Advancing Low-Emission Urban Design Through Parametric Modelling and Life Cycle Assessment

Mariusz Hermansdorfer[1,2], Christian Oettinger[1], Hans Skov-Petersen[2], Pia Fricker[3], Kristoffer Negendahl[4]

[1]Henning Larsen Architects, Copenhagen/Denmark · mrhe@henninglarsen.com
[2]University of Copenhagen, Copenhagen/Denmark
[3]Aalto University, Helsinki/Finland
[4]Technical University of Denmark, Lyngby/Denmark

Abstract: This research paper presents the development and application of Urban Decarb, a parametric tool based on Life Cycle Assessment (LCA) designed to integrate carbon knowledge into the early stages of urban development to guide low-emission design. By modelling key components of urban fabric and utilizing the visual programming environment of Grasshopper, Urban Decarb provides a dynamic platform for comparing the carbon footprint of various urban design scenarios. Case studies from Fælledby and Aarhus Sydhavn (DK) illustrate the tool's utility, showing significant reductions in Global Warming Potential (GWP) through material innovation, reuse of existing infrastructure, and holistic design strategies. A novel approach introduced in this study is the use of *carbon goggles*, a conceptual visualization method aiding in identifying high-carbon elements within existing urban infrastructure, thus informing sustainable redevelopment strategies. These insights reflect the importance of incorporating sustainability from the outset of urban planning to create low-carbon cities. The paper calls for integrating such tools into broader urban planning and policy-making processes, underscoring the necessity of multidisciplinary collaboration for the advancement of urban sustainability.

Keywords: Decarbonization, urban planning, Life Cycle Assessment

1 Introduction

Life Cycle Assessment (LCA) provides a methodology to evaluate environmental emissions over a product or system's full lifecycle from raw material extraction, production, construction, use, maintenance, and end-of-life stages (ISO 14040) (Fig. 2). While LCA is commonly utilized to assess individual buildings, few computational tools and standardized methods exist to evaluate entire urban areas, especially during early planning phases when impactful design decisions are made but uncertainties are high (SHARIFI & MURAYAMA, 2013). Developing ways to integrate LCAs with urban design can provide data-driven guidance to reduce emissions from district-scale development projects.

This research aims to advance low-emission urban design through developing an LCA-based parametric tool called Urban Decarb that integrates carbon knowledge into the early design stages of urban development projects. Urban Decarb models the embodied carbon (from materials) and operational carbon (from energy use) emissions of key urban components including buildings, parking facilities, roads, bridges, green spaces, water systems, and energy systems. The tool is developed using the visual programming language Grasshopper, enabling integration with the 3D modeling software Rhinoceros commonly used by urban designers and architects. Customizable parameters relate emissions factors to geographic and geometric input data extracted from digital urban models. Case studies of a residential neighborhood in Copenhagen (DK) and a business district in Aarhus (DK) help validate the proposed methodology.

Journal of Digital Landscape Architecture, 9-2024, pp. 858-872. © Wichmann Verlag, VDE VERLAG GMBH · Berlin · Offenbach. ISBN 978-3-87907-752-6, ISSN 2367-4253, e-ISSN 2511-624X, doi:10.14627/537752080.

2 Literature Review

Previous studies have highlighted that urban areas have a significant environmental impact, with cities responsible for over 70% of global CO2 emissions (C40 Cities, 2018). Buildings account for 35% of total annual global CO_2-eq emissions, of which building materials account for 8%, and building operations account for 27% (ARCHITECTURE 2030, 2024). However, cities represent intricate, dynamic systems where the interplay between buildings, transportation, infrastructure, public spaces, socioeconomic activities, and governance extends beyond mere numerical contributions to CO2 emissions. This interconnectivity shapes the overall urban carbon footprint, with each element not only contributing individually but also influencing others in a complex web of interactions (Fig. 1). For instance, the design and density of buildings affect transportation needs and energy consumption patterns, while governance policies can drive or hinder the adoption of sustainable practices across sectors. Understanding these systemic interactions is crucial for developing comprehensive strategies aimed at reducing the urban carbon footprint, necessitating a holistic approach that considers the multifaceted nature of urban systems and their interdependencies (ERICKSON & TEMPEST 2014).

Table 1: Elements and contributors for the various urban categories after LOTTEAU et al.

