, leading climate scientists provide a detailed modelling of the rapid decarbonization action required to enable meeting the Paris Agreement. Along with a detailed roadmap with reduction pathways for different sectors, the authors promote the application of a simple heuristic: *"To calibrate for short-term realpolitik, we propose framing the decarbonization challenge in terms of a global decadal roadmap based on a simple heuristic—a "carbon law"—of halving gross anthropogenic carbon-dioxide (CO_2) emissions every decade. Complemented by immediately instigated, scalable carbon removal and efforts to ramp down land-use CO_2 emissions, this can lead to net-zero emissions around mid-century, a path necessary to limit warming to well below 2°C."* (Rockström et al., 2017)

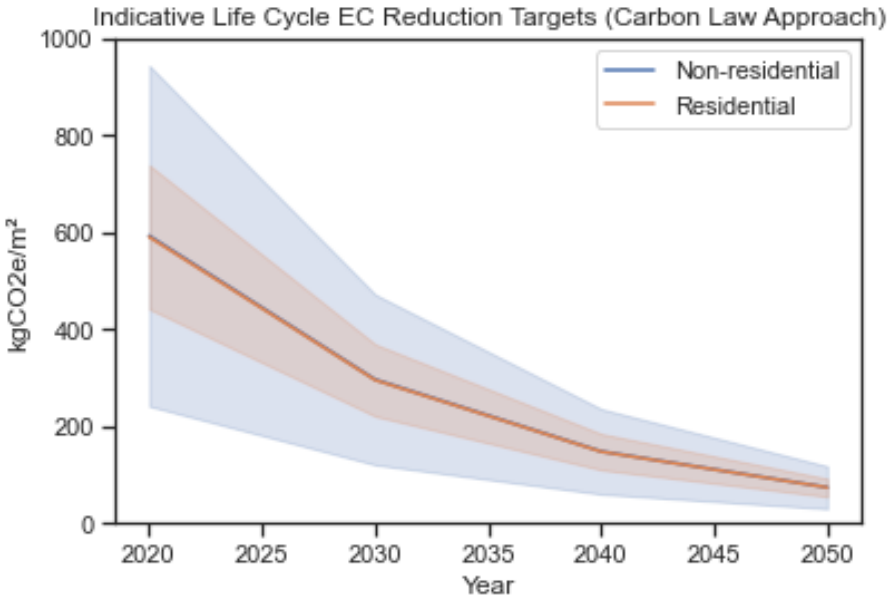

Figure 67: Indicative reduction targets for full life cycle embodied carbon emission [kgCO2e/m²] of residential and non-residential buildings, respectively, based on chapter 3, (Röck et al., 2022c; Rockström et al., 2017). (Röck et al., 2020)

Figure 67 presents an indicative reduction pathway for embodied carbon emissions of buildings, starting from the current baseline of about 600 kgCO2e/m² (mean), as presented earlier, and applying the simple heuristic proposed in the "carbon law" approach for the timeframe of 2020 to 2050. The figure implements the suggested 'halving [of GHG emissions] every decade' and applies it to the whole life cycle embodied carbon emission values for residential and non-residential buildings, respectively. The analysis hence shows that indicative target values for full life cycle embodied carbon in 2030 would be half of what it is today, i.e., around 300 kgCO2e/m². As an intermediate step, a reduction target in line with the latest climate science for 2025 could be 450 kgCO2e/m². Going further, embodied carbon levels will have to be about halved each decade, leading to indicative target values for full life cycle carbon of 150 kgCO2e/m² in 2040, and 75 kgCO2e/m² in 2050, respectively. For a detailed understanding of what such a reduction pathway could mean, we calculate reduction targets for individual life cycle stages based on the mean values obtained in the baseline analysis. Figure 68 and Table 34 present these values that propose indicative targets for the production stage (A123); construction process (A45); the use phase, including maintenance, repair and replacement (B1234); the

deconstruction process (C12); and the end of life stage (C34), respectively, and illustrate how embodied carbon emissions should reduce by 2030, 2040 and 2050 with a carbon law approach.

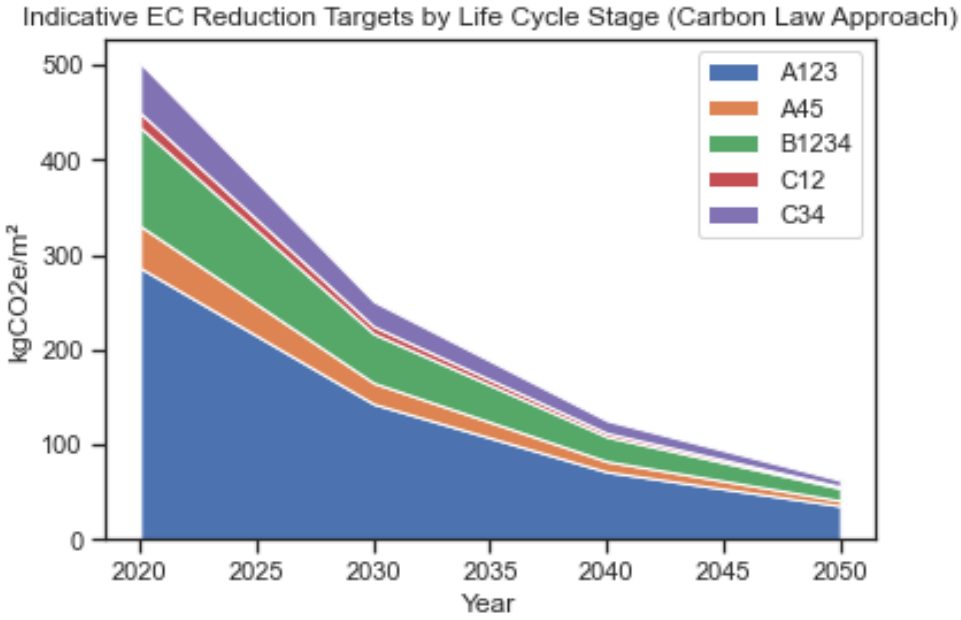

Figure 68: Indicative reduction targets for embodied carbon emission of different life cycle stages [kgCO2e/m²], based on chapter 3, (Röck et al., 2022c; Rockström et al., 2017). (Röck et al., 2020)

Table 34: Indicative reduction targets for embodied carbon [kgCO2e/m²] from different life cycle stages, based on mean values in EU-ECB data and application of the Carbon Law (Röck et al., 2022c; Rockström et al., 2017). (Röck et al., 2020)

Year	Life cycle stages				
	A1-3	A4-5	B1-4	C1-2	C3-4
2020	286.26	44.20	103.76	15.38	52.41
2030	143.13	22.10	51.88	7.69	26.21
2040	71.56	11.05	25.94	3.84	13.10
2050	35.78	5.52	12.97	1.92	6.55

While this application of the carbon law approach is a simple exercise to give an indication of the drastic reduction of embodied carbon emissions from buildings, it provides a hint on the required trajectory. The definition of more specific, relative reduction targets is required and underway, but implementation of ambitious carbon reduction strategies must not wait another decade for methodological discussion to move forward and allocation issues to be settled. The relative reduction target approach showcased here could, for example, enable to the application of reduction pathways from other sources and contexts, such as the pathways proposed in the latest IPCC AR6 report, based on latest carbon emission budget calculations, or decarbonization pathways of the European Union and its Member States, as outlined in the respective environmental policy documents. It might further support the alignment of different stakeholder perspectives, e.g., by using relative reduction targets from building and construction-related industry sectors. There is ongoing discussion on how specifically to define ‘carbon budgets for buildings’ and how to do so in a manner that is consistent across countries, industry sectors and building-related activities (IEA EBC, 2016). We consider it important to engage with this struggle for a common understanding of emission allowances and reduction pathways for different areas of action like “buildings” and actors. At the same time, we want to highlight approaches that can be useful in guiding in the right direction regarding the (embodied) carbon emissions reduction needed in the

coming decades, which can be applied today, using relative reduction targets and related pathways, such as the carbon law approach. While we present the application of the approach based on the average baseline results, a more specific application on country level could be considered for future research. Furthermore, the approach of applying relative reduction targets can be applied beyond the carbon law, e.g. drawing from national determined contributions (NDCs) and relative carbon reduction targets for different industry sectors potentially defined therein. The analysis of indicative reduction target presented in this study lays out the need for drastic reduction of life cycle embodied carbon in coming years and decades. The general trajectory and necessity of substantial reductions in emissions levels is in line with previous research on the topic (R. Frischknecht et al., 2019a; IEA EBC, 2016) and, in particular, the ambition of achieving 'absolute sustainability' in the context of building construction and operation (Brejnrod et al., 2017). Similar emission reduction trajectories have recently been called for in a joint declaration of expert researchers on building life cycle assessment from IEA EBC Annex 72 in the so-called Graz Declaration and Monte Verità Declaration on a built environment within planetary boundaries (IEA EBC Annex 72, 2021).

The indicative baseline for whole life cycle embodied carbon emissions ranges from around 400 to 800 kgCO2e/m² with a mean value of around 550 kgCO2e/m² for residential buildings, and from about 100 to 1200 kgCO2e/m² for non-residential buildings, with a mean value of 450 kgCO2e/m², respectively. The investigation of contribution from different life cycle stages shows that the largest fractions – almost 2/3 of embodied carbon emissions - occur upfront, i.e. during the production stage (A1-3) and construction process stage (A4-5), with on average about 340 kgCO2e/m² (63% of whole life cycle embodied carbon emissions).While emissions of the use stage (B) and end-of-life (C) activities may change for buildings constructed now, we want to emphasize the amount of "upfront" carbon, emitted during the production and construction process stages (A), which are taking place for production and construction of new buildings today, using contemporary technologies and causing related emissions today. Our findings emphasize the importance of upfront carbon and the urgent need to reduce "the carbon spike" as soon as possible in order to avoid lock-in effects and committed emissions from new building construction and operation. Suitable, legally binding target values for whole life carbon of buildings should be sought across Europe and implemented no later than 2025. The indicative baseline presented in this paper and expanded on in the underlying research project reports, can serve as a starting point for further developing the required benchmarks for reducing whole life carbon of buildings across Europe. The application of the carbon law approach enables the provision of indicative reduction targets for embodied carbon emission for both whole life cycle embodied carbon as well as different life cycle stages. Applying relative reduction targets could provide an approach for implementing existing target pathways, e.g. from the latest IPPC report or according to European Union policy. While the targets proposed for buildings in 2050 do not seem feasible today, there is evidence to at least support the first steps, and embark on an ambitious decarbonization pathway for reducing whole life cycle and embodied carbon of buildings until 2030 and beyond.

