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Environmental impact and architectural forming:

How Life Cycle Assessment supports decision-making from early design stage in a BIM environment

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Abstract

Life Cycle Assessment (LCA), as a comprehensive method for assessing the environmental impact of buildings, has gained widespread application in recent years. Leveraging the advantages of Building Information Modeling (BIM), the BIM-LCA integration in the architectural design process has become a trend. To avoid the huge costs that design changes may incur in the late stage of building design, there is a growing trend to propose a simplified approach of BIM-LCA to intervene from the early stage. Building on this trend, this study further aims to expand the scope of LCA application by providing the assessment results of different volumetric options of the building from the LCA perspective to assist architects in their decision-making process. It encourages architects to include consideration of building materials as early as possible. This study proposes a design workflow of building massing, specifying the intervention timeline for LCA, and completing the LCA calculation based on an LOD-100-level BIM model, in addition to offering a comprehensive LCA report with visualisation dashboards. With the assistance of the computational algorithm developed in this study, the automated modeling of building elements can rapidly upgrade the LOD level of a Rhino model to 200, simultaneously synchronizing it into Revit and automatically establishing the corresponding family type of building elements, then exporting the list of building material quantities. Through a case study of a residential project located in Milan, the results demonstrate the feasibility of conducting BIM-LCA studies and calculations at the early stage of building volumetric design. The produced LCA results offer architects more quantitative evidence to support their decision-making, enabling the optimization of the design from the LCA perspective. This further extends the scope of LCA application, as well as reduces the threshold to its use, contributing to the further reduction of the environmental impact of buildings and improving sustainability from the design stage onwards.

Keywords:

Life Cycle Assessment (LCA), Building Information Modelling (BIM), Sustainability, Level of Development (LOD), Building Massing Design.

Content

1 | Introduction

The architectural design industry has undergone evident transformations in recent years, encompassing a wide range of aspects, including changes in workflow, design philosophy renewal, and iterations of design tools. Building Information Modelling (BIM) stands as a game-changing tool that has not only revolutionized the conventional collaboration between architects and engineers but it has also inspired innovative approaches to both design and construction. Architects are no longer constrained by the potentially inefficient or costly construction concerns of the past, instead, with the aid of digital tools, design becomes much freer, with more sophisticated and comprehensive strategies under consideration. Also, digital tools can provide more quantitative and analytical data, enabling designers to weigh the pros and cons from more perspectives, turning the design into a data-informed process.

Meanwhile, global awareness of sustainability issues is continuously on the rise. The notion of green buildings has become a consensus amongst users, investors, and designers. When designing sustainable buildings, utilizing efficient digital tools to optimize architectural sustainability becomes an essential approach. In spite of considerable improvements in efficiency compared to the past, building design, as a multi-actor, complex collaborative task, is still difficult to be modified drastically at a later stage without incurring high labor and construction costs.

An emerging common view within the architectural profession is to integrate sustainability principles early in the architectural design process, aiming to make decisions conducive to sustainable solutions whenever possible. The author's internship experience at leading international architectural design firms further underscores this perspective. These renowned firms prioritize sustainability in their projects, demonstrating their commitment and responsibility towards environmental issues. As architects with significant influence over the finished configuration of a building, key aspects of practicing sustainability in architecture include assessing the material resources consumed by the building and selecting recyclable or bio-based materials whenever feasible. For instance, MATRIX ONE, a project completed in 2023 by MVRDV Architect, incorporates sustainable considerations from various perspectives, aiming to achieve 90% reusability rate of materials at the end of its life cycle. Similarly, BIG architectural firm has established dedicated research positions in the field of LCA, showcasing their proactive approach towards sustainability integration. These examples reflect the growing importance of considering sustainable practices from the very inception of architectural design.

Deeply influenced and inspired by these experiences, the author chose to explore the convergence of BIM technology and sustainability within the context of the built environment in this research. The paramount objective of sustainability lies in minimizing the environmental impact of buildings throughout their entire life cycle. An instrumental method in achieving this goal is the application of Life Cycle Assessment (LCA) to comprehensively evaluate a building's environmental footprint.

Conventionally, LCA, as a synthesis approach, has primarily

Figure 1.1 Image of project MATRIX ONE. Source: https://www.mvrdv.com/projects/393/matrix-one.

focused on assessing the carbon footprint of different materials and construction processes, covering the extraction of raw materials, construction, use, and end-of-life phases. However, the complexity of buildings as comprehensive products demands a broader perspective. Its embodied emission and environmental impact during the usage phase are not solely contingent upon material choices but also potentially linked to other aspects such as the building's geographical location, design approach, particular morphology, and more. In light of this, this research endeavors to extend the scope of LCA by investigating how architectural form influences the overall hidden environmental impact of a building.

Overall, the main objective of this study is to explore how LCA results can support early-stage architectural design decisions in the BIM environment, with a particular focus on the impact of building form. By integrating LCA analysis into design strategy as early as possible, architects can effectively evaluate and compare different design options from a carbon footprint perspective, prioritizing sustainability from the outset. The obtained data provides a deeper insight into the influence of building form and spatial configurations on its embodied carbon emissions, assisting designers to optimize not only the shape but also the combination of materials under the chosen design.

To achieve the goals, a design methodology that specifies not only the intervention time point of the LCA study but also the characteristics of LCA should be properly defined. The LOD level of the digital model adopted for the LCA study is supposed to stay at 100, ensuring the flexibility of personalized modifications by architects with minimal time costs. The software selected for both modeling and LCA data exporting is required to be aligned with the mainstream working conventions of the architects and to maximize its capabilities as much as possible. There is also a necessity to avoid insufficient data exchange between different software, thus streamlining the process of assessing the environmental impact of different design options.

Only if an algorithmic tool developed for LCA calculations enables the designers to expedite the evaluation process and facilitate real-time LCA testing, will the tool be widely accepted and implemented. Additionally, visualizations of LCA results serve as valuable aids for interpretation and comparison can not be ignored in the methodology.

Incorporating LCA analysis into the early conceptual stage of architectural design, although requiring further validation, this research aims to expand the scope of LCA, bridging the gap between building form and environmental impact, and offering new perspectives on the relationship between design and sustainability.

In conclusion, this study aims to empower designers with the capability to make more sustainable decisions by providing real-time dynamic tools to calculate embodied emission of each building form. Whether proposing the integration of LCA in the early design stage, defining derived workflows, or developing efficient decision-aiding tools, the objective is to promote the advancement of sustainable concepts in the field of architectural design, fostering deeper levels of sustainable implementation in building design. Ultimately, the aspiration is for architectural design to progress towards a greener, more energy-efficient, and environmentally friendly future.

2 | New wave of architectural design

2.1. Sustainability

Figure 2.1 Conceptual pollution and emission. Source: freepik.

Since the term 'sustainable development' gained prominence with its first notable appearance in the literature titled 'World Conservation Strategy,' published by IUCN, UNEP, and WWF in 1980[74], later defined by the UN-established Brundtland Commission as "Sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs" in 1987[11], the goal of mitigating the impacts on the ecosystem and improving human well-being has gradually become mainstream and prioritized. Globally, people are increasingly aware of the urgency of climate change, resource depletion, environmental pollution, and other issues.