Categories	Buildings (B)	Open spaces (OS)	Networks (N)	Mobility (M)
Elements	- Buildings	- Roads - Sidewalks - Parking - Green spaces	- Electricity network - Water network - Wastewater network - Gas network - District heating network	- Passenger car - Train - Bus
Contributors	- Construction materials - Construction waste - Maintenance materials - Maintenance waste - Heating - Cooling - Domestic hot water - Ventilation - Specific electricity - Cooking - Drinking water - Domestic wastes - Wastewater - Demolition waste	- Construction materials - Construction waste - Maintenance materials - Maintenance waste - Public lighting - Water for maintenance - Public wastes - Demolition wastes	- Construction materials - Construction materials - Maintenance materials - Maintenance waste - Demolition waste	- Vehicle manufacturing - Daily mobility

While LCA is an established method used to calculate building-related carbon emissions, there is no standard approach to assessing urban-scale emissions, especially during early planning phases. To measure and compare the environmental impacts of products or systems on a common basis, the term *functional unit* is commonly used (EN15978 2011). When juxtaposing the environmental impact of two different building designs, the functional unit might be defined as *the environmental impact per square meter of living space over a 50-year lifespan* (HAUSCHILD 2018).

LOTTEAU et al. (2015) reviewed neighborhood-scale LCA studies and found differing boundaries, methods, and functional units demonstrating a lack of standardization. DAVILA & REINHART (2013) concluded that urban LCA tools need to better integrate with design workflows. As urban form influences building energy use, transportation needs, and infrastructural demand, modeling urban areas as whole systems can guide low-carbon planning (RAMASWAMI et al. 2012).

Parametric LCA tools show promise in linking urban design to emissions knowledge. Models based on GIS and BIM data facilitate rapid computation of LCA results relevant to early design decisions. Coupling LCA with generative design has also been shown to optimize low-carbon structural systems (DE WOLF et al., 2020). Recently, tools like *Tally* and *Sustrans* have demonstrated integrating embodied carbon data into BIM workflows (MONCASTER et al. 2019). However, a review by POMPONI et al. (2021) concluded better integration is needed between urban design tools, sustainability assessments, and optimization processes.

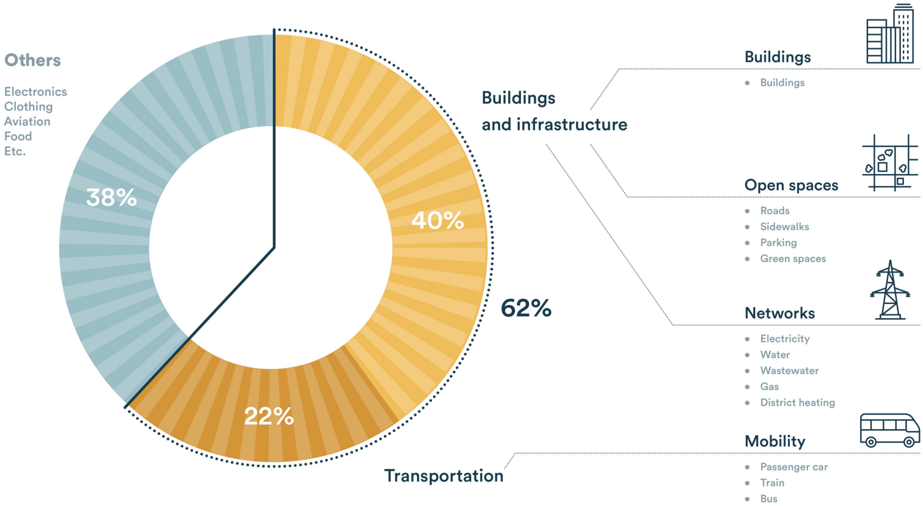

Fig. 1: Annual global carbon emissions matched with the element categories proposed by LOTTEAU et al. 2015. Buildings, infrastructure, and transportation constitute 62% of all carbon emissions.

3 Methodology

3.1 Functional Unit and System Boundaries

The methodology proposed in this research is designed to facilitate the integration of urban life-cycle assessment (LCA) into the early stages of urban development planning. Utilizing a streamlined process based LCA approach tailored for the neighborhood scale, the research introduces a multi-dimensional functional unit that encapsulates a comprehensive view of the environmental impacts. It includes total emissions, emissions per unit floor area, and emissions per inhabitant calculated over a 50 or 80-year lifespan, thus balancing environmental assessment with spatial and social considerations (LOTTEAU et al. 2015; FAMIGLIETTI 2022).

The system boundaries are set to include the primary components that constitute the urban fabric, specifically targeting buildings, parking systems, roads, green spaces, and associated infrastructure (Table 1). The life-cycle stages are delineated according to Danish regulations, (BR18), which ensures comprehensive coverage from material production, construction, and use/operation to maintenance and eventual end-of-life scenarios (Fig. 2).