More generally, this analysis, as presented in (Röck et al., 2022a), showed that decarbonization action can be informed by the definition of relative reduction targets. These can assume consistency of assessment methods, i.e., the same life cycle stages and building parts as well as data sources, in both baseline values as well as LCA conducted to prove target compliance. Thereby enabling stakeholders to define the starting point and trajectory for carbon reduction in the coming years, seemingly avoiding some of the methodological inconsistencies still present in building LCA practice today. The approach of relative reduction targets is gaining traction, as is visible by the example of the recently published science-based targets (SBTi) proposal for the setting reduction targets for (upfront) embodied carbon of building portfolios, which adopts a similar, relative reduction target approach.

Stock modelling using meta-analysis life cycle data

An investigation on the use of meta-analysis life cycle data presented in chapter 2 for bottom-up building stock modelling in the Austrian context was presented by the author and colleagues in (Truger et al., 2022) – selected excerpts of this conference paper are presented in the following. The study aims to assess Austria's building related emissions including all relevant emission sources of the field of action. We use a process-based life cycle assessment (LCA) to estimate annual emissions related to buildings in Austria and cross-check the results with an input-output LCA estimate.

Considering the difference between top-down and bottom-up perspectives on the emissions across the life cycle of buildings, as previously discussed in (Habert et al., 2020a), we suggest a comprehensive system boundary of annual building-related GHG emissions on a country level comprising the whole "field of action" for buildings – see Figure 69. First, we include emissions from residential and non-residential (i.e., service and industry sector) buildings which together form the total building stock in a country. Second, we account for different emission scopes, including operational and embodied emissions. We define operational emissions to be emissions arising through space heating and cooling, including hot water supply as well as emissions from building's maintenance and real estate service activities. Space heating and cooling emissions can be further distinguished between direct and indirect operational emissions. Direct emissions refer to all emissions whose sources are located physically in the building (e.g., fossil fuel consuming equipment for water and space heating). Indirect operational emissions arise from energy consumption (i.e., electricity and district heat) in the building, including also emissions in the fuel supply chain. Embodied emissions originate from production activities for construction materials and transport as well as building-related (de-)construction activities across the building life cycle. They comprise direct emissions arising at the building site itself, transport, waste and disposal activities at the end-of-life as well as emissions embodied in deployed building materials. Thus, embodied emissions also consider indirect emissions arising in regional and global supply chains of the building-related construction industry (compare also (United Nations Environment Programme (UNEP) and Global Alliance for Buildings and Construction (GABC), 2022)).

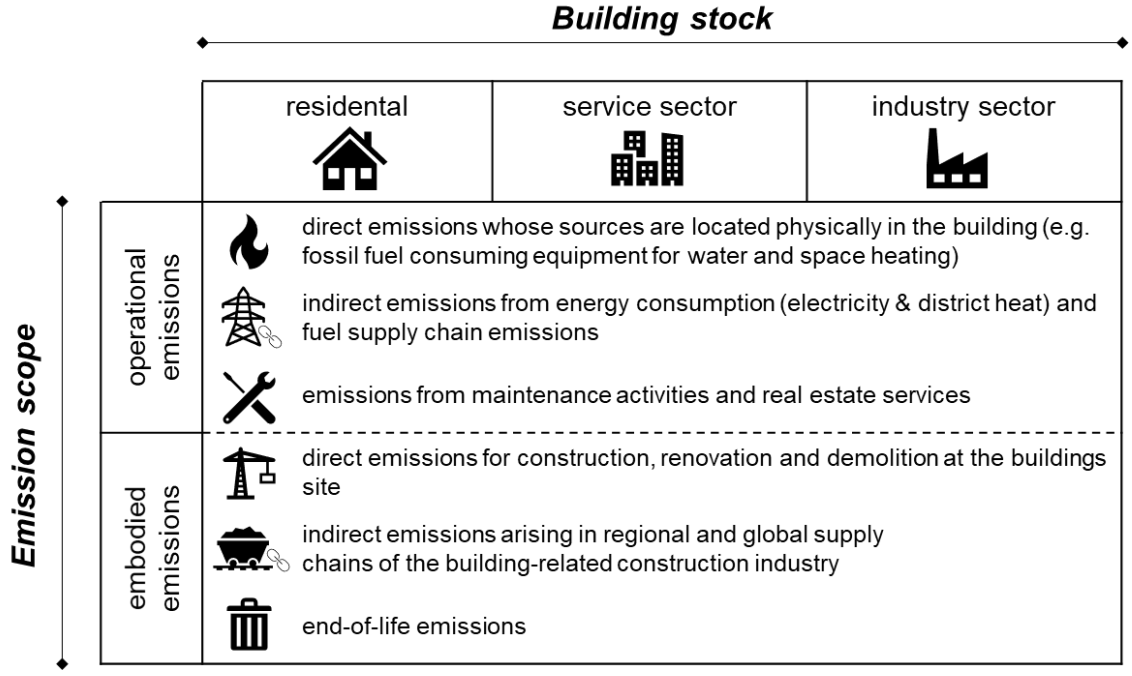

Figure 69: Proposed system boundary of the "field of action" for buildings, to be considered for emission evaluation of a national building stock. (Truger et al., 2022)

To evaluate the embodied emissions of buildings, we use life cycle assessment, which allow to estimate environmental impacts over the entire life cycle, including raw material extraction, production, use phase and disposal (Klöpffer and Grahl, 2014). As the main approach we employ a process-based LCA of buildings to estimate national embodied emissions through a bottom-up perspective, supplemented by statistical data on the national building stock. To complement this assessment, we provide estimates from an Input-Output based LCA, which are based on a top-down macroeconomic point of view.

Process-based LCA approach

The process-based assessment of the embodied emissions of buildings is based on building LCA data from the study of (Röck et al., 2020c), and building stock data from Statistics Austria (Statistik Austria, 2021a), supplemented by data from TU Wien's Energy Economics Group.

The LCA data builds upon a meta-study of published building LCA studies conducted in the context of the IEA EBC Annex 72 as presented in (Röck et al., 2020c). The data were harmonised to a reference service life of 50 years and given per square meter gross floor area (GFA) and year (kg CO_2-eq/m^2a). Out of the global data set of LCA studies, a limited sample was defined including only studies from Austria and neighbouring countries, or studies from European countries in the same climate zone as Austria. As a result, 354 building LCA case studies, mostly residential or office buildings, were analysed in this study. These studies are characterized according to seven different building types. To estimate the embodied emissions of new buildings' construction, the case studies were first filtered to include only new construction or existing building cases (271 cases), and cases which state embodied emissions separately (194 cases). In order to ensure the comparability of the studies, they were further filtered by their scope, i.e., the life cycle stages and building elements considered in the respective study, applying the life cycle phase model of the related standard for building LCA, EN 15978. Only studies including life cycle stages of modules A (production and construction), B (use stage), and C (deconstruction) were included in the analysis (163 cases). These were further filtered to only consider studies including all most relevant building parts (i.e., structure, internal elements, building services, and foundation). The final sample includes 87 building LCA case studies. The mean value of the embodied GHG emissions per area and year was estimated per building type, and also per LCA module.

In order to assess the total embodied emissions of new construction in Austria, statistical data on new construction was analysed and filled in with data from TU Wien for better detail in building types (e.g. dividing "office buildings" into small and large office buildings). The newly constructed area per building type was then multiplied by the estimated emission value for module A, considering the entire emissions not divided by the buildings' estimated service life. Refurbishment case studies for module B5 are assessed separately from the same basis of case studies, as well as additional literature. 64 case studies out of the original 354 case studies were used, including residential buildings and non-residential buildings, but no office buildings were in the studied sample. Refurbishment emissions for office buildings are based on (Marique and Rossi, 2018). The estimated emission factors for different building types and life cycle stages are applied to different building stock data. While the emission factors were originally harmonized to a reference service life of 50 years, and given in kgCO_2-eq/m^2a, the embodied emissions occur in the year of construction (or replacement/refurbishment/demolition) and are therefore used in kgCO_2-eq/m^2. Module A1-A3 is multiplied by the area of newly constructed buildings in 2014 (Statistik Austria, 2021b). Modul B4 (replacement) is based on the building stock built before 1990, with the assumption that 1% of the buildings go through replacement every year. The refurbishment rate for module B5 is set to 1,5% of the whole building stock (Amman et al., 2020). For the end of life (module C), data on the demolishing of buildings from Statistics Austria was used. Multiplying the respective building stock data with the average emission factors gives an estimate of yearly embodied emissions of buildings in Austria.

To compare the emission estimates of the process-based LCA, we complement our analysis by a cross-check, using an Input-Output (I-O) LCA. The boundary selection of process-based LCAs necessarily implies a truncation bias, potentially leading to underestimations (Säynäjoki et al., 2017c) amounting up to tens of percentage points at the building level (Lenzen and Treloar, 2002). Input-output LCA, first introduced by Leontief in the 1970s (Leontief, 2018), exhibits a broader, top-down perspective than process-based LCA by considering the whole economy. Based on economic Input-Output matrices, I-O LCA estimates environmental impacts of final demand along international supply chains (Chang et al., 2010). While Input-Output tables translate a transaction in one economic sector into the distribution of value added across the whole economy, the environmental impact of this transaction is assessed by extending the I-O tables by sector-specific emission intensities. This achieves full system completeness and does not lead to a truncation bias (Säynäjoki et al., 2017c). However, related uncertainties with this approach stem from the underlying assumptions that the (weighted) average values reported in the I-O tables are representative for all products and firms of a specific sector (i.e. homogeneity assumption and aggregation error) and that emissions linearly correlate with the product's market price (i.e. linearity assumption) (Crawford, 2011; Crawford et al., 2018). Despite its limitations, the environmentally extended I-O analysis is particularly suited to assess entire sectors (Crawford et al., 2018) and thus to cross-check our results obtained by the process-LCA approach.