According to the report of the United Nations, the population living in cities is predicted to increase up to 67%, by 2050[50], and the global primary energy consumption more than doubled in 2018[41]. Excessive primary energy consumption, for its part, can lead to resource depletion and GHG emissions as well as air pollutants. These challenges necessitate a comprehensive re-evaluation of our lifestyles and economic paradigms, resulting in gradual transformations that significantly influence various industries, policy frameworks, and societal behaviors.

The architectural design industry is undoubtedly one of those industries that will be profoundly impacted. From an environmental perspective, as per the latest energy statistics report published by the International Energy Agency (IEA) in 2021, buildings rank among the most energy-intensive sectors, accounting

Figure 2.2 ZCB Zero Carbon Building. Source: https://www.archdaily.com/282880/zcb-zero-carbon-building-ronald-lu-and-partners

for approximately one-third of the final energy demand[3]. At the same time, buildings in the EU account for about 50% of all extracted material, and 36% of greenhouse gas emissions, which mainly stem from construction, usage, renovation, and demolition based on the European Commission's report[19,20]. Therefore, implementing measures to reduce energy and material consumption within the building sector will play a pivotal role in making significant strides toward achieving targeted emission reductions within the desired time frame.

Architects are acutely aware that the most effective way to reduce the environmental impact of buildings is by integrating sustainable strategies into the design process. The sustainable strategies have developed over time to be diverse, including the utilisation of natural ventilation to reduce the energy demands for cooling during hot summer months, implementing green roof systems to decrease greenhouse gas emissions, and many others.

Take the first zero-carbon building completed in Hong Kong in 2012 as an example, shown as Figure 2.2, certain design strategies were adopted to achieve energy-saving and emissions-reduction goals. The architects implemented a properly inclined roof to optimize sunlight reception at the best angle while employing a strategy with photovoltaic panels covering the entire roof surface to enable the building to generate electricity on-site. Through this approach, a substantial amount of annual electricity consumption is offset, and there is even an expectation of surplus energy being fed back into the local power grid to cover the embodied energy of building materials.

Furthermore, there is a growing awareness of the importance of minimizing the environmental impact of construction materials, reducing the use of toxic materials, and so on. To enhance designers' understanding of the environmental impact of various materials, the Centre for 9

Figure 2.3 Construction Materials Pyramid. Source: https://www.materialepyramiden.dk/

Industrialised Architecture at Royal Danish Academy has developed the "Construction Materials Pyramid." The primary objective of this pyramid is to visually guide architects in making thoughtful considerations when selecting materials, encouraging them to prioritize decarbonization in their choices. Similarly influenced by decarbonization principles, Architecture studio White Arkitekter made a resolute choice to use cross-laminated timber as the primary structural material in the design of a 75-meter tall building. The architects conducted a comprehensive life-cycle analysis during the design stage, spanning 50 years, in their efforts to

Figure 2.4 Sara Kulturhus Centre. Source: https://whitearkitekter.com/

achieve a "carbon-negative" building. These practices firmly reflect the transformative impact of sustainable concepts on traditional design approaches.

Economically, it is increasingly emphasized that sustainable strategies not only save energy and operating costs but also offer long-term economic benefits to projects. These benefits are now recognized to outweigh the short-term incremental costs that may have been a concern in the past. The world's first prefabricated carbon-positive building, designed and constructed by the Australian design company ArchiBlox in Melbourne in 2015, exemplifies this point very well. Despite the additional upfront costs due to smart thermal control systems, including in-ground cool tubes, sliding edible garden walls, and a green roof system, when considering the overall picture, the building's total energy consumption decreases throughout both winter and summer seasons. Moreover, the results of the life-cycle assessment reveal that the Archi+ Carbon Positive House reduces carbon emissions by 101% annually, equivalent to planting an astonishing 6095 local trees. This success demonstrates that investors and occupants are progressively recognizing the long-term benefits that outweigh short-term financial investments. It reinforces the importance of assessing a building's quality

Figure 2.5-2.6 Archi+ Carbon Positive House. Source: https://www.archiblox.com.au/

through a lens that prioritizes the human habitat, community, and the built environment over initial economic considerations.

Consequently, from a social perspective, the recognition and implementation of sustainability have become highly attractive and reputable aspects of building design. Embracing sustainable practices is seen as a demonstration of good social responsibility and identity. The gradual establishment and refinement of relevant codes and regulations further foster a strong commitment to sustainability throughout the entire life cycle of a building, spanning from the design and construction phases to the operational phase and end-of-life.

2.2. Sustainable decision-making

All shifts in the notion mentioned above are driving the decision-making of architectural design toward more integrated and holistic considerations. Distinguishing itself from traditional concerns of building design, which focus on aspects such as aesthetics of massing, orientation, proportion, scale, texture, shadow, and light, sustainability demands that designers incorporate long-term costs: environmental, economic, and human[38].

This may involve embracing renewable, recycled, or environmentally friendly materials to curtail resource consumption and minimize wastage. It could also involve strategies like harnessing natural light and optimizing building form to improve building performance. Integration of solar and other renewable sources could substantially enhance overall energy efficiency. Additionally, the incorporation of nature-centric design elements to enhance the space's healthfulness and livability could also be considered.

The ICTA-ICP building, co-designed by H Arquitects and DATAAE, exemplifies architectural practice driven by sustainable principles. Located within the Universitat Autònoma de Barcelona campus, this research center deviates from conventional design by employing a double-skin facade consisting of rows of transparent shutters made from low-cost

Figure 2.7-2.9 Research centre in Universitat Autònoma de Barcelona. Source:https://www.domusweb.it/en/

corrugated polycarbonate. These shutters serve as the building's "bioclimatic skin." Due to their ability to automatically adjust the angle of opening based on weather conditions, they regulate the internal temperature, thus enhancing the overall energy efficiency of the building.

Furthermore, design decisions like the zigzag-shaped skylights on the atrium roof, rooftop vegetable gardens, and internal partitions made entirely of wood are all geared towards allowing the building to react and adapt constantly. This minimizes the consumption of non-renewable energy and reduces environmental impact. The architects' starting point was to make the most of the natural possibilities offered by the environment. It can be asserted that compared to traditional architectural

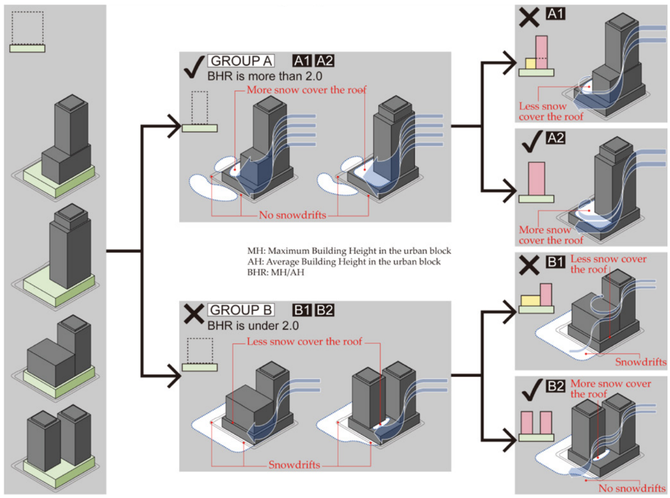
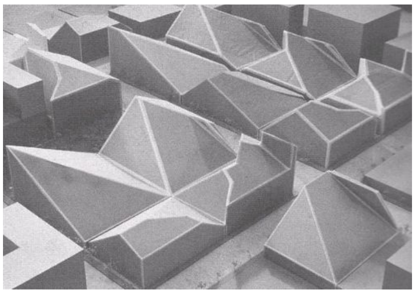


Figure 2.10 Design guidelines of urban blocks in winter city.
Source: https://www.mdpi.com/2071-1050/9/11/2132

approaches, the incorporation of sustainable principles as the guiding force behind most design decisions is commendable.