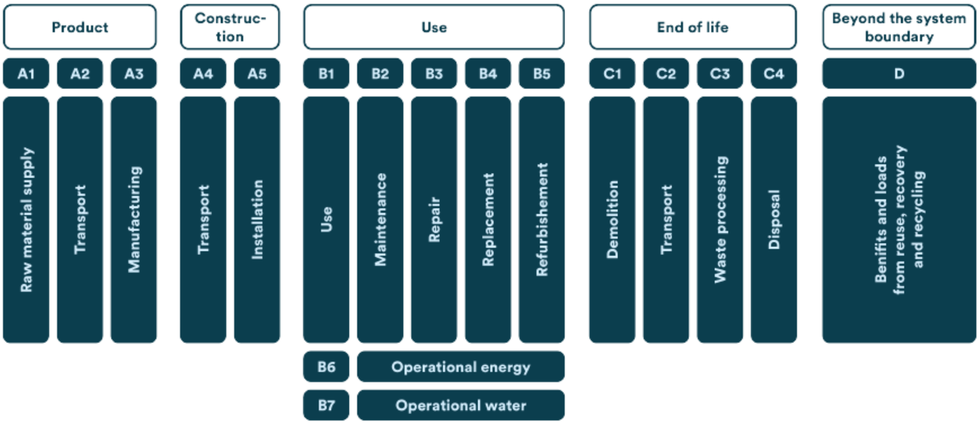

Fig. 2: Life-cycle stages according to EN 15978. Danish regulations include A1-A3, B4, B6, C3-C4, with A4-A5 being currently optional

3.2 Data Collection and Prioritization

The primary source of data for LCA are Environmental Product Declarations (EPDs). An EPD is a standardized document that provides transparent and comparable information about the life-cycle environmental impact of products. They are based on a detailed LCA, and typically follow specific standards (such as the *ISO 14025* and *EN 15804*) to ensure consistency and comparability. They include information on the environmental impacts of a product, such as resource consumption (water, energy, materials), emissions to air, water, and soil, waste generation, and other aspects like potential impacts on global warming, ozone depletion, water pollution, and more.

In the data collection process for Urban Decarb, industry-specific data and their relevance concerning geographical representation were prioritized. Thus, local industry-specific Danish data sources, including some datasets from *EPD Danmark*, are preferred, with supplemental data drawn from the regional generic European database *Ökobaudat* (2022) when necessary. For open spaces, the Danish *InfraLCA* infrastructure database provides the foundational data, complemented by detailed landscape carbon sequestration figures to assess the environmental benefits of urban greenery (Tozan 2022).

3.3 Computational Workflow

The computational workflow is centered around the Rhino/Grasshopper modeling environment, leveraging the Grasshopper plugin for its versatility in handling geodata and its capacity for direct integration with the design processes. The LCA calculations are executed through Grasshopper components designed to be adaptable to various project-specific requirements. These components are tasked with importing geospatial data, assigning emissions factors to building elements, calculating total emissions, and facilitating scenario comparisons through generated charts. This modular approach allows for seamless integration with different design workflows and ensures that the tool can be tailored to diverse urban development projects.

3.4 Energy and Structural Modeling

Operational energy is modeled via the Dragonfly plugin for Grasshopper (DRAGONFLY 2024), which abstracts complex 3D geometries into manageable 2D floor segments, each characterized by their dominant functional usage. This abstraction is further refined to account for the urban heat island effect through the utilization of localized weather data. Additionally, the inclusion of building-integrated photovoltaics within the model exemplifies the incorporation of renewable energy features in urban planning.

For material quantification, the methodology employs direct extraction techniques from the Rhino model complemented by generative structural analysis, as detailed by ROBATI et al. (2021). The assessment of existing building stocks incorporates replacement factors, enabling a comparative analysis between renovation, transformation, and new construction options. Building life-cycle extension is achieved by integrating design parameters that enhance flexibility and adaptability, promoting sustainable long-term use.

3.5 Interface and Tool Refinement

The Urban Decarb tool features a user-friendly interface that visualizes LCA outputs, facilitating clear communication of results. Continuous feedback loops with urban designers and iterative design simulations are integral to the tool's development, ensuring it remains responsive to the evolving needs of urban sustainability.

Through this methodology, the research aims to provide urban planners and architects with an accessible, robust tool for making informed design decisions that contribute to the reduction of carbon footprints in urban development projects. As an example, Urban Decarb employs a novel approach to data visualization – *carbon goggles*, wherein carbon emissions data are mapped onto a three-dimensional model of the urban development project, allowing users to visually identify hotspots of high emissions within specific components or areas of the project (Fig. 6). This feature enables urban designers and architects to immediately understand the environmental impact of their designs and make informed decisions to optimize for lower emissions.

3.6 Comparison with Existing LCA Tools

The Urban Decarb tool is positioned within the landscape of LCA software as a specialized solution for urban scale assessments. When juxtaposed with existing tools, such as *One Click LCA* (ONE CLICK LCA 2024) and *Athena Impact Estimator for Buildings* (IMPACT ESTIMATOR 2024), which predominantly cater to building-specific evaluations, Urban Decarb differentiates itself by addressing the broader scope of urban planning. This includes the ability to assess communal and infrastructural components such as roads and green spaces, which are often overlooked in traditional building-focused LCA tools.