Input-Output LCA approach and comparison

Building on the approach of (Muñoz and Steininger, 2010) and (Steininger et al., 2018), we conduct an environmentally extended multi-regional I-O analysis based on the Global Trade Analysis Project (GTAP) database V10 (Aguiar et al., 2019) with base year 2014. We construct an emission data set for this base year by following a similar approach as in (Steininger et al., 2018) and include industrial process emissions for each region, as this type of emissions appears especially relevant for building materials such as steel and cement. Based on this newly constructed emissions data base and the economic GTAP data base, we calculate consumption-based GHG emissions of the Austrian economy on a sectoral level. The I-O model is specified as:

$$e^* = e\,\hat{x}^{-1}\,(I - Z\hat{x}^{-1})^{-1}\hat{y}$$

with:

e^*	Vector of emissions re-allocated on the basis of consumption-based accounting
e	Vector of sectoral emissions allocated according to a production-based principle across countries
$\hat{x}$	Diagonalized vector of sectoral outputs across nations
I	Identity matrix
Z	Matrix of intermediate inputs within and among regions
$\hat{y}$	Diagonalized vector of sectoral final demands across countries

We further decompose sectoral emissions into regional and sectoral sources by using a diagonalized vector of region-specific sectoral emission intensities $\widehat{e_r \widehat{x_r}^{-1}}$, for the example of Austria as region r, instead of a matrix of sectoral emission intensities of all regions $e\,\hat{x}^{-1}$ in the above specification. More details on the MRIO specifications can be found in (Miller and Blair, 2009; Muñoz and Steininger, 2010).

Referring to the outlined system boundary of the "field of action" for buildings (Figure 69), we consider emissions induced by final demand of private households and the government and investment demand by firms for goods and services produced by building-related sectors. Also, we include emissions induced by intermediate demand of economic sectors for these building-related goods and services, which we calculate by applying the emission factors derived from the I-O analysis. Building-related sectors include construction (NACE sectors 41 and 43), real estate activities (NACE sector 68) and services to buildings and landscape activities (NACE sector 81). Embodied emissions estimated by the I-O approach thus include all building types (i.e., residential, service sector and industry buildings) located in Austria that are newly built, maintained or renovated in a given year. They include direct emissions that arise at the construction site itself and indirect impacts attributable to uncut international upstream supply chains of the building-related construction industry. However, end-of-life emissions beyond direct demolition works that occur outside of the building-related construction sector (e.g., transport, recycling and disposal of materials) are not captured by this estimation. Given the different nature of process-based and I-O LCA, estimating emissions based on a (preferably) common system boundary yields diverging results. I-O LCA tends to produce significantly higher estimates than process-based LCA (comp. (Takano et al., 2014b; Zhu et al., 2020)). Even at the level of a single building, I-O LCA is found to estimate emissions up to twice as high as process-based estimates (Säynäjoki et al., 2017c). While it is difficult to trace back the exact sources of the difference in results (Säynäjoki et al., 2017c), the aim of using both approaches is to obtain a validated range of building-related emissions and identify hotspots of the building sector from a life-cycle perspective.

Whole life carbon emissions at national level

Figure 70 presents the total annual embodied emissions of 4.3 Mt CO_2-eq/a, derived by the process-based approach. Their decomposition shows that 66% of the embodied emissions per year are allocated to residential buildings, which also make up the largest part of the building stock and new construction activities (see Figure 70). Non-residential service buildings and industry buildings account for 22% and 12% of the emissions, respectively. From a life cycle stage point of view, 45% of yearly embodied emissions are released through new construction activities, followed by renovation activities with 40%. Maintenance and replacement, as well as demolition at the end of life have lower impacts in comparison, with 15% and 1%, respectively.

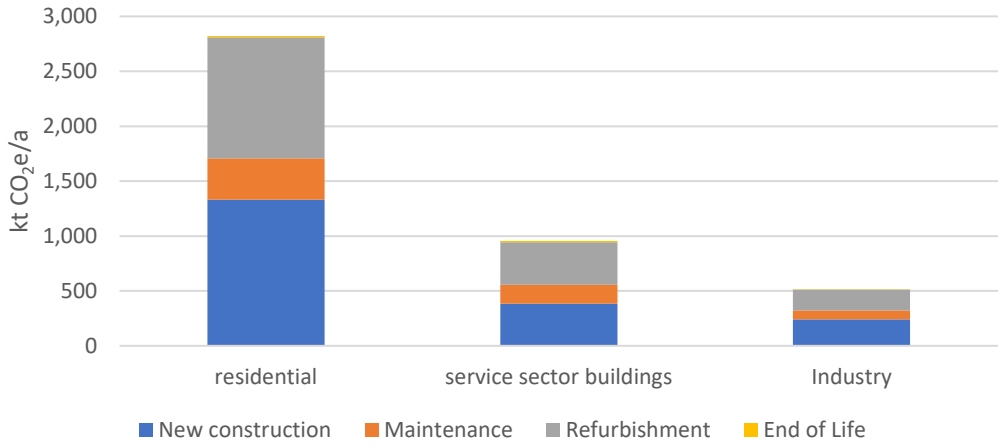

Figure 70: Breakdown of the annual embodied carbon emission (kt CO_2e/a) from different types (residential, service sector buildings, industry) of buildings by life cycle stage, derived following a process-based approach. (Truger et al., 2022)

Although the LCA studies were filtered by their scope regarding building elements and life cycle stages, there can still be considerable differences in details – and hence, in the results. Especially technical and

electrical equipment are often neglected in LCAs. (Hoxha et al., 2021) show significant differences between a simplified and a very detailed LCA for an office building case study. Thus, we propose to use a correction procedure to the LCA results with lacking detail in the calculations. (Hoxha et al., 2021) use an office building at a university as a case study. The detailed LCA accounts for embodied emissions that are 66% higher than the simplified version, with the largest gaps happening in life cycle stages A1-A3 (electrical and technical equipment, internal walls) and B4 (replacement of electrical and technical equipment). As the emission gap is dependent on the life cycle stage and was quantified for an office building it is not directly applicable to residential buildings as well. As multiplying simplified LCA results with low calculated emissions with a correction factor may enforce the underestimation, we propose instead to add an absolute emission amount for the relevant life cycle stages, such as technical equipment. Correcting the emission factors on the building level yields the result of 4.8 Mt CO_2-eq/a instead of 4.3 Mt CO_2-eq/a (+12%).

Finally, we can give an indication of the total annual building related emissions in Austria (see Figure 71). The operational emissions of the Austrian building stock were estimated to account for 17.1 Mt CO_2-eq/a, consisting of direct emissions of residential and service buildings, operational emissions of industry buildings (1.2 Mt CO_2-eq), and indirect emission through the supply chain, including the use of electricity and district heat (8.9 Mt CO_2-eq). The embodied emissions, estimated by the process-based LCA, add further 4.3 Mt CO_2-eq. This number is significantly higher when using the IO LCA (13.6 Mt CO_2-eq, shown in green). Since the process-based approach can underestimate the emissions, a correction factor was used to account for lacking detail in the LCA studies. With this factor, the results are closer to the IO based results with 4.8 Mt CO_2-eq. The height of the correction factor was estimated and needs further research but shows that it can close part of the emission gap between process-based and IO based LCA results.

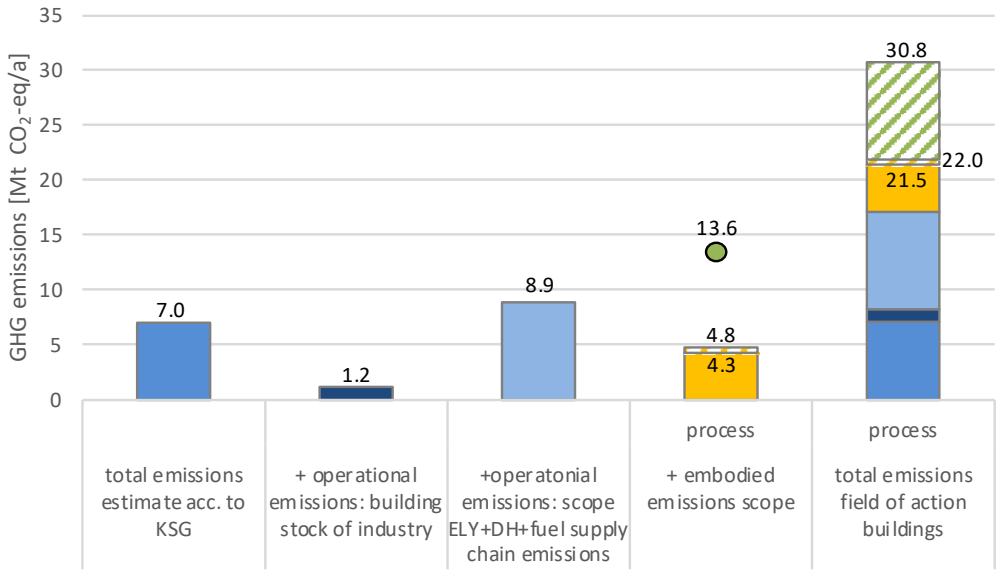

Figure 71: Composition of annual GHG emissions attributable to the Austrian field of action buildings in 2014; process: estimated by process-based LCA approach; IO: estimated by multi-regional input-output model; KSG: national climate protection law (Klimaschutzgesetz); ELY: electricity; DH: district heat. (Truger et al., 2022)

The emission estimates shown in this study indicates that the "field of action" for buildings to decrease overall GHG emissions goes beyond direct operational energy and is linked to the development in many economic sectors (e.g., industry, energy and heating sector). In this context, adopting a full life cycle perspective is crucial as it reveals important emissions "embodied" in building-related processes (e.g., material production, transport, refurbishment or end-of-life). Investigating the „field of action" for

buildings at the national level allows to identify environmental hotspots in the life cycle of buildings located in a specific country, and economic sectors most relevant to building-related emissions most.

The learnings from this study also informed the definition of the project proposal and development of the method applied in the study for supporting the development of a roadmap for the reduction of whole life embodied carbon in the EU (Le Den et al., 2023) which is conducted by the author and colleagues. The study, however, is not based on the meta-study life cycle data presented in chapters 2 to 4, but instead used an early version of the SLiCE building data model and high-resolution building LCA data as presented in chapter 7 (SLiCE building LCA: A model for life cycle analysis of buildings across scales).

Spatiotemporal resolution of life cycle information

This thesis presents and analyses whole life carbon of building using different data models and methods. Figure 72 provides a visual comparison of the spatiotemporal resolution of LCI and LCIA data in different models (i.e., chapters of this thesis).

Here it is important to distinguish the processes for establishing the respective data as they have substantial influence on the data granularity and model resolution, respectively. Two main types of data generation have been presented in this thesis: 1) Meta-analysis based on systematic review and/or mapping with consecutive data collection, and 2) Dedicated building LCA models, which use LCI input on different granularity levels to conduct LCIA and hence generate, for example, whole life carbon results.