The optimization goals of sustainable design strategies can also be tailored according to specific environmental requirements. For instance, a research team in Japan devised an innovative urban block design concept for regions like Sapporo[71], characterized by heavy snow and strong winds.



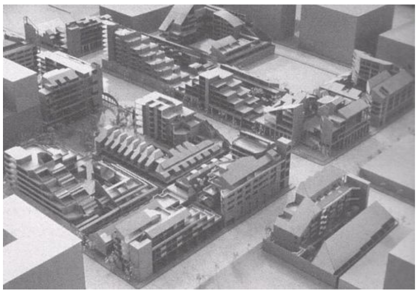


Figure 2.11-2.12 Solar envelopes on the Spanish street grid system in Los Angeles (Left) and Buildings within the solar envelopes (Right). Source: LOW-TECH magazine

Their sustainable objective focused on minimizing the energy required for snow removal from public spaces. By selecting high-rise, high-density areas and continuously refining block designs through comparing various building forms and configurations in snow and wind conditions, the team managed to reduce the snow drifts and lower the energy needed for snow clearance during winter, enhancing the overall sustainability of the urban environment in winter cities.

Another case that illustrates how sustainable goals influence architectural form is the 10-year housing study conducted by USC's School of Architecture's Solar Studio. This research carried out under the solar envelope, continually tested sustainable growth possibilities and deduced patterns for architectural forms that optimize solar exposure and cross-ventilation within complex urban blocks. As depicted in the image 2.11, the tiered rooftop terraces, distinct from the conventional simple rectangular volumes, suggest that designers can achieve maximum year-round sunlight and energy benefits without compromising architectural aesthetics.

Many subsequent residential projects have been influenced by this pattern, such as BIG's mixed-use residential project VI/\ 57 West in New York City, which exemplifies the extreme expression of architectural form aimed at maximizing sunlight intake.

Driven by the need for standards and the assessment of sustain-able building levels, as well as the intention to steer architectural design towards more environmentally friendly directions, a plethora of environmental sustainability assessment tools including LEED, GreenStar, DGNB, and others, have emerged across different countries and regions, with the establishment of BREEAM in 1990 as the first commercially available tool for buildings in the UK[46]. These tools have gradually evolved to utilize more mature assessment methods, comprehensive criteria, and broader scopes of evaluation.

Figure 2.13-2.14 VI/\ 57 West.
Source: divisare.

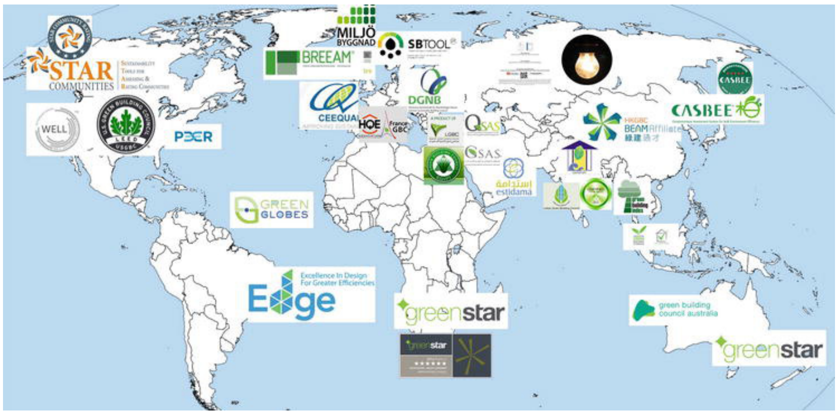


Figure 2.15 Common rating assessment systems around the world. Source: Green Building Rating Systems as Sustainability Assessment Tools: Case Study Analysis

Moreover, the focus of assessing the environmental attributes of building materials in these assessment tools has logically progressed from simple descriptive accounts of resource use, ecological impacts, and health-related characteristics to comprehensive 'eco-profiles' based on rigorous life-cycle assessment protocols[18]. These assessment protocols, although voluntary, have gradually evolved into principles and instruments guiding design decisions based on their reliability in providing objective and credible benchmarks.

However, the implementation of sustainability assessments has in the past been regarded as a time-consuming task which typically conducted at the end of a project, hardly ever having a fundamental impact on the design. Attempting design modifications in response to unfavorable assessment results can be costly in terms of both labor and time to repeat the whole process. Researchers and scholars over the last few years have been constantly calling for exploring the possibility of fully implementing sustainable assessment into the decision-making process of architectural design[8, 27, 44].

This underlines the need for, in contrast to traditional static methods, a continuously dynamic assessment tool that provides feedback on design modifications. It would be more in line with current needs. Designers are encouraged to employ such tools to start engaging in whole-life perspective thinking as early as possible to make more environmentally favorable decisions.

2.3. Digitalization process

Benefiting from advancements in computer technology coupled with the gradual adoption of digital design modeling in the architecture industry, Building Information Modeling (BIM) has been developed as a digital information management system that represents one of the most crucial and promising transformations in the AECO industry.

Firstly, BIM enables designers to manage all project design data in a digital format integratively, facilitating seamless data access throughout the whole project life-cycle[70]. Second, by consolidating multidisciplinary information into a single model, BIM is steadily supplanting CAD as the real-time collaboration tool for all stakeholders in the industry.