While above mentioned tools may provide detailed analyses for individual buildings, Urban Decarb extends the assessment to the neighborhood level, embracing the complexity and diversity of urban environments. This is facilitated by its integration with Rhino/Grasshopper, providing a flexible and dynamic modeling platform that is closely aligned with the design process, as opposed to a static, standalone software environment.

Furthermore, the tool's emphasis on local and regional data sources ensures a higher degree of specificity and relevance to the Scandinavian context, which is not always available in more global LCA databases. This regional focus is vital for the accuracy of LCAs, given the significant variations in construction practices, material availability, and regulatory environments across different geographies.

4 Case Study: The Fælledby Neighborhood

4.1 Comparative Scenario Analysis

Utilizing Urban Decarb, a detailed comparative analysis was conducted for Fælledby, an 18-hectare residential development (Fig. 3) within a 223-hectare nature reserve of Amager Fælled in Copenhagen, Denmark. To maintain the natural character, over half the site will remain undeveloped. The study aimed to assess the carbon impact of two divergent construction methodologies: the *Baseline* scenario involving traditional concrete and brick materials, and the *Timber* scenario focusing on sustainable timber framing and Cross Laminated Timber (CLT).

4.2 Scenario Setup and Description

Baseline Scenario (Concrete and Brick Construction):

This scenario represents the conventional construction approach, using materials commonly employed in urban developments. It includes the use of concrete for foundational structures and brickwork for walls and facades. The assumptions in this scenario are based on standard practice, where end-of-life considerations often involve demolition and material disposal without significant recycling or reuse.

Timber Scenario (Timber Framing and CLT):

The alternative scenario posits a forward-thinking construction process utilizing timber as the core structural material. Timber framing and CLT are considered for their carbon sequestering capabilities during the growth of the timber, providing a natural offset for carbon emissions during the production phase. This scenario also considers the different pathways for end-of-life treatment, including potential reuse and recycling of timber materials.

Fig. 3: The Fælledby masterplan in Copenhagen by Henning Larsen Architects, with approximately 2.000 housing units accommodating 5.000 inhabitants on 18 ha

4.3 Results Analysis

The comparative analysis revealed that the *Timber* scenario offered a 34% reduction in the life-cycle Global Warming Potential (GWP) per square meter compared to the *Baseline* scenario (Fig. 4). The primary differences between the two design options emerged in the production phase (A1-A3) and the end-of-life phase (C3-C4) (Fig. 5). Across scenarios, buildings contributed to more than 97% of the overall neighbourhood's carbon footprint. Landscaping including unmaintained meadows provided relatively minor carbon sequestration.

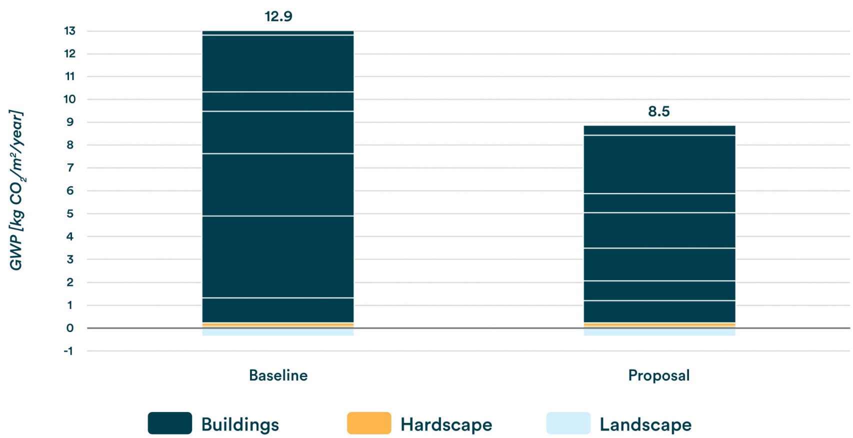

Fig. 4: Comparison of GWP of various urban elements for Fælledby baseline and proposal

Production Phase (A1-A3):

The *Timber* scenario showcased a significant decrease in carbon emissions due to the lower impact of timber production and the inherent carbon storage within the timber. The *Baseline* scenario, with its reliance on concrete and brick, showed higher initial carbon emissions due to the energy-intensive production processes.

End-of-Life Phase (C3-C4):

Conversely, the *Timber* scenario indicated a potential increase in end-of-life emissions due to the assumptions about disposal and recycling practices for timber (Fig. 5). These assumptions are critical as they reflect the current waste management practices and highlight the need for improved end-of-life strategies for timber products.