On the one hand, the data analysed in (Röck et al., 2020b) (chapter 2) and (Röck et al., 2022c) (chapter 3) is based on systematic data collection from external sources through pre-defined data collection template with the goal of synthesizing data from multiple studies through statistical analysis (meta-analysis). For the whole life carbon meta-analysis of (Röck et al., 2020b) (chapter 2), data granularity was limited to STI:A/0, i.e., the use of aggregated whole life carbon results on building level, albeit distinguishing operational and embodied carbon. The dedicated embodied carbon meta-analysis (Röck et al., 2022c) (chapter 3) towards benchmarking advanced reporting requirements and data processing abilities, making it feasible to use and analyse LCIA data at spatiotemporal resolution STI:B/0, i.e., emission results per life cycle stage and on building level as a default option. Certain data partners were able to provide WLC data at resolution STI:B/-1, i.e., emission results by life cycle stage for different building elements. An additional advancement of this meta-analysis was the collection of material quantities for the top five building materials (by mass contribution), which data partners could select from a pre-defined list of material types and then specify quantity accordingly. However, it is important to acknowledge that in the type of meta-analysis conducted through these models, the feasible data granularity was limited mostly by the human factor, i.e., the effort required to provide the data in the predefined structure. While some data could be obtained in an automated way from pre-existing database (e.g., from CSTB, France), most of the data reporting was done manually. Future data collection for whole life carbon benchmarking should seek to further automate data exchange and reduce effort required to provide data. Alignment with the reporting standards offered by initiatives such as Level(s) (Directorate-General for Environment (European Commission), 2021; European Commission, 2017) is particularly promising. On the other hand, the SLiCE building data model (chapter 5) and its implementation for the SLiCE building LCA model (chapter 6) elaborate on modelling logic and algorithms developed within the MMG+_KULeuven building LCA tool (Allacker, 2010; Trigaux, 2017). While these tools receive similar LCI inputs, the granularity of outputs differs due to different modelling approaches and related resolution. The MMG model consists of different files (W: work sections, E: elements, B: buildings) which each provide assessment results per life cycle module (STI:C).

However, each file aggregates the spatial information on the next-lower level, to reduce computational burden of the spreadsheet-based model. This way, building level analysis can assess the contribution of building elements by life cycle module (STI:C/-1), and element level analysis can reveal the contribution of work sections by life cycle module (STI:C/-2). It is, however, not possible to assess the contribution of work sections or materials at building level (STI:C/-2; C/-3). It is one of the advances offered by the SLiCE building LCA model, to make it feasible to provide analysis across different spatial dimensions, from building to material level and everything in between. The SLiCE building life cycle assessment model also extends the temporal resolution of the MMG model with additional information on nested life cycle modules as well as on the specific times at which processes and flows take place (per year). The SLiCE building LCA model hence provides a maximum spatiotemporal resolution STI:D/-3, which can be aggregated as needed at all lower resolution levels.

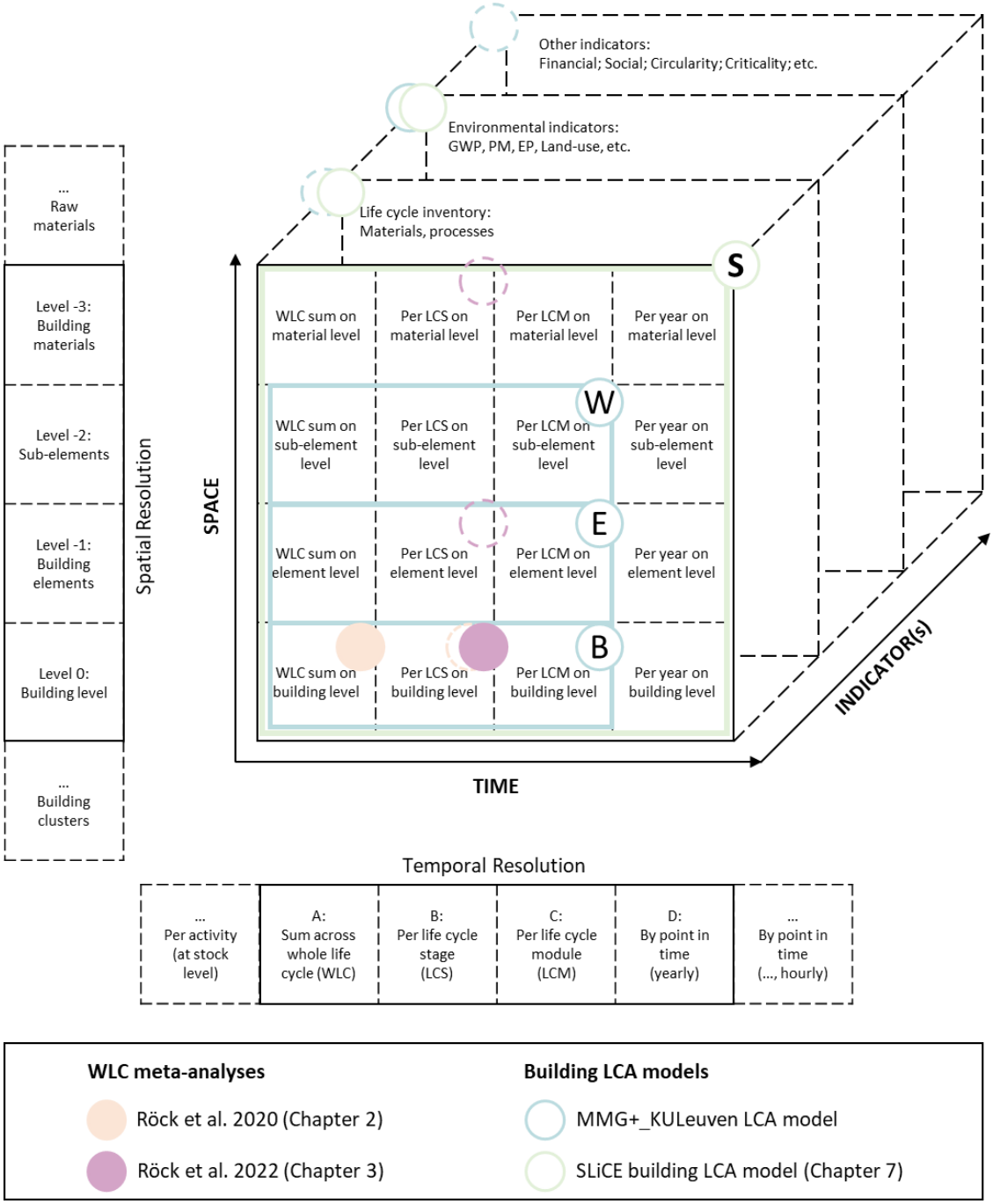

Figure 72: Comparison of spatiotemporal resolution of LCI and LCIA data in different models (chapters).

Regarding life cycle indicators, the meta-analyses of chapter 2 and 3 were limited to an analysis of whole life carbon (GWP indicator) and the documentation of energy use and material quantities (top five materials by mass). The MMG model provides a comprehensive set of LCA indicators (including but not limited to GWP) and an environmental single score (environmental cost) as well as life cycle costing data. SLiCE uses the same set of LCA indicators and elaborates with regards to providing specific information on processes as well as material inflows and outflows (by point in time). Normalization and weighting to obtain an environmental single score are not yet fully integrated in the SLiCE building LCA model but possible through the SLiCE hotspot analysis tool. Currently there is no financial data for life cycle costing linked to SLiCE, however this is an aspect for future development.

SLiCE strengths and weaknesses, opportunities and threats

An analysis of the strengths and weaknesses as well as opportunities and threats (SWOT) of the SLiCE model are presented in Table 35, particularly investigating the goal to "Support rapid decarbonization of buildings and stocks across Europe through open development and application of SLiCE". Selected aspects of this analysis are elaborated in the following sections.

Table 35: SWOT analysis for SLiCE application to support rapid decarboniuation of buildings and stocks across Europe

Goal		
"Support rapid decarbonization of buildings and stocks across Europe through open development and application of SLiCE"		
	Strengths	**Weaknesses**
	What the model does well	Areas to be improved
Internal	a. SLiCE offers an extendable solution for high resolution life cycle modelling of buildings micro to macro-scale. b. SLiCE enables analysis of high-level KPIs as well as detailed analysis of hotspots in life cycle information. c. SLICE enables consistent data structures, efficient data storing, creation, removal, update, and deletion of data. d. Most importantly, SLiCE supports analysis of indicator results explicit timing, e.g., of process and flows (per year), as well as detailed information on nested life cycle stages. e. SLiCE provides indication of mass in/out flows, and link to Technosphere flows for retrieving further information and linking to other models in the future. f. Practical application examples already showcase the potential of SLiCE for modelling comprehensive life cycle assessments. g. Existing use cases include assessment of bio-based building element solutions; whole life carbon analysis at building level; or archetype-based modelling and macro-scale scenario analysis of the EU building stock.	a. Need to streamline modelling of detailed life cycle inventories to reduce time and cost as well as complexity. b. Need to implement analytics to support analysis of existing model components/items for effective analysis and QA. c. Need to fully integrate upscaling to maintain high resolution across scale and increase flexibility in scenario modelling. d. Need to develop automated adaptation of LCA background data for easy regionalization and database upgrades.
	Opportunities	**Threats**
	Potentially beneficial factors / initiatives	Potential problems / risks / obstacles
External	a. Need of policy and decision makers to understand life cycle related carbon impact of buildings, portfolios and stocks at scale is growing due to both regulatory developments and market dynamics. b. Prevailing trade-off between increasing relevance to strategic decision-making and declining data granularity and model resolution when life cycle modelling at macro-scale.	a. Threat of perceived high level of accuracy due to high level of detail, i.e., suggesting more credibility/representativeness (BIM/GIS analogy: Level of Detail (granularity and resolution) vs. Level of Specification (robustness of a value/information)). b. Threat that higher effort and limitations in available data might hinder application as detailed modelling in SLiCE requires detailed inputs/assumptions to achieve expected high-quality outcomes (e.g., high quality

c. Existing models do not provide the required resolution and level of information offered by SLiCE.
d. Making SLiCE openly available (CC, share-alike) can support its future development and spread application for informing decision makers across Europe

inputs on building stock characterization, materialis and element build-ups in different contexts).

SLiCE-based building LCA model and building stock level analysis

The SLiCE approach aims to connect high-definition building level LCA with macro-level building stock analysis, thereby enabling an understanding of the links between building-level measures and macro-level effects, relevant to inform a deliberate development of national or transnational building stocks along climate and environmental targets – as illustrated in Figure 73.