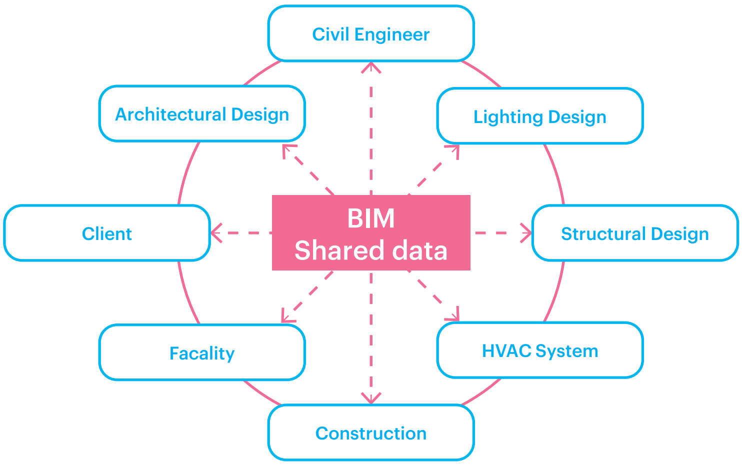


Figure 2.16 Shared data between project participants on BIM system. Source: Self-produced

The adoption of BIM has yielded substantial and tangible benefits to the industry. Notably, it has significantly improved collaboration and coordination, leading to cost and time savings. Furthermore, the application of BIM has elevated the overall design quality, resulting in more accurate designs and higher-quality deliverables[12]. As shown in Figure 2.18, with the support of data-rich BIM models, both construction planning and prefabrication decisions can be made in advance, thus avoiding construction errors that deviate from the design expectations when the project is handed over for downstream uses. The Crossrail project, as one of the earliest

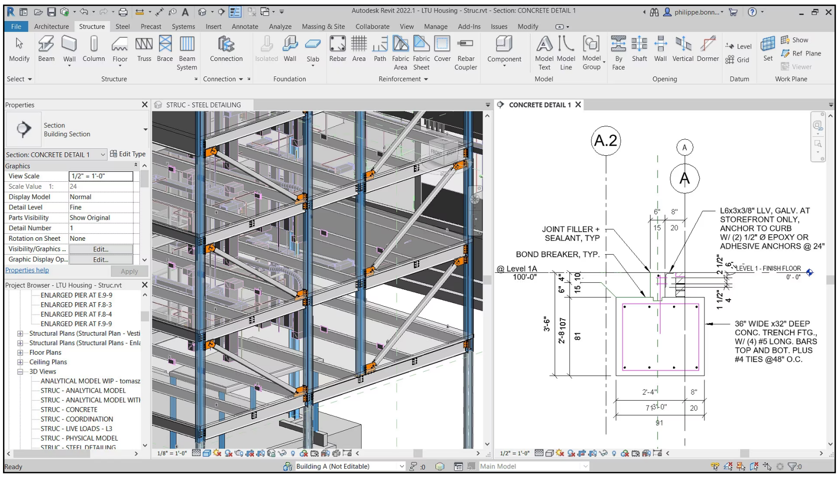


Figure 2.17 Data-rich BIM model for informed decisions. Source: Autodesk.

government-supported large-scale public infrastructure projects in the UK, has demonstrated the tremendous convenience and revolutionary nature of applying BIM technology throughout its entire lifecycle. The visual 3D models ensure a more intuitive way of understanding, while the integration of information from various disciplines for clash detection also enhances carbon efficiency. The use of 4D models in the project is particularly beneficial for analyzing schedules and visualizing conflicts, which may not be apparent in typical Primavera-style Gantt charts and diagrams [68]. Figure 2.18 is one example of the typical BIM report. These advantages make the project more manageable and amenable to cost-effective improvements.

The digital nature of BIM also allows for rapid collection, processing, and analysis of design data, facilitating better architectural decision-making and faster performance simulation. As early as 2014, researchers from Ottawa proposed leveraging the advantages of BIM models to quantitatively assess environmental impacts during the conceptual phase[37], simulating energy consumption of building components. This approach visualized energy analysis and lighting simulations to assist

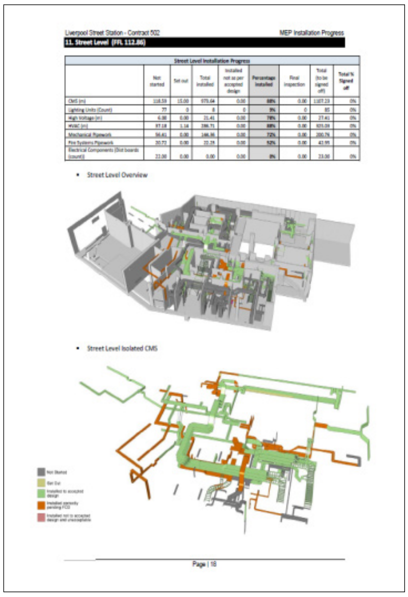


Figure 2.18 4D model output in a typical BIM report.
Source: Crossrail project: Application of BIM (Building information modeling) and lessons learned.

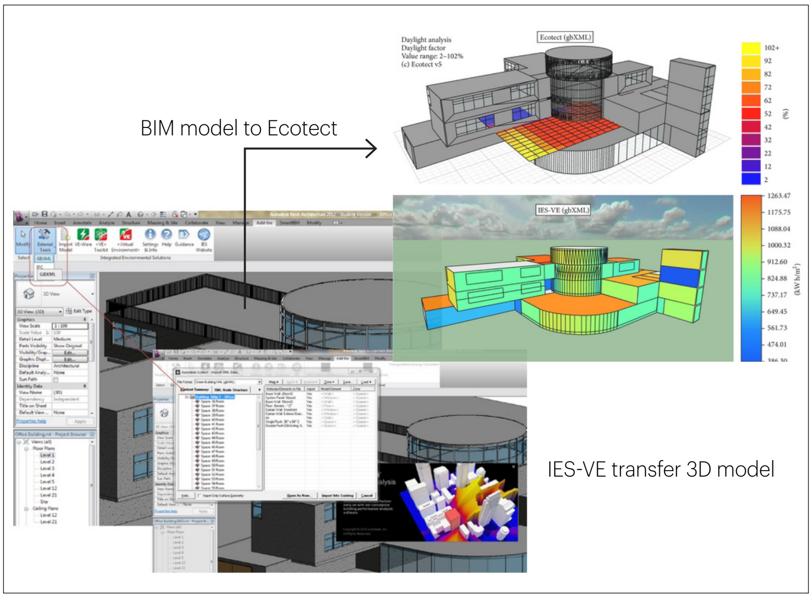


Figure 2.19 BIM-based design comparison in terms of building performance in conceptual phase.
Source: An Automated BIM Model to Conceptually Design, Analyze, Simulate, and Assess Sustainable Building Projects.

designers in making energy-efficient architectural choices through comparative evaluations. This efficiency far exceeds the capabilities of traditional paper-based documentation, enabling the realization of previously unattainable possibilities and guiding every decision within the whole life-cycle perspective towards more scientific and optimized outcomes.

20 Further, the development of visual programming tools, such as Dynamo released in 2012, and Grasshopper in 2007, has made architectural design more data-driven. This data-driven approach is evident not only in the designer's ability to quickly generate complex architectural forms for easy comparison and optimization of multiple scenarios[40], as shown in Figure 2.20, but also in strenghthening the integration and interaction between BIM tools and various data sources and third-party plugins.