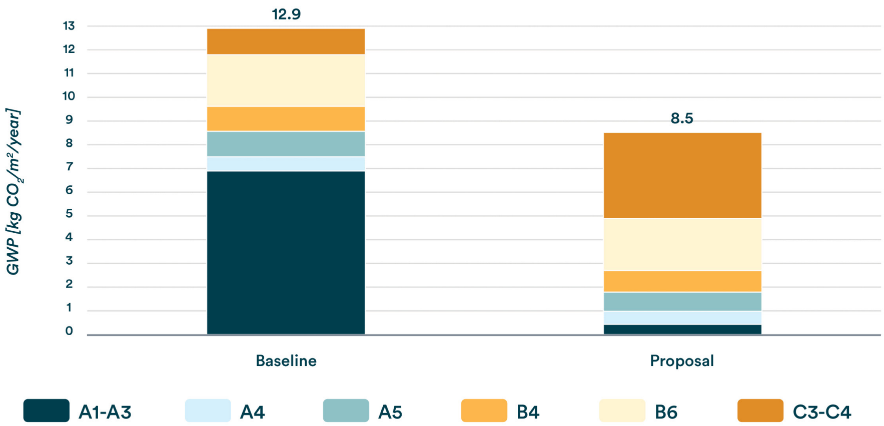

Fig. 5: Comparison of GWP of various lifecycle stages for Fælledby baseline and proposal

5 Case Study: Aarhus Sydhavn

5.1 Carbon Goggles

A similarly comprehensive comparative analysis was performed on Aarhus Sydhavn using Urban Decarb. Spanning over a 5-hectare plot, it is an industrial area positioned near the heart of Aarhus, Denmark. The site is earmarked for a significant transformation from a predominantly low-rise industrial zone to a dense urban business district.

The initial phase of the study began with an innovative approach – viewing the existing infrastructure through c*arbon goggles* (Fig. 6). This metaphorical lens offered a clear visualization of the site's existing embodied carbon footprint, providing crucial insights into which parts of the industrial area were the most carbon intensive. This step was pivotal in prioritizing which elements should be targeted for transformation rather than demolition. It is rooted in the principle that retaining and repurposing existing structures can often be more sustainable than building anew, due to the embodied carbon already present in the materials and construction. Therefore, the *carbon goggles* approach not only informed the subsequent scenario analysis but also set the foundation for a more nuanced and environmentally conscientious strategy for urban redevelopment.

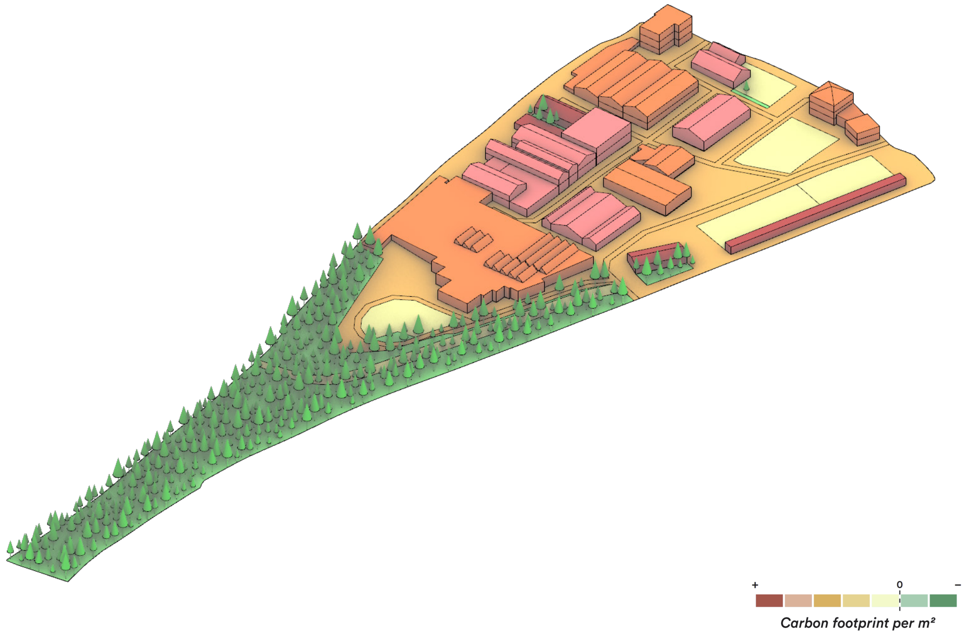

Fig. 6: *Carbon goggles* color-code the existing site elements according to their carbon emissions per square meter spanning from +25 to -5 kg $CO_2/m^2/y$

5.2 Scenario Analysis

Subsequently, three scenarios were developed to assess the sustainability of different development strategies and understand their environmental impacts: *Conventional*, *Transformation*, and *Transformation + Biogenic* (Fig. 7).

Conventional serves as the baseline, representing typical urban development practices. It involves the construction of new buildings predominantly using concrete and brick, without the transformation of existing structures. It does not prioritize the reuse of the existing infrastructure, and parking is provided both above and below ground. Moreover, in this scenario, existing trees and landscapes are removed to make way for the new development.