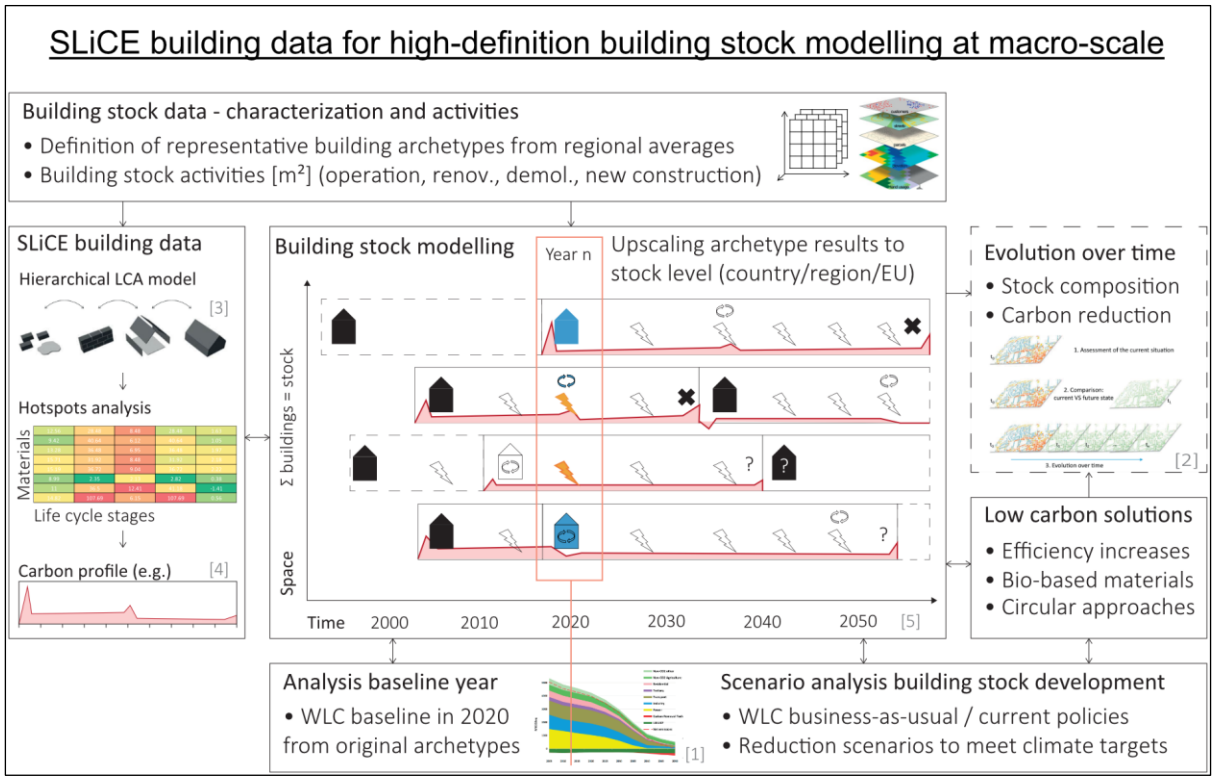

Figure 73: Illustration of SLiCE building data use for building stock modelling at macro-scale within the whole life carbon roadmap support study (Le Den et al., 2023). (Picture references: [1](European Commission (EC), 2018a), [2] (Mastrucci et al., 2017b), [3](Allacker, 2010; Trigaux, 2017), [4](Röck et al., 2020b), [5](Habert et al., 2020a))

However, while SLiCE is successfully being deployed in research projects already today, at this point, the upscaling of building level SLiCE data to building stock level is based on the manual exchange of SLiCE datasets for integration within the external building stock scenario models, developed by BPIE colleagues in the WLC roadmap study (Le Den et al., 2023). The current workflow is limited by computational abilities during upscaling (thus far using MS Power Query), requiring aggregation and a loss of granularity of SLiCE data. The interface from building to building stock level hence requires further elaboration towards an integrated modelling that utilizes the full potential of the SLiCE data model and maintains the high data granularity during upscaling. A recently started new research project will elaborate on the SLiCE model with regards to both the building level archetype modelling, moving towards an even more parametric and combinatorial modelling approach to enable investigation of a higher variety and number of archetypes, as well as regarding the upscaling to national and transnational buildings stocks, elaborating on the previous upscaling routine and developing integrations with

established building stock turnover models such as the MESSAGEix-buildings stock turnover model (STURM) (Huppmann et al., 2019; Mastrucci et al., 2020a).

Need for high-quality data inputs for building and building stock modelling

Building and building stock modelling depend on high quality data inputs to inform, for example the steps of building stock characterization, building archetype definition and modelling, as well as upscaling and scenario analysis. This is true also for SLiCE based building LCA, which can offer highly granular data and support high resolution building LCA modelling and upscaling but depends on the quality of data inputs from external sources, just like all building and building stock modelling.

Models such as SLiCE are increasingly able to support high-definition building life cycle analysis across spatiotemporal scales and, given the required inputs, will allow to move from a limited number of representative archetypes to modelling based on large numbers of real-world building cases, thereby refining building stock modelling and advancing abilities for modelling and monitoring the environmental impact of building stock development.

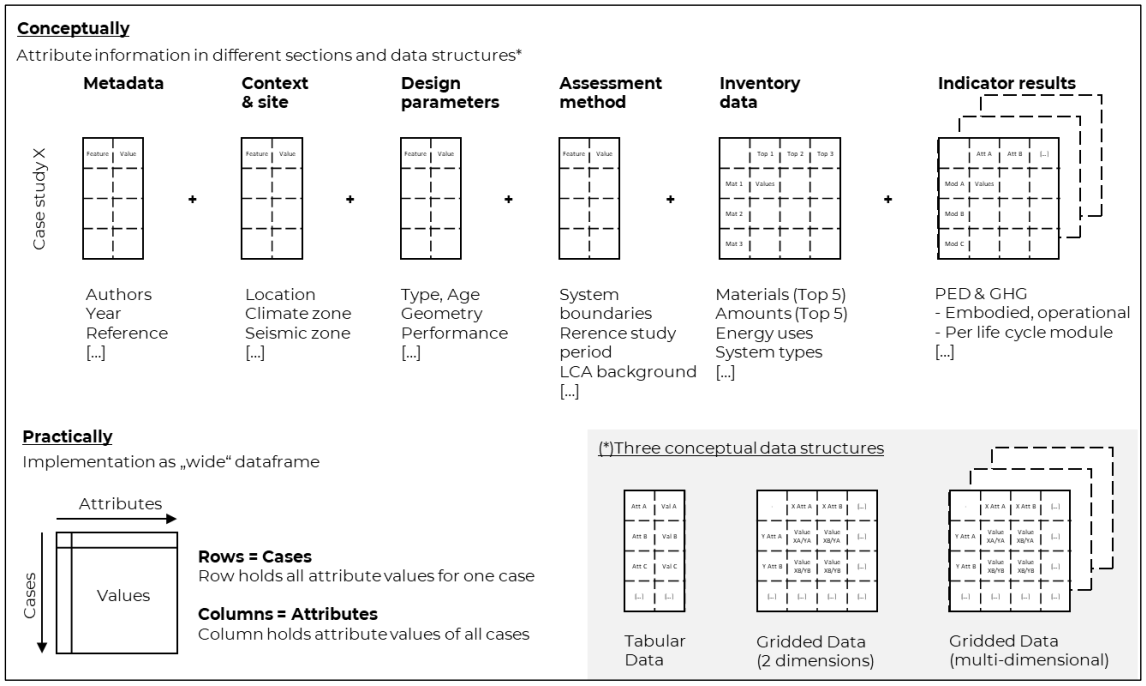

Figure 74: Conceptual logic and practical implementation of comprehensive attributes for description of the object of assessment, the building, as presented in chapter 4 (Open database on embodied and whole life carbon of buildings).

To advance not just the modelling of buildings, for example via the SLiCE building data model, but also the analysis of building data at scale (think machine learning), a comprehensive description of the object of assessment, the building, is required. To achieve a comprehensive and practical description of the building, the SLiCE data model's ability to provide high-granularity LCI and LCIA information must therefore be combined with reporting of other relevant information on the building, using for example the attributes (Figure 23) proposed in chapter 4 (Open database on embodied and whole life carbon of buildings). The Level(s) sustainability reporting framework, as the main reference for regulatory initiatives on sustainability reporting requirements in context of EU buildings, as well as the ongoing revision of the EPBD and the anticipated requirement for whole life carbon disclosure within energy performance certificates (EPCs), provide a particular opportunity to advance building life cycle data and reporting. It is clearly desirable that building datasets providing a comprehensive description of the building (Figure 74) as well as detailed LCI and LCIA data are established for an increasing

number of buildings, ideally shared openly to enable benchmarking and data-driven analysis of building performance.

Methods for modelling carbon reduction and removal strategies

A benefit related by the high level of granularity offered by SLiCE is the ability to pinpoint the energy and materials flows as well as associated environmental impacts related to different building materials, work sections or elements. This does not only enable in-depth environmental hotspots analysis, but also allows to identify parts of the building life cycle information affected by different carbon reduction strategies and their ex-post modification (i.e., change of impacts in the model data) for modelling effects of carbon reduction strategies on a given baseline building or archetype. While already useful and successfully deployed in the WLC roadmap study (Le Den et al., 2023), this approach requires further refinement in future studies for modelling carbon reduction and removal strategies with the goal of enabling modifications of the foreground inventory and consecutive re-run of the life cycle impact assessment stage. Here again, the modelling depends on respective high-quality input, in this case a sufficiently detailed description of carbon reduction and removal strategies, including not only their scope (i.e., the building types, elements, work sections and/or materials as well as life cycle stages affected), but also the impacts with regard to changes in the amount of energy or materials as well as characterized results (i.e., on the GWP indicator).

Information and documentation requirements for benchmarking

The present thesis presents two meta-analyses on the whole life carbon of buildings, i.e., the systematic collection and analysis of building life cycle data from external sources. In absence of comprehensive information and documentation requirements, the data collection introduces an interface between potentially highly detailed life cycle data from the primary model or source and the information and documentation requirements specified in the data collection template or procedure. A proposal for (minimum, standard, and advanced) information and documentation requirements is illustrated in Figure 75 based on a prioritization of attributes considering the value of the information and effort required to obtain it. The prioritization logic has also been applied to the attributes presented in chapter 4 (Open database on embodied and whole life carbon of buildings).