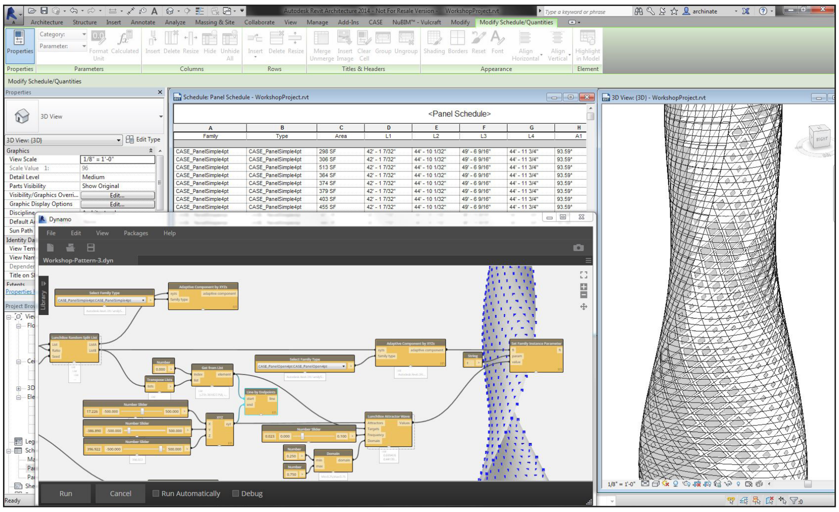


Figure 2.20 Generate complex architectural forms. Source: Autodesk screenshot.

The extension of programming tools enhances the functionality of BIM, enabling designers to access a wealth of external data, including building material information and various others, while also allowing project managers to link project data to external systems[62].

There are already over a thousand plugins available on the official Autodesk App Store interface that can be integrated with Revit, covering a wide range of functionalities. Among them, there are plugins that assist in design decision-making and reference external databases.

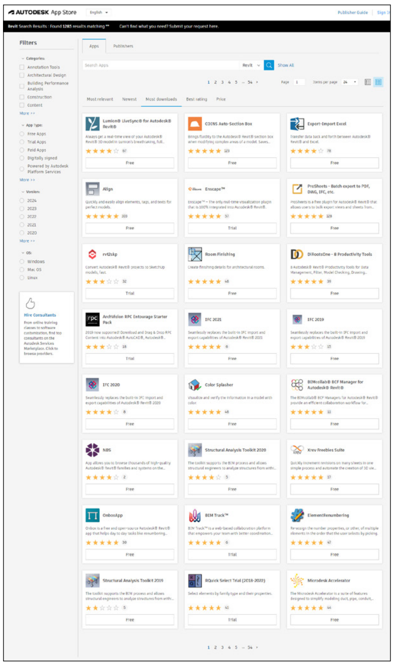


Figure 2.21 Plugins on Autodesk App Store. Source: Self-produced.

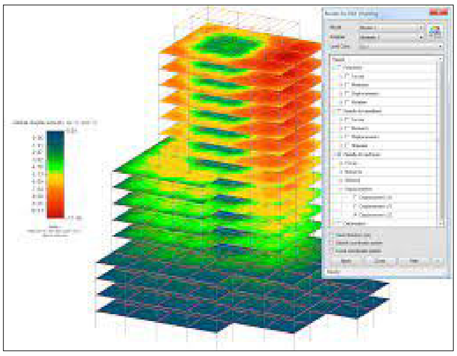


Figure 2.22 Structural Analysis Toolkit (left). Source: Autodesk.

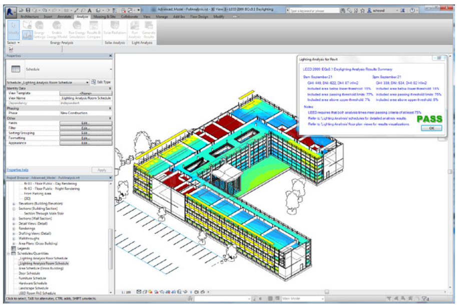


Figure 2.23 Lighting Analysis. Source: Autodesk.

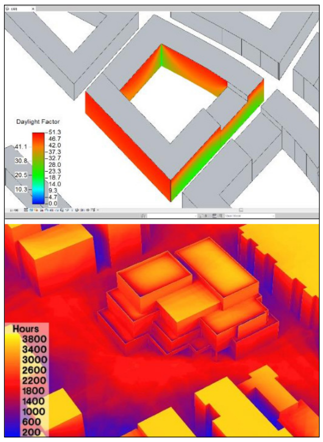


Figure 2.24 Plugins developed by scholars for assessing daylight. Source: [35].

For instance, the Structural Analysis Toolkit aids in transferring models and conducting linear and nonlinear analyses for various types of structures, facilitating the design of steel, concrete, and wood structural elements. The Lighting Analysis plugin allows for the rapid acquisition of solar lighting data and offers automatic daylighting analysis for LEED certification. Additionally, there are numerous plugins developed by various scholars, such as the one shown in the Figure 2.24, created by M. Miri and Elmira, which assist architects or urban designers, or planners in assessing daylight conditions in external or internal spaces by calculating different daylight metrics at various design stages[47].

During the early conceptual phase, architects favor visual programming software like Grasshopper, which offers even more countless analysis and decision-support plugins. Common ones including Ladybugs and Honeybee are already highly mature in terms of daylighting and energy analysis. Karamba3D facilitates rapid and accurate execution of structural finite element analysis, Kangaroo allows for the quick and rational creation of arches and domes, aiding in optimizing forms and creating origami-like shapes.

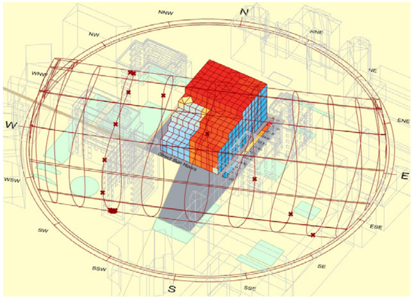


Figure 2.25 Ladybugs analysis.
Source: Self-produced.

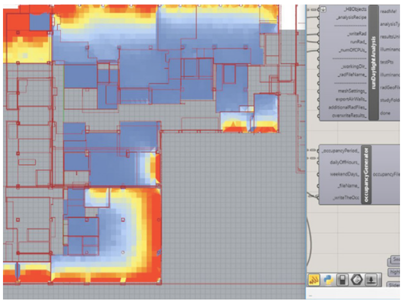


Figure 2.26 Honeybee analysis.
Source: parametric-architecture.

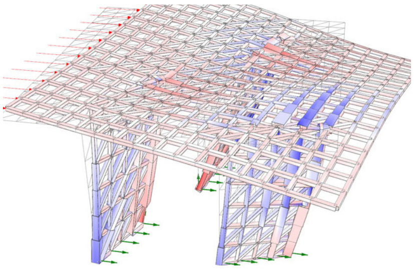


Figure 2.27 Karamba3D.
Source: parametric-architecture.

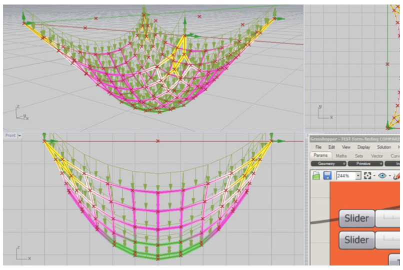


Figure 2.28 Kangaroo analysis.
Source: parametric-architecture.

Such interactive extensions break down the knowledge and data barriers that existed between different specialized fields and professions, enhancing information transparency and providing designers with more choices and support.