In contrast, the *Transformation* scenario seeks to integrate sustainability into the redevelopment process. While it also involves constructing buildings with concrete and brick, it diverges from the *Conventional* by incorporating the transformation of existing buildings wherever possible, thus preserving the embodied energy and materials. The infrastructure is maintained rather than replaced, reducing the environmental impact associated with constructing new networks. This scenario also modifies parking solutions, exclusively utilizing aboveground structures, and importantly, it preserves all existing trees and landscape, which can offer carbon sequestration benefits.

The *Transformation + Biogenic* scenario builds upon the principles of the *Transformation* scenario by incorporating biogenic materials into the building process. This approach introduces a hybrid model that combines the transformation of existing buildings with the construction of new structures using materials like timber framing and CLT, which are known for their lower carbon footprint and carbon sequestration capabilities. Similar to the *Trans-*

formation scenario, this option maintains the existing infrastructure and landscape, but it significantly lowers the carbon footprint by leveraging biogenic materials.

While all scenarios engage with the existing urban fabric of Aarhus Sydhavn, they differ markedly in their approach to materials, building transformation, infrastructure use, parking solutions, and landscape preservation. These differences are critical in determining the overall environmental footprint, with the *Transformation + Biogenic* scenario likely offering the most significant reductions in carbon emissions, as evidenced by the projected 34% reduction in GWP compared to the baseline.

Fig. 7: Three design scenarios for the Aarhus case study illustrating how various design strategies influence the overall carbon footprint

6 Insights and Implications for Design Approach

The Fælledby case study emphasizes the substantial environmental advantages of innovative construction methods, where the use of biogenic materials such as timber framing and CLT in the *Timber* scenario led to a remarkable 34% reduction in life cycle GWP in comparison to the conventional use of concrete and brick. This reduction not only reflects a decrease in immediate carbon emissions during the production phase but also leverages the long-term benefits of carbon sequestration inherent in timber, thereby enhancing the sustainability of the buildings throughout their life cycle.

In the Aarhus Sydhavn study, the strategy of assessing the site through *carbon goggles* (Fig. 6) allowed for a targeted approach towards sustainability, emphasizing the renovation and adaptation of pre-existing structures over demolition and new construction. This approach, coupled with the implementation of biogenic materials and the conservation of natural landscapes in the *Transformation + Biogenic* scenario, culminated in a notable decrease in GWP. The preservation and integration of existing green areas further contribute to the ecological resilience of the urban landscape, adding another layer of environmental benefit and illustrating the comprehensive nature of sustainable urban transformation.

From these case studies, several implications for the wider design domain were identified:

1) **Material Innovation:** There is a clear need to integrate sustainable materials such as timber into urban development to harness their environmental benefits. This also calls for designers to be informed about the life cycle impacts of the materials they choose.
2) **Existing Infrastructure Utilization:** The transformation of existing buildings and infrastructure can be more sustainable than new construction due to the embodied carbon already present. This approach can be integral in reducing the environmental impact of redevelopment projects.
3) **Holistic Design Strategies:** Design approaches should account for the entire life cycle of the development, from material production to end-of-life scenarios. This holistic view encourages the consideration of future recycling and reuse, which can further reduce the carbon footprint.
4) **Scenario Analysis as a Planning Tool:** Using tools like Urban Decarb for scenario analysis can guide decision-making processes in urban planning by comparing the potential impacts of different design and development pathways.

These insights suggest that sustainable urban design is not solely about choosing the right materials but also about reevaluating existing practices and infrastructure with a view toward transformation and reuse. By applying lessons from these case studies, designers and urban planners can make informed decisions that significantly reduce the environmental impact of development while creating resilient and sustainable urban spaces.

7 Discussion

7.1 Benefits of Urban Decarb

Urban Decarb represents a significant advancement in integrating environmental considerations within the urban design process. By incorporating parametric life-cycle assessments within customizable 3D urban modelling platforms, the tool enables designers to embed carbon awareness at the inception of the planning phase. At this early stage, despite the presence of high uncertainties, crucial decisions about the urban form, density, infrastructure, and material application are made. The capacity of Urban Decarb to provide rapid evaluations of emissions impacts introduces a quantitative dimension to decision-making processes traditionally dominated by qualitative considerations. This evidence-based approach prompts a re-evaluation of conventional design priorities, positioning sustainability as a foundational element of urban aesthetics and functionality.

7.2 Limitations and Areas for Improvement

Despite its utility, the application of LCA to neighbourhood-scale planning is not without challenges. One of the most significant limitations is the availability of reliable and geographically specific emissions data, which is essential for the accuracy of LCA results. Urban areas are characterized by complex, dynamic changes that occur over extended periods, presenting difficulties for the typically static boundaries applied in conventional LCA frameworks (SHARIFI & MURAYAMA, 2015).

To enhance the Urban Decarb tool, the integration of predictive scenario modelling could offer a more dynamic and flexible approach to account for the spatiotemporal variations inherent in urban development. Furthermore, the potential of automated optimization algorithms remains underutilized; these algorithms could serve as powerful instruments in steering design decisions towards lower emissions pathways.