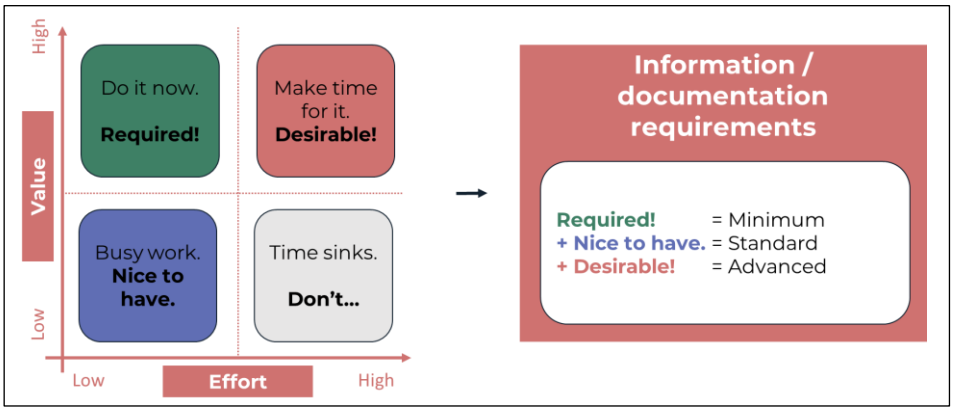

Figure 75: Prioritization of attributes for definition of information and documentation requirements (required, standard, advanced), as presented in chapter 4 (Open database on embodied and whole life carbon of buildings).

Further elaboration on the attributes and data structures for a comprehensive and harmonized documentation of building life cycle information is required to enable benchmarking of whole life carbon at scale. This is certainly also true for other sustainability performance indicators of buildings. Only with increasing quality of the datasets does it make sense to further increase the quantity of data collected. While benchmarking benefits from considering indicator results for different subsets, i.e., for all buildings of a similar type, or from a similar region, this is only useful if both high quality and

quantity of the data are ensured. The analyses presented in this study showed considerable variations even for the embodied carbon values related to the product stage (A1-3), the stage that would be most robust, as it can mostly build on measured information rather than life cycle scenarios. A further analysis of the drivers of the variation in product stage results – beyond obvious subsets such as the type of building use, the structural system, and the choice of materials – should be pursued, for example by the deployment of machine learning based methods for quantifying attribute influence on the target variable (e.g., product stage embodied carbon.)

Sufficiency and building LCA: Challenges and opportunities

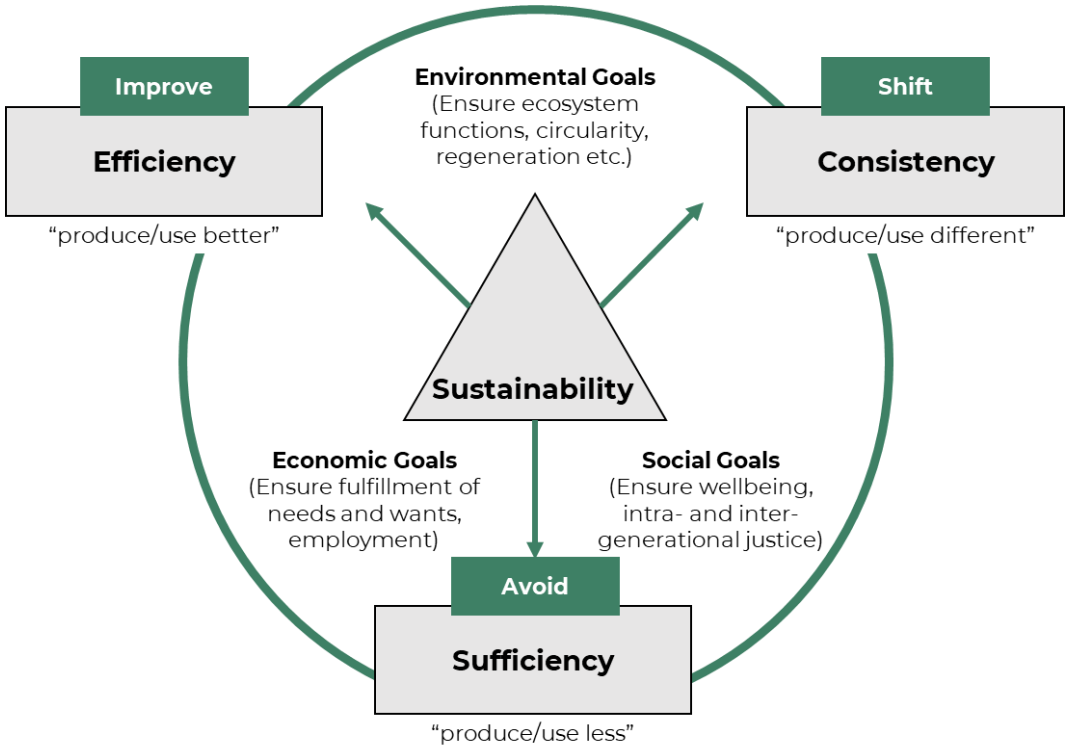

Figure 76: Dimensions and strategies of sustainability. Showing the dimensions of environmental, economic, and social goals; as well as the strategies of efficiency ("use better" / improve), consistency ("produce different" / shift), and sufficiency ("consume less" / avoid). Own figure based on (Billenstein et al., 2021)

LCA is a valuable tool for evaluating the environmental impacts and benefits of various sustainability strategies (see Figure 76), including both efficiency and consistency approaches. Efficiency strategies involve improving a building's energy performance, while consistency strategies involve shifting to alternative energy sources or materials. However, LCA encounters challenges when it comes to assessing sufficiency strategies, which are characterized as *'a set of measures and daily practices that avoid demand for energy, materials, land, and water while delivering human well-being for all within planetary boundaries'* (Intergovernmental Panel on Climate Change (IPCC), 2023a).

One of the main difficulties arises from sufficiency strategies involving a change in the "functional unit" (FU) used in LCA. The FU is a fundamental concept in LCA, and its consistency is essential for meaningful comparisons. Sufficiency strategies, such as utilizing existing building space instead of constructing new buildings or reducing floor area per capita, necessitate a change in the FU. This presents a challenge because traditional building LCAs primarily employ FUs based on building floor area rather than the number of users. To explore sufficiency-related strategies, it becomes relevant to shift the perspective in building LCA from impacts per square meter of floor area to impacts per user

(per capita) as well as to apply system expansion, to address impacts beyond the individual building and investigate building stocks and the built environment at large. However, this shift introduces various new complexities regarding the consideration of a building's quality and interactions between buildings and non-building systems. It is important to acknowledge that buildings can be of high or low quality, independent of their floor area or user capacity. Therefore, the consideration of both functional and social performance criteria is vital to ensure that sufficiency strategies genuinely deliver the intended benefits of reducing environmental pressures while promoting well-being for all within planetary boundaries.

Furthermore, a variety of sufficiency strategies for buildings (Zimmermann et al., 2023) are available to avoid energy and resource use while ensuring wellbeing for inhabitants, as illustrated in Figure 77. Beyond the previously discussed reduction of floor area per capita, sufficiency encompasses different strategies of activating, adapting, extending, or complementing existing building structures as well as the creation of new buildings, where necessary and designed in a way that delivers *'human well-being for all within planetary boundaries'*. The complex interrelations between this use of existing structures and the change in demand for new construction necessitates the previously mentioned system expansion to look beyond individual buildings as well as potentially moving from a process-based to a consequential approach at both building and building stock level.

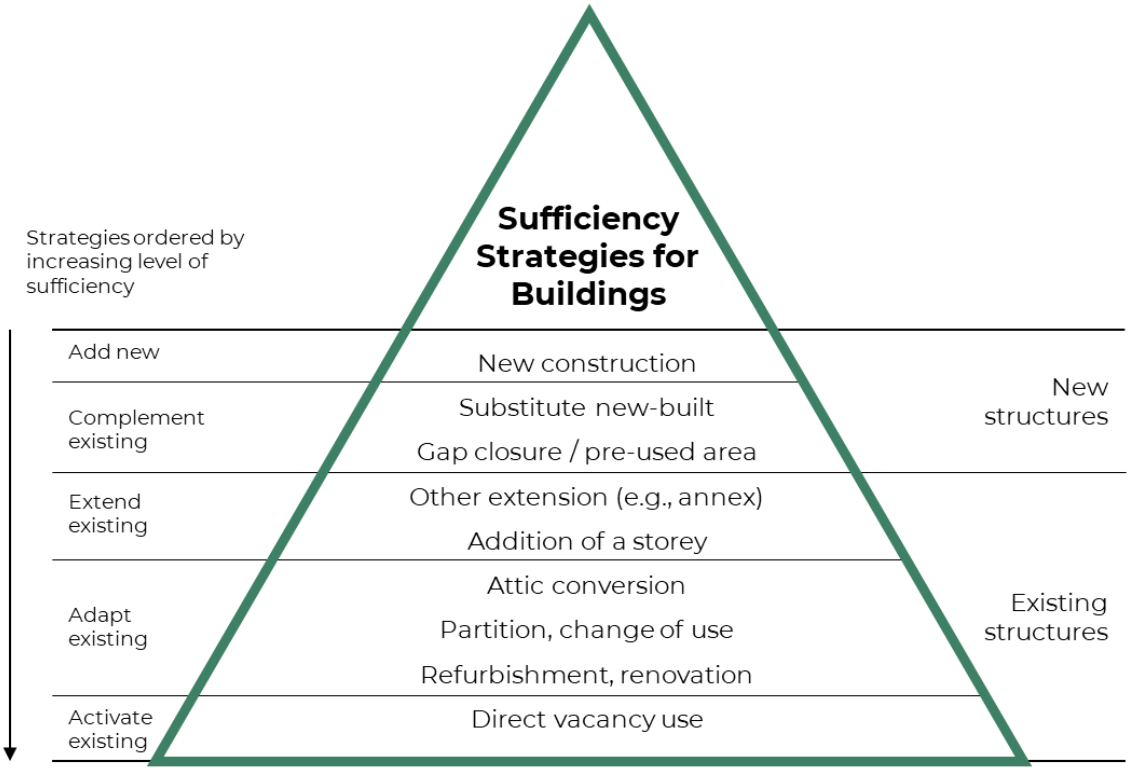

Figure 77: Sufficiency strategies for buildings, involving strategies for both new and existing structures, aimed at activating, adapting, extending, or complementing the existing, as well as adding new. Own figure building on (Billenstein et al., 2021; Zimmermann et al., 2023).