2.4. Enhanced sustainability empowered by digitalization

The growing emphasis on sustainability and the enhancement of computer technology have together catalyzed a new trend in architectural design: a comprehensive and data-driven approach that supports the selection of more optimized solutions for sustainable design through comparisons. These comparisons can focus on the environmental impacts of the building, and its performance simulations, and even consider integrating individual buildings into the broader context of communities and cities to achieve urban sustainability.

Taking daylight analysis of buildings as an example, design strategies have evolved from basic orientation analysis to today's continuous, more refined optimization of overall building surface daylight duration throughout the entire architectural design process. In the case of MVRDV's Chengdu Jiaozi Complex Tower project in China, all facades of the three high-rise buildings within the site underwent sun-hour analysis. In areas with intense sunlight, higher-density vertical shading, and energy-efficient glass were used, while in areas with lower daylight duration, a more transparent design strategy was employed. This evolution of customizing shading methods on the same facade based on the context and the project's geographical location reaffirms the current trends in design.

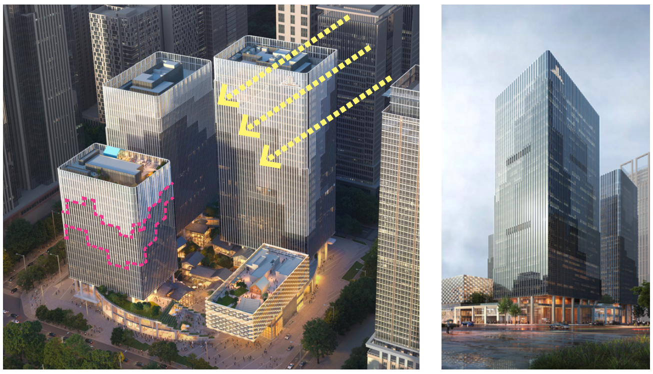


Figure 2.29 Chengdu Jiaozi office tower. Source: MRVDV.

Moreover, extensive research indicates that decisions made during the early stages of building design greatly influence their environmental impact or costs[10, 42]. Thus, the comparative processes should ideally occur as early as possible to avoid the substantial human resource and time costs wasted in making changes when negative results are obtained in the later stages.

Among the various comparative approaches, although not as extensive as research related to such acoustic, energy, or lighting performance analysis, the implementation of LCA to reduce environmental impact during the early design stage, specifically the production stage, has gradually gained widespread attention and discussion in the past decade.

The limitations in interoperability between LCA and BIM software have been addressed step by step as well. BIM technologies can be used already in the early design phase to perform structural analysis, environmental control, material selection, and building systems control[24]. As a result, the feasibility of integrating LCA into early-stage building design for comparative and optimized solutions is enhanced.

In the past, building LCA was relatively independent and often conducted toward the end of the project. These assessments involved a comprehensive evaluation of the materials used in the building. Assessments were typically carried out by professionals external to the project design team, often in a consulting role. However, with the emergence of assessment tools that integrate with design software, such as Tally and One Click LCA, which facilitate high-speed information exchange and integrate vast databases, there has been a rapid shift in the industry. These tools now provide support for design decisions, breaking the previous impasse where it was challenging to improve the sustainability of building design regarding materials themselves and material combinations.

Architects are no longer limited by their professional constraints and information barriers, allowing them to move beyond the traditional criteria of materials, such as appearance and strength.

As shown in the Figure 2.30, the conclusions derived from material assessments conducted by Tally software for different design scenarios of the exterior cladding system became crucial evidence for the designer's decision to opt for Translucent Panel Cladding. On the other hand, One Click LCA offers plugins that can be used with both Revit and Rhino design software. The Figure 2.33 illustrates the process of using One Click LCA to estimate the environmental impact of materials during the early stages of architectural design.

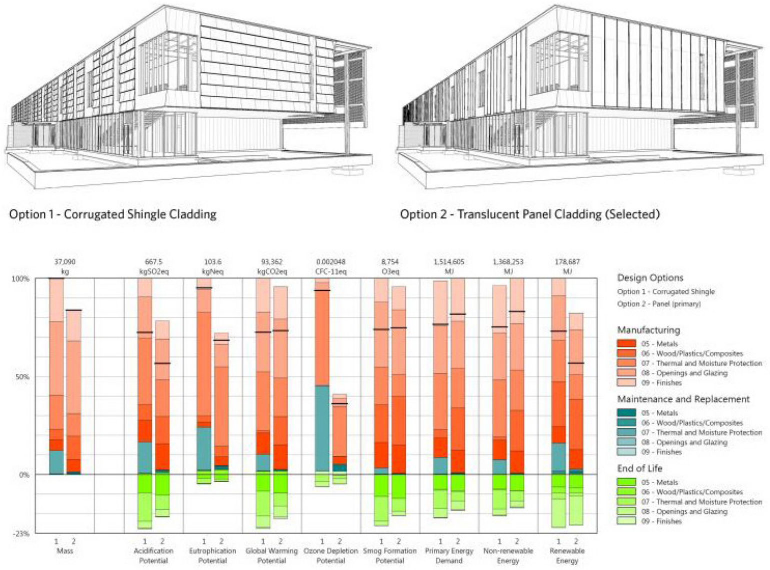


Figure 2.30 Comparison of two design scenarios in Tally. Source: Tally.

In general, the acceleration of digitalization in the construction industry is increasingly supporting the transition from manual design decisions to faster and more scientifically assisted computer-aided processes, especially when executing LCA. The evaluation process is evolving into a dynamic, life-cycle-supported, multidisciplinary decision-making process. With the aid of visual programming tools, the intervention time point for comparative assessments is progressively advancing, allowing for earlier integration. The dynamic nature of the real-time results enables designers to adjust and optimize their designs in a more streamlined and common approach.

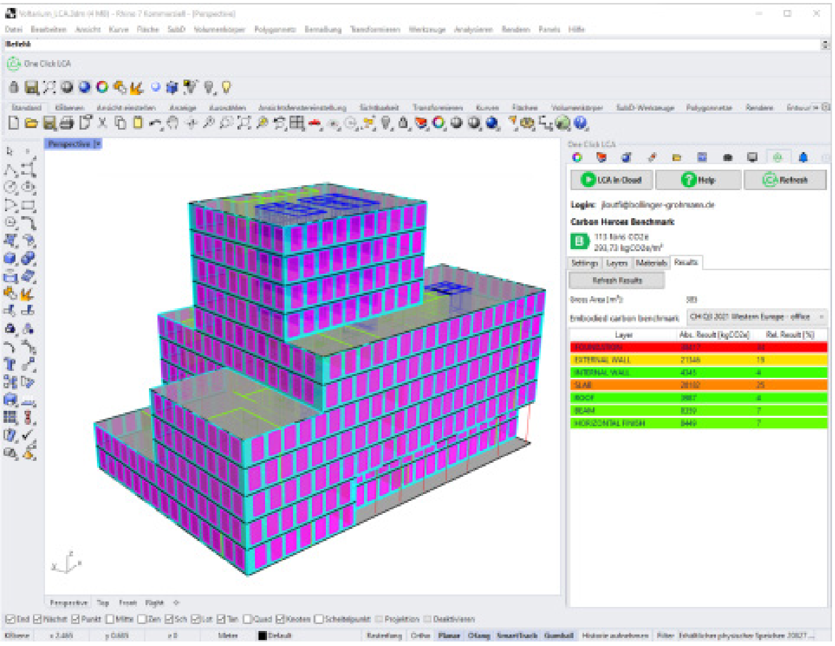


Figure 2.31 Conduct LCA in early design phase in OneClick LCA. Source: OneClick LCA.