Cross-disciplinary engagement is another area that requires attention. For the tool to gain widespread acceptance and use, it must be accessible and intuitive not only to planners but also to educators, developers, policymakers, and the public at large. Increased engagement from these stakeholders can lead to better-informed decisions and improved sustainability outcomes. The validation of Urban Decarb through additional case studies, demonstrating its practical utility, will be pivotal in encouraging its adoption.

7.3 Broader Implications

The discussion extends beyond the technical capabilities of tools like Urban Decarb, contemplating the systemic transformations necessary to support carbon-neutral and socially equitable cities. It is recognized that achieving such ambitious goals will require concerted efforts that span governance systems, financial structures, cultural norms, and societal values. Tools like Urban Decarb can play a critical role in this transition by providing the data and insights needed to inform policy and practice. However, they must be complemented by broader systemic changes that address the multifaceted nature of urban sustainability challenges.

Urban Decarb offers a promising approach to incorporate carbon considerations into urban design. Its benefits, however, must be considered alongside its current limitations and the broader context in which it operates. As the field of urban sustainability evolves, tools like Urban Decarb will need to adapt and integrate within a holistic framework that considers the myriad factors influencing the sustainability of urban environments. This comprehensive approach will be essential to drive meaningful progress toward the sustainable cities of the future.

8 Conclusions

As urbanization continues to escalate globally, the role of cities becomes increasingly pivotal in the narrative of climate change. Tools like Urban Decarb emerge as instrumental in harnessing the power of parametric urban modeling and life-cycle assessment (LCA) to inform sustainable urban development. This tool links the intricate web of urban form, energy consumption, materials, transportation, and infrastructure to the overarching goal of emissions reduction. Despite the inherent uncertainties present in the preliminary stages of planning, the early integration of carbon knowledge is crucial for steering projects towards both local and international climate action goals.

The future evolution of Urban Decarb is anticipated to be influenced by technological advancements, urban planning trends, and the increasing urgency of climate change mitigation. As computational power grows and data analytics become more sophisticated, the tool is expected to incorporate more detailed simulations of urban metabolism, capturing the flows of energy, water, materials, and waste with greater precision. The integration of real-time data through Internet of Things (IoT) sensors could enable dynamic modeling that reflects the current state of urban systems and predicts future scenarios with higher fidelity.

Advancements in artificial intelligence (AI) and machine learning algorithms may offer the potential to automate much of the LCA process, providing urban planners with predictive insights and more robust decision-making tools. AI's capacity to process and analyze large datasets can significantly streamline the identification and evaluation of environmental impacts associated with various materials and construction techniques. For instance, predictive modeling facilitated by machine learning can extrapolate from historical LCA data to estimate the environmental footprint of new urban projects, incorporating complex variables such as material sustainability, construction methods, and urban form. Furthermore, machine learning models could be used to optimize building orientations within a development to enhance energy efficiency, leveraging pattern recognition to analyze and apply insights from existing data on solar exposure and thermal performance.

Urban planning trends, such as the push towards smart cities, circular economies, and net-zero developments, will shape the functionality and priorities of Urban Decarb. The tool is expected to evolve to account for the circularity of resources, aiming to minimize waste and promote the reuse and recycling of materials within urban development. As cities aspire to become more self-sustaining, the scope of Urban Decarb could expand to model the environmental impacts of urban agriculture, renewable energy integration, and decentralized waste and water treatment systems.

The role of Urban Decarb within the larger context of urban planning will also be influenced by the evolving nature of governance and policymaking. As sustainability becomes more deeply integrated into legislative frameworks, tools like Urban Decarb will need to be adaptable to new regulations and standards. This will require ongoing collaboration across multiple disciplines, including urban planning, environmental science, public policy, and community engagement.

To further enhance Urban Decarb's capabilities, future work should focus on several key areas:

1) **Incorporating Mobility and Networks:** Recognizing that transportation is a significant contributor to urban emissions, future iterations of Urban Decarb should quantify emissions from various transportation scenarios to inform urban design decisively.
2) **Integrating Automated Floor Plan Generation:** To refine the internal component estimations, an automated floor plan generator could be incorporated, minimizing simplifications.
3) **Expanding the Database for Open Spaces:** Enriching the data available for hardscape, landscape, and infrastructure components will enhance the tool's applicability beyond buildings, catering to a global portfolio of projects.
4) **Including Additional Impact Categories:** To prevent burden-shifting, Urban Decarb should assess a broader spectrum of environmental impacts, potentially extending to biodiversity assessments, physical well-being, social sustainability, etc.
5) **Focusing on Urban Scale Flexibility:** Investigating how urban density and access to public transportation and amenities influence the lifespan of buildings could lead to more sustainable urban development.