Sufficiency studies further showed that resource and energy use can be avoided in part by shifting from systems of provisioning that favour private ownership over to systems of provisioning based on public or collective ownership (Brand-Correa et al., 2020; Grubler et al., 2018; Millward-Hopkins et al., 2020). Again, this has implications for sufficiency metrics on the building level as it leads to more complex scenarios of building use and hence a potentially ambiguous, or at least more complex to establish,

functional unit in building LCA. Sufficiency and its consideration in the LCA of buildings and building stocks is therefore a particularly interesting field for further scientific inquiry.

This thesis explored the concept of sufficiency and its incorporation into the development of metrics for the whole life carbon assessment of buildings. Specifically, it proposes the use of per-capita values to gain insights into the sufficiency potential of different building types - see chapter 3 (Towards benchmarking embodied carbon of buildings in Europe). Chapter 4 (Open database on embodied and whole life carbon of buildings) presents a variety of relevant attributes for describing a building, including attributes related to its geometry and layout, as well as functional performance and use related criteria, such as the number of users. However, additional attributes will be required for describing and understanding aspects related to the wellbeing of users within a building. These can range, for example, from occupational density (i.e. the number of m² per capita), over user satisfaction due to comfort as well as users' agency and co-ownership (Hirschberg et al., 2022). Furthermore, the understanding of occupational density requires elaboration to account for differences between and temporal dynamics of residential and non-residential building use. Approaches such as full time equivalence, or the notion of population equivalence (Mirabella and Allacker, 2021) offer valuable ideas for moving forward. The development of relevant sufficiency-metrics could benefit from a combination of building LCA and building energy simulation, especially the related profiles of user presence and behaviour.

8.4. Further research

The research and outcomes presented in this thesis are humble contributions to the wide fields of sustainable construction, industrial ecology, and regenerative development research at large. Several aspects require further investigation and elaboration. A selection of topics for further research is presented in the following.

Increasing building data quality, quantity, and availability

The research presented in this thesis is heavily data-driven and as such relies on the availability of high quality data in appropriate quantities and with suitable granularity. Data on both individual buildings as well as building stocks are still scarce, especially regarding data on material use and embodied impacts such as whole life carbon. While some hopefully useful data could be established for publication in this doctoral research, closing existing data gaps is an open challenge which require further research and dedicated resources. Data needs identified include data for building stock characterization, that can provide higher detail than current statistical data. Only detailed material and energy characterization data on both existing and new buildings will allow moving from archetype-based models towards building-by-building approaches for building stock modelling at the macro-scale. The utilization of GIS and remote sensing are promising routes to further establish highly granular data on the built environment and hence support the characterization and modelling of building stocks. As not all entities and researchers will be able to apply advanced GIS and remote sensing workflows, there is also value in advancing existing archetype definition (such as from TABULA/EPISCOPE) towards the development of archetypes suitable for representing both energy and material-related characteristics for different building types and contexts. A particular topic of interest for future research is the analysis of the whole life carbon emissions per-capita. The per-capita metric deployed in the meta-analysis presented in this thesis is currently based on a simplified approach of calculating occupancy density using the estimated number of occupants. A more refined understanding of the number of users and respective full-time equivalents (Mirabella and Allacker, 2021) could help inform sufficiency oriented perspectives in future research.

Implementation of life cycle assessment and whole life carbon data

A particular potential for the generation of building level data are existing and upcoming reporting requirements regarding disclosure of the whole life carbon emission of buildings. National as well as European initiatives, such as the Level(s) Sustainability Reporting Framework offer a unique chance for harmonized reporting of buildings' sustainability performance, including regarding their environmental impact, whole life carbon, material quantity and energy use. Such data will be highly valuable to policy makers, researchers, and industry professional alike, given data will be systematically collected and published accordingly. Furthermore, initiatives such as the digital building logbook (European Commission (EC) et al., 2021; Gómez-Gil et al., 2022b), the EU Sustainable Finance Taxonomy (European Commission (EC), 2022, 2021a) and the general move towards clear corporate sustainability reporting and disclosure requirements (European Commission (EC), 2021b; Official Journal of the European Union, 2022) provide opportunities to advance the generation of building life cycle information and its use to inform strategic decision making across the building value chain in Europe and beyond. Further efforts in establishing open databases on the life cycle carbon and environmental impacts of buildings and infrastructure will be required to understand the current state and set clear decarbonization targets. Data generation or collection and benchmarking can and should take place on both the level of different building parts, such as building structures, as well as on the complete building level, to understand the contribution of different parts and stages based on comprehensive and comparable functional units.

Machine learning for building LCA and whole life carbon

The insights and data presented in this thesis lead to follow up research questions regarding the drivers of embodied carbon. Further research is needed to understand to which degree the different attributes are driving embodied life cycle emissions (Heeren et al., 2015; Lasvaux et al., 2016; Wiedenhofer et al., 2018) as well as how attribute influence differs regarding emissions from different life cycle stages (such as influence on upfront embodied carbon emissions versus influence on total whole life carbon). A potentially useful indicator in this regard is to consider material use intensity as a proxy for embodied carbon. However, even there it remains to be investigated what the quantifiable relation of building material intensity is with embodied emissions, for different building types and contexts. It will be important to understand and identify clusters of building archetypes based on material use intensity and how these differ for buildings of different type (SFH, MFH, office, etc) or country of the building. Machine learning-based methods can be applied to support the above investigations (Barros and Ruschel, 2021; D'Amico et al., 2019; Geyer and Singaravel, 2018), for example regarding attribute influence, as well as to further explore the potential to predict embodied carbon (ranges), potentially informed by the CarbEnMats buildings dataset presented in this thesis – See chapter 4 (Open database on embodied and whole life carbon of buildings). An automated estimation of whole life and embodied carbon values can also support benchmark comparison and the practical implementation of benchmarking in national governance. For example, when checking submission for building construction permits, it will be important to understand what the probable outcome for a given design project is and whether reported whole life carbon or even LCA results are plausible.

Integrating the built environment in Earth system modelling

As the climatic and ecological emergency continues to accelerate, while further increases in global construction activity are projected, there is a clear need for methods and models to assess, monitor and manage ecosystem functions (Baeten et al., 2019; Bennett et al., 2009; Chapin et al., 2009) and the environmental impacts of the dynamics of the built environment in a way that supports long-term regenerative development of both natural ecosystems and the built environment in the context of a regionalised bioeconomy (European Commission (EC), 2018b; Ivanova et al., 2017; Maes et al., 2020).

It is required to explore the nexus of built environment and ecosystem functions with the goal of understanding the problems, conceptualising solutions, and developing methods and tools for informing a regenerative development of natural and built environments. A relevant direction for further research is the development of integrated frameworks for modelling, monitoring and management of bioregional ecosystem functions and built environment dynamics to support regeneration and resilience in Earth system governance (Dooley et al., 2022; Keith et al., 2022; Steffen et al., 2018). The research and development of computational methods and tools for the environmental modelling of buildings presented in this thesis – including the use of SLiCE for the analysis of scenarios for decarbonization of the European building stock and advanced assessment of bio-based building materials (Mouton et al., 2023b; Vanoverberghe, 2022) – can be starting points for exploring such an integration.

Beyond technology: the need for social innovation and regenerative development

The methods and models presented in this thesis provide data, metrics, and methods for the environmental assessment of buildings across their life cycle. Such methods are required to inform a regenerative design of individual building tasks as well as the development of building stocks at large. However, as the application of different carbon reduction strategies shows, technological strategies and building level measures are only a part of the answer to the question of how a regenerative development of the built environment can be enabled (Attia, 2016; Blanco et al., 2022; Naboni et al., 2019; Pedersen Zari et al., 2022). It is becoming increasingly clear that beyond technological solutions for reducing the environmental footprint of products such as buildings, there is a need for demand-side measures and the thorough consideration of sufficiency principles (Andersen et al., 2019; Brejnrod et al., 2017; Grubler et al., 2018; Millward-Hopkins et al., 2020; Rao and Min, 2018; Stephan and Crawford, 2016). Further research must investigate the possibility and implications of reducing new construction rates and shifting resources and capital towards refurbishment and regenerative development of existing building stocks. Beyond aspects of whole life carbon, energy, and material use, it is a fundamental societal challenge to enable a green and socially just transformation of the built environment. Social innovations for regenerative buildings (Audretsch et al., 2022; Rebekka Hirschberg et al., 2022; Marchesi and Tweed, 2021) are needed to reduce environmental footprints of individuals as well as organisations and enable the move towards a sustainable mode for society. Quantifying perspectives such as that of building LCA, are useful and must be complemented with both quantitative and qualitative research on the social and economic implications of different carbon reduction and removal strategies in view of the necessity to move towards climate justice and post-growth economies (Bauwens, 2021; Froese et al., 2023; Hickel et al., 2022).

A variety of strategies will be required to enable the regenerative development of buildings and regenerative spatial systems at large. *"Not one or the other, but all at once"*, is one of the more common findings of sustainability studies these days when it comes to deciding on which sustainability strategies to prioritize. In that sense, one can hope that the recent increase in interest regarding strategies of sufficiency by stakeholders across science, industry and policy making will yield concrete outcomes that lead to a reduction in energy and material demand while ensuring *wellbeing for all within planetary boundaries*. In a building context, sufficiency strategies for buildings – as presented in Figure 77 – emphasize the importance of activating, adapting, extending, complementing or thoughtfully adding to the existing building stock. For both existing building adaptation as well as new building construction, low-tech and solar building design (Mouton et al., 2023b), the cascading and circular use of fast-growing bio-based materials (Churkina et al., 2020; Directorate-General for Climate Action (European Commission) et al., 2021; Mouton et al., 2023a) and certainly the use of renewable energy are imperative measures for enabling future-proof and regenerative building design fit for a challenging 21st century.

Future research is need on both technological as well as social innovation to enable a reduction of energy and material use in Global North countries to substantially and urgently reduce GHG emissions and other environmental impacts. The call for deliberate degrowth in wealthy and mature economies, such as most of the EU, and a general move beyond our economies' growth-dependency certainly has an important place in this debate (Buch-Hansen and Nesterova, 2023; Hickel, 2021; Wiedmann et al., 2020). The idea of deliberate degrowth opens up many new threads of scientific inquiry including strategies, methods and practices to enable the development towards regenerative spatial systems.