3 | Methods and tools
for sustainable building projects

3.1. Life-Cycle Assessment (LCA) for buildings

LCA originated at the beginning as a tool for quantitatively assessing the materials, energy flows, and environmental impacts of simple products. However, when applied to a building, a complex "mega product" with a long life span, extremely heterogeneous use of materials, and varying functionality, it proved to be highly challenging. First of all, the LCA methodological framework consists of four stages: Definition of goals and scope, Life Cycle Inventory (LCI) analysis, Life Cycle Impact Assessment (LCIA), and Life Cycle Interpretation.

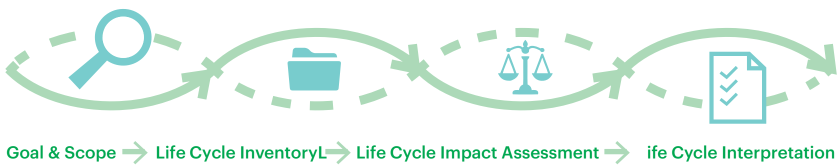


Figure 3.1 LCA methodological framework. Source: self-produced.

The establishment of goals for the life cycle assessment of a building is in general universally aimed at assessing the environmental impacts of the building as a whole in terms of all the materials used, energy consumption. It is a crucial phase in making LCAs, especially in making comparative LCA, as it determines how to define the functional unit equivalent to compare different products or buildings and how to interpret the results. However, due to the complexity of buildings, the goal-setting may be somewhat emphatic in different assessment programs, with a tailored set of assumptions and prerequisites.

The scope of the building LCA is more pragmatic, and together with the goal jointly establish the functional unit, system boundaries, and quality criteria for inventory data[64].

System boundary

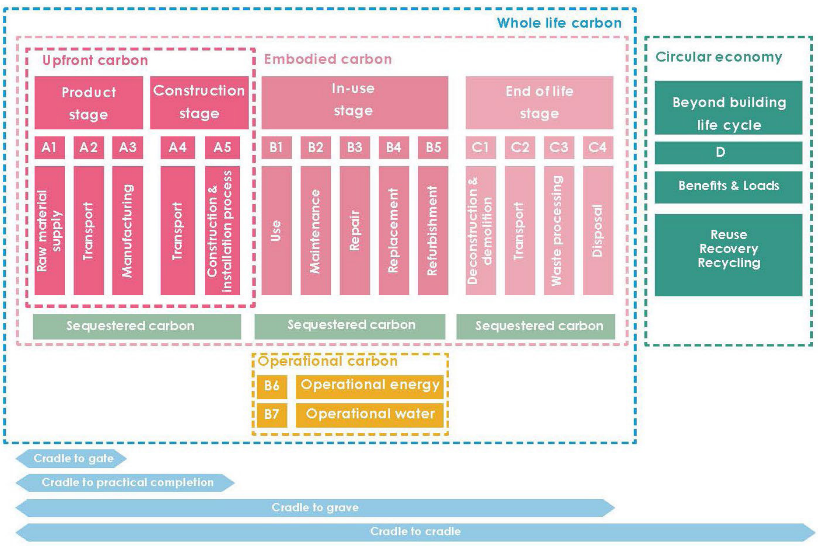


Figure 3.2 The EN 15978 system boundaries, demonstrating the stages constituting a whole life carbon assessment. Source: LETI Embodied Carbon Primer.

In general, the system boundaries for a comprehensive analysis cover the entire lifecycle of the building, from the product stage to the end-of-life stage. Specifically, according to EN15978, the system boundaries for analysis include the material production stage (Modules A1-A3), material transportation stage (Module A4), construction and installation stage (Module A5), the use stage or the so-called operational stage for buildings (Modules B1-B7), the end-of-life stage (Modules C1-C4), and finally, Module D[1]. The inclusion of module D, which deals with the potential of reuse and recycling, is discretionary and not mandatory, unlike modules A1-A3, which are essential for any lifecycle assessment. This means that Module D may be considered beyond the system boundary, highlighting its optional nature, especially in EPD reports of building materials.

Functional unit

The functional unit for building LCA typically encompasses three dimensions: space, time, and service[22]. In the space dimension, it involves evaluating the entire building, a portion of it, or a specified amount of space, such as an office measured by area or volume. The time dimension pertains to the building's lifespan, and the service dimension relies mainly on the building's occupants or the products outputted by it.

However, both functional unit and system boundaries can be customized to align with specific LCA scopes and goals for performing more accurate comparisons or calculations. As an example, Kamari et al. (2022) tailored the system boundaries of LCA in their recent study on the early application of LCA tools in sustainable building design[39], which only included modules A1-A3 since the goal setup was focused on the embodied environmental impact.

Life Cycle Inventory (LCI) analysis

Life Cycle Inventory (LCI) analysis, as the second major and essential step of LCA, for architectural projects mainly involves the synthesized collection and compilation of information on the physical materials and energy flows of the various stages of a building's life cycle, for quantifying the inputs and outputs of the system under study[61]. In executing a complete LCA project, the data LCI collects intuitively relates not only to foreground processes, such as the procurement of construction materials or other physical

Figure 3.3 Sample of available LCI database. Source: OpenLCA.

items but also to background processes, such as the electricity or other energy consumed during site-based construction of the materials. LCI is an iterative process and there is no perfect one-size-fits-all database for all projects. In fact, the LCI database for each building project is unique, evolving with the changing goals and scope. The database for a cost-effective project aiming to minimize construction expenses will differ significantly from that of a project with a strong focus on sustainability, unconstrained by tight economic limitations.

Currently, there are numerous LCI databases available either free of charge or on the commercial market. Although initially, such databases were relatively small projects in the academic domain, with LCA becoming a key tool for sustainable innovation, more databases have been developed with the support of state governments, universities, research institutes, and other entities. Consequently, some of the databases are quite locality-specific in terms of their data types.

Platforms that provide comprehensive LCI databases include ecoinvent, Ökobaudat, and others that can meet the needs of most regions, as shown in Figure 3.3. Additionally, there are increasingly more free platforms that aggregate a wealth of EPDs data, including INTERNATIONAL EPD SYSTEM, EPD Italy, IBU, and so on. EPD stands for Environmental Product Declaration, which is a document that transparently communicates the environmental performance or impact of any product or material over its lifetime. By collecting large amounts of EPD, a reliable LCI database can also be established under the fact that standards and methods for the LCA of building materials have gradually become more standardized. For instance, EN 15804 describes the methodology for producing EPD at the product level, while EN 15978 specifies the indicators, calculation rules, and system boundaries at the building level which all contribute to the standardization.