Urban Decarb represents a meaningful step forward in the integration of sustainability into urban planning. Its initial applications underscore its potential in guiding the creation of low-carbon cities. To overcome current limitations and realize its full potential, Urban Decarb must evolve in tandem with technological, planning, and governance advancements, fostering a multidisciplinary approach to building the resilient and sustainable urban landscapes of the future.

Acknowledgments

The authors would like to thank Henning Larsen Architects for generously providing us with access to all data related to the case studies.

References

ARCHITECTURE 2030 (2024), Why the Building Sector? https://architecture2030.org/why-the-building-sector/ (24.02.2024).

C40 CITIES (2018), Consumption-based GHG emissions of C40 cities. https://www.c40.org/researches/consumption-based-emissions (24.02.2024).

DANISH TRANSPORT (2018), Construction, and Housing Authority. Building Regulations 2018 (BR18).

DANISH ROAD DIRECTORATE (2015), InfraLCA: LCA-data for building roads and railways. 2015.

DAVILA, C. C. & REINHART, C. (2013), Urban energy lifecycle: An analytical framework to evaluate the embodied energy use of urban developments. In PLEA 2013. Sustainable Architecture for a Renewable Future. Fraunhofer IRB Verlag.

DE WOLF, C., HOXHA, E. & FIVET C. (2020), Comparison of environmental assessment methods when reusing building components: A case study, Sustainable Cities and Society, 61, 2020, 102322. https://doi.org/10.1016/j.scs.2020.102322.

DE WOLF, C., OCHSENDORF, J. & COX, D. (2020), Integrating structural performance and life cycle impact in conceptual structural design using interactive computational methods. Journal of Building Engineering, 32, 101610.

DRAGONFLY (2024), https://www.ladybug.tools/dragonfly.html (24.02.2024).

EN15978 (2011), Sustainability of construction works Assessment of environmental performance of buildings Calculation method. Tech. rep. 2011.

ERICKSON, P. & TEMPEST, K. (2014), Advancing climate ambition: How city-scale actions can contribute to global climate goals. Stockholm Environment Institute, Seattle, WA, USA, 2014.

FAMIGLIETTI, J. et al, Developing a new data-driven LCA tool at the urban scale: The case of the energy performance of the building sector, Energy Conversion and Management, 256, 2022, 115389. https://doi.org/10.1016/j.enconman.2022.115389.

HAUSCHILD, M., ROSENBAUM, R. & OLSEN, S. (2018), Life cycle assessment: Theory and practice. Tech. rep. 2018.

IMPACT ESTIMATOR (2024), https://calculatelca.com/software/impact-estimator/.

INTERNATIONAL ENERGY AGENCY (2019), Global Status Report for Buildings and Construction 2019. https://www.iea.org/reports/global-status-report-for-buildings-and-construction-2019 (24.02.2024).

ISO 14040 (2008), Life Cycle Assessment (LCA) – Principles and Guidelines. 10.1016/B978-012373654-3.50006-7. 2008.

Lotteau, M., et al (2015), Critical review of life cycle assessment (LCA) for the built environment at the neighborhood scale. Nov. 2015. DOI: 10.1016/j.buildenv.2015.06.029.

MONCASTER A. M. et al (2019), Widening understanding of low embodied impact buildings: Results and recommendations from 80 multi-national quantitative and qualitative case studies. Journal of Cleaner Production, 235, 378-393. https://doi.org/10.1016/j.jclepro.2019.06.233.

ONE CLICK LCA (2024), https://www.oneclicklca.com (24.02.2024).

POMPONI, F., SAINT, R., AREHART, J. H. (2021), Decoupling density from tallness in analysing the life cycle greenhouse gas emissions of cities. npj | urban sustainability, 1, 33 (2021). https://doi.org/10.1038/s42949-021-00034-w.

RAMASWAMI, A. et al. (2020), A Social-Ecological-Infrastructural Systems Framework for Interdisciplinary Study of Sustainable City Systems: An Integrative Curriculum Across Seven Major Disciplines. Journal of Industrial Ecology, 16 (6), 801-813. DOI: 10.1111/j.1530-9290.2012.00566.x.

REINHART, C. & DAVILA, C. (2016), Urban building energy modeling – A review of a nascent field. Building and Environment, 97, 196-202. https://doi.org/10.1016/j.buildenv.2015.12.001.

ROBATI, M. et al (2021), Carbon value engineering: A framework for integrating embodied carbon and cost reduction strategies in building design. Building and Environment, 192, 2021, 107620. https://doi.org/10.1016/j.buildenv.2021.107620.

SHARIFI, A. & MURAYAMA, A. (2013), A Critical Review of Seven Selected Neighborhood Sustainability Assessment Tools. Environmental Impact Assessment Review, 38, 73-87. https://doi.org/10.1016/j.eiar.2012.06.006.

TOZAN, B. et al (2022), The influence of EPD data on LCA results. 2022 IOP Conf. Ser.: Earth Environ. Sci. 1078 012105.