8.5. Conclusion

The doctoral research presented in this thesis addresses the pressing need for a shift towards a regenerative built environment and the role of data on the life cycle impacts of buildings in driving this shift. The research aimed to overcome limitations in building life cycle assessment (LCA) to inform policy making and regulation for reducing the climate impacts of individual buildings and building stocks. It fills research gaps related to embodied carbon in building life cycles, the metrics and methods needed for supporting European climate policy, and proposes new models for comprehensive life cycle assessment for buildings and building stocks.

The research approached the challenge from a data-oriented, technocratic perspective, recognizing the importance of data in informing decision making by policy makers and stakeholders at various levels. The data and analyses presented in this thesis aim to provide useful heuristics and rules of thumb that help both experts and laypeople understand the challenge of decarbonizing building construction and operation. Additionally, the thesis proposes advanced methods and models for modelling high-resolution life cycle information of buildings across spatiotemporal scales, thereby contributing to the development of tools necessary for informed decision making and deliberate development towards a regenerative future.

The research findings and discussions highlight that our current challenge extends beyond technological progress. The analysis of whole life carbon reduction pathways at the European scale, using the proposed SLiCE model, emphasizes the need to reduce new construction activity and prioritize the refurbishment and regenerative development of existing building stocks. It is crucial to determine which building tasks are relevant and contribute to societal well-being while minimizing carbon emissions and to do so in a democratic manner.

In summary, this doctoral research contributes to the understanding of building-related life cycle impacts, provides valuable data and metrics, and proposes new models and approaches for leveraging the life cycle modelling of buildings and building stocks to support informed decision making. It underscores the importance of addressing the climate crisis through a collective effort and emphasizes the need for immediate and transformative action with special attention to the built environment.

APPENDIX

List of acronyms

Acronym	Meaning
BIM	Building information modelling
BIPV	Building integrated photovoltaics
BSA	Building stock aggregation
CED	Cumulative energy demand
CO_2	Carbon dioxide, also referred to as 'Carbon'
EBC	[IEA] Energy in Buildings and Communities Program
EC	Embodied Carbon
EF	Environmental footprint
EPBD	Energy performance of buildings directive
EPC	Energy performance certificate
EU	European Union
GHG	Greenhouse gas (emissions)
GIS	Geographical information systems
GWP	Global warming potential
IEA	International Energy Agency
ILCD	International reference life cycle data system
I/O	Input/Output (modelling)
IPCC	Intergovernmental panel on climate change
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MFA	Material flow analysis
MFH	Multi-family house
OEF	Organization environmental footprint
PEF	Product environmental footprint
PV	Photovoltaic
RSP	Reference study period
SDG	Sustainable Development Goal(s)
SFH	Single family house
SLiCE	[Data structure and assessment models for] scalable high-definition life cycle engineering and analysis
SLR	Systematic literature review
UI	User interface
WLC	Whole Life Carbon

Glossary

Term	Meaning
Biogenic carbon (emissions)	"Carbon released as carbon dioxide or methane from combustion or decomposition of biomass or biobased products." (Intergovernmental Panel on Climate Change (IPCC), 2023b)
Carbon budget	"Refers to two concepts in the literature: (i) an assessment of carbon cycle *sources* and *sinks* on a global level, through the synthesis of evidence for *fossil fuel* and cement emissions, emissions and removals associated with *land use* and *land-use change*, ocean and natural land sources and sinks of *carbon dioxide (CO2)*, and the resulting change in atmospheric CO2 concentration. This is referred to as the global carbon budget; (ii) the maximum amount of cumulative net global *anthropogenic* CO2 emissions that would result in limiting *global warming* to a given level with a given probability, taking into account the effect of other anthropogenic climate *forcers*. This is referred to as the Total Carbon Budget when expressed starting from the *pre-industrial* period, and as the remaining carbon budget when expressed from a recent specified date." (Intergovernmental Panel on Climate Change (IPCC), 2023b)
Climate change	"A change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the United Nations Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: 'a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods'. The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition and climate variability attributable to natural causes." (Intergovernmental Panel on Climate Change (IPCC), 2023b)
Carbon dioxide (CO2)	"A naturally occurring gas, CO_2 is also a by-product of burning fossil fuels (such as oil, gas and coal), of burning biomass, of land-use changes (LUCs) and of industrial processes (e.g., cement production). It is the principal anthropogenic greenhouse gas (GHG) that affects the Earth's radiative balance. It is the reference gas against which other GHGs are measured and therefore has a global warming potential (GWP) of 1." (Intergovernmental Panel on Climate Change (IPCC), 2023b)
Carbon dioxide removal (CDR)	"*Anthropogenic* activities removing *carbon dioxide (CO_2)* from the *atmosphere* and durably storing it in geological, terrestrial, or *ocean* reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical CO_2 *sinks* and direct air carbon dioxide capture and storage (DACCS) but excludes natural CO_2 *uptake* not directly caused by human activities." (Intergovernmental Panel on Climate Change (IPCC), 2023b)
Carbon footprint	"Measure of the exclusive total amount of emissions of carbon dioxide (CO2) that is directly and indirectly caused by an activity or is accumulated over the

	lifecycle stages of a product (Wiedmann and Minx, 2008).” (Intergovernmental Panel on Climate Change (IPCC), 2023b)
Carbon neutrality	“Condition in which anthropogenic carbon dioxide (CO2) emissions associated with a subject are balanced by anthropogenic CO2 removals. The subject can be an entity such as a country, an organisation, a district or a commodity, or an activity such as a service and an event. Carbon neutrality is often assessed over the lifecycle including indirect (‘scope 3’) emissions, but can also be limited to the emissions and removals, over a specified period, for which the subject has direct control, as determined by the relevant scheme.” (Intergovernmental Panel on Climate Change (IPCC), 2023b)
Carbon intensity	“The amount of emissions of carbon dioxide (CO2) released per unit of another variable such as gross domestic product (GDP), output energy use or transport.” (Intergovernmental Panel on Climate Change (IPCC), 2023b)
Climate justice	“Justice that links development and human rights to achieve a human-centred approach to addressing climate change, safeguarding the rights of the most vulnerable people and sharing the burdens and benefits of climate change and its impacts equitably and fairly (MRFCJ, 2018).” (Intergovernmental Panel on Climate Change (IPCC), 2023b)
Decarbonization	“Human actions to reduce carbon dioxide emissions from human activities.” (Intergovernmental Panel on Climate Change (IPCC), 2023b)
Earth system model (ESM)	“A coupled *atmosphere*–ocean general circulation model (AOGCM) in which a representation of the *carbon cycle* is included, allowing for interactive calculation of atmospheric *carbon dioxide (CO2)* or compatible emissions. Additional components (e.g., atmospheric chemistry, *ice sheets*, dynamic vegetation, nitrogen cycle, but also urban or crop models) may be included.” (Intergovernmental Panel on Climate Change (IPCC), 2023b)
Embodied carbon	The term ‘embodied carbon’ in this thesis is synonymous to the more accurate term ‘embodied GHG emissions’. Both refer to the GHG emissions, expressed as CO_2 equivalents ($kgCO_2e$), related to the material-related process-emissions from production, use, and end-of-life processing of building materials and construction products. The term ‘embodied emissions’ is commonly used in the field of sustainable construction and in line with relevant related standards, such as EN 15804 and EN15978. See the meaning of ‘embodied [emissions, water, land]’ for the general definition of embodied (sometimes also called ‘embedded’) environmental impacts according to the IPCC.
Embodied (embedded) [emissions, water, land]	“The total emissions [water use, *land use*] generated [used] in the production of goods and services regardless of the location and timing of those emissions [water use, land use] in the production process. This includes emissions [water use, land use] within the country used to produce goods or services for the country’s own use, but also includes the emissions [water use, land use] related to the production of such goods or services in other countries that are then consumed in another country through imports. Such emissions [water, land] are termed ‘embodied’ or ‘embedded’ emissions, or in some cases, (particularly with water) as ‘virtual water use’ (Davis and Caldeira, 2010; Allan, 2005; MacDonald et al., 2015).” (Intergovernmental Panel on Climate Change (IPCC), 2023b)
Equivalent carbon dioxide (CO_2) emission (CO_2e)	“The amount of carbon dioxide (CO2) emission that would have an equivalent effect on a specified key measure of climate change, over a specified time horizon, as an emitted amount of another greenhouse gas

	(GHG) or a mixture of other GHGs. For a mix of GHGs it is obtained by summing the CO2-equivalent emissions of each gas. There are various ways and time horizons to compute such equivalent emissions (see greenhouse gas emission metric). CO2-equivalent emissions are commonly used to compare emissions of different GHGs, but should not be taken to imply that these emissions have an equivalent effect across all key measures of climate change." (Intergovernmental Panel on Climate Change (IPCC), 2023b)
Greenhouse gases (GHGs)	"Gaseous constituents of the *atmosphere*, both natural and *anthropogenic*, that absorb and emit radiation at specific wavelengths within the spectrum of radiation emitted by the Earth's surface, by the atmosphere itself, and by clouds. This property causes the *greenhouse effect*. Water vapour (H_2O), *carbon dioxide (CO_2)*, *nitrous oxide (N_2O)*, *methane (CH_4)* and *ozone (O_3)* are the primary GHGs in the Earth's atmosphere. Human-made GHGs include *sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs)*, *chlorofluorocarbons (CFCs)* and *perfluorocarbons (PFCs)*; several of these are also O_3-depleting (and are regulated under the *Montreal Protocol*)." (Intergovernmental Panel on Climate Change (IPCC), 2023b)
Models	"Structured imitations of a system's attributes and mechanisms to mimic the appearance or functioning of systems, for example, the climate, the economy of a country, or a crop. Mathematical models assemble (many) variables and relations (often in a computer code) to simulate system functioning and performance for variations in parameters and inputs." (Intergovernmental Panel on Climate Change (IPCC), 2023b)

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Since 2018	**Co-Founder** wohnlabor.at, Vienna/Graz, Austria
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2012-2016	**BIM/VDC Engineer** Markus Pernthaler Architekten ZT GmbH, Graz, Austria
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PUBLICATIONS

International journal articles (peer-reviewed)

- Mouton L, Allacker K, **Röck M**. Environmental Potentials of Bio-based Construction Materials - Life Cycle Assessment of Regenerative Design Strategies (1/2). Energy and Buildings, 2022. DOI: https://doi.org/10.1016/j.enbuild.2022.112767
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“Our task is to make trouble,
to stir up potent response to devastating events,
as well as to settle troubled waters
and rebuild quiet places.”

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Donna J. Haraway