Building material manufacturers and suppliers are also increasingly aware of the significance of providing more environmentally friendly products with lower environmental impacts and a higher percentage of recyclable materials in their product composition.

Abbreviation	Impact indicator	Unit of measurement	Meaning
GWP	Global Warming Potential	kgCO2-Eq	Global warming potential is a relative measure of how much heat a greenhouse gas traps in the atmosphere. The global warming potential is calculated in carbon dioxide equivalents meaning that the greenhouse potential of emission is given in relation to CO2. The time range for the assessment is defined to be 100 years.
ODP	Ozone Depletion Potential	kgCFC-11-Eq	Ozone depletion potential represents a relative value that indicates the potential of a substance to destroy ozone gas as compared with the potential of chlorofluorocarbon-11 which is assigned a reference value of 1, resulting in an equilibrium state of total ozone reduction.
AP	Acidification Potential	kgCO2-Eq	The acidification of soils and waters occurs predominantly through the transformation of air pollutants into acids, which leads to a decrease in the pH-value of rainwater and fog from 5.6 and below. Acidification potential is described as the ability of certain substances to build and release H+ions and is given in sulphur dioxide equivalents.
EP	Eutrophication Potential	kgPO43-Eq	Eutrophication is the enrichment of nutrients in a certain place. It can be aquatic or terrestrial. All emissions of Nitrogen and Phosphorus to air, water and soil and of organic matter to water are aggregated into a single measure.
POCP	Photochemical Ozone Creation Potential	kgC2H4-Eq (ethylene-eq)	Radiation from the sun produces aggressive reaction products, like ozone, in the presence of nitrogen oxides and hydrocarbons.
ADPe	Abiotic Depletion Potential Elements	Antimony kg Sb-Eq	Abiotic depletion describes the reduction of the global amount of non-renewable raw materials and is determined for each extraction of minerals and fossil fuels based on the remaining reserves and rate of extraction.
ADPf	Abiotic Depletion Potential fossil fuels	MJ, net calorific value	Abiotic depletion describes the reduction of the global amount of fossil fuels.

Table 3.1 Impact categories in EN15804+A1. Source: EN15804+A1.

Life cycle impact assessment (LCIA)

Life Cycle Impact Assessment (LCIA), as a further development of inventory analysis, primarily aims to convert the inventory data of materials to a range of potential impacts[4]. The visualization of the data is now much improved owing to LCIA's advantage of being able to group and categorize the initial impacts on various aspects of the environment, i.e., different emissions that cause the same impact are converted into the same impact category, sharing a single unit.

Although the amount of method varieties in LCIA is relatively high, for instance, ecoinvent is currently employing as many as 17, as shown in Figure 3.4[34]. However, common impact categories are climate change, acidification, resource depletion, and so on, which usually cover human health, natural resources, and ecosystem quality[61]. Specifically, EN 15804, as the most widely applied international standard for producing EPD of building products, specifies 7 indicators with precise meanings and units, taken from the CML Impact Assessment method version 4.1, as shown in Table 3.1. Whereas 'EN 15804:2012+A2:2019', approved in 2019, has been updated to 13 indicators,

Method	Background publication
CML 2001	Guinée et al. 2001a; b
Cumulative energy demand (CED)	Own concept
Cumulative exergy demand (CExD)	Boesch et al. 2007
Eco-indicator 99	Goedkoop & Spriensma 2000a; b
Ecological Footprint	Huijbregts et al. 2006
Ecological scarcity 1997	Brand et al. 1998
Ecological scarcity 2006	Frischknecht et al. 2009
Ecological Damage Potential (EDP)	Köllner & Scholz 2007a; b
EDIP - Environmental Design of Industrial Products 1997	Hauschild & Wenzel 1997, DK LCA Center 2007
EDIP - Environmental Design of Industrial Products 2003	Hauschild & Potting 2005
EPS - environmental priority strategies in product development	Steen 1999
IMPACT 2002+	Jolliet et al. 2003
IPCC 2001 (Global Warming)	Albritton & Meira-Filho 2001; IPCC 2001
IPCC 2007 (Global Warming)	IPCC 2007
ReCiPe (Midpoint and Endpoint approach)	Goedkoop et al. 2009
TRACI	Bare 2004; Bare J. C. et al. 2007
USEtox	Rosenbaum et al. 2008
Selected LCI indicators	ecoinvent final reports

Figure 3.4 LCIA method employed in ecoinvent. Source: Implementation of Life Cycle Impact Assessment Methods: Data v2.2 (2010) ecoinvent report No. 3.

Abbreviation	Impact indicator	Unit of measurement
GWP-total	Climate change (total)	kgCO_2 eq
GWP-fossil	Climate change (fossil)	kgCO_2 eq
GWP-biogenic	Climate change (biogenic)	kgCO_2 eq
GWP-luluc	Climate change (land use and land use change)	kgCO_2 eq
ODP	Ozone layer depletion (ODP steady state)	kg CFC-11 eq
AP	Acidification potential (accumulated exceedance)	mol H^+ eq
EP-F	Eutrophication (aquatic freshwater)	kg PO_4^{3-} eq
EP-M	Eutrophication (aquatic marine)	kg N^- eq
EP-T	Eutrophication (terrestrial)	mol N eq
POCP	Photochemical ozone creation potential (tropospheric ozone formation potential)	kg NMVOC eq
ADPE	Depletion of abiotic resources - elements, ultimate reserves	kg Sb eq
ADPF	Depletion of abiotic resources - fossil fuels	MJ
WDP	Water use (Water (user) deprivation potential - weighted water consumption	m^3 (world equivalent deprived)

Table 3.2 Impact categories in EN15804+A2. Source: EN15804+A2.

as shown in Table 3.2, which will be mandatory to comply with from 2022. During the current transition period, EN 15804+A1 is still the main reference standard for most of the building product EPDs available in the market, existing simultaneously with EPDs produced in accordance with EN 15804+A2. Overall, LCIA helps designers and decision-makers gain a better understanding of resource utilization and the environmental harm caused by emissions[23].

Life Cycle Interpretation

The final step in LCA involves interpreting the results of LCI and LCIA in line with the set goals and scope, making it a systematic identification and quantification process. ISO 14044 also outlines a scheme for the interpretation phase with three key elements:

- Identifying significant issues based on previous data results (hotspot analysis).
- Conducting evaluation considering completeness, sensitivity, and consistency checks.
- Addressing conclusions, limitations, and providing recommendations.

In the context of building projects, the interpretation process is more complex given that it encompasses all preceding phases, especially when the functional unit and system boundaries are not straightforward and intuitive. Professional expertise is often required for thorough review and assessment.

Based on the graphical representation of LCA in the ISO 14040 standard, the entire LCA process can be summarized in Figure 3.5. In summary, performing LCA is not a process-oriented, linear research process without the possibility of revisiting. Instead, it is a synthetic and iterative assessment that requires ongoing review and adjustments as new data enters the pool. Particularly for building LCA projects, it is crucial to establish clear research objectives and scope with well-defined system boundaries, especially for ensuring the relative accuracy of comparison outcomes or individual assessment results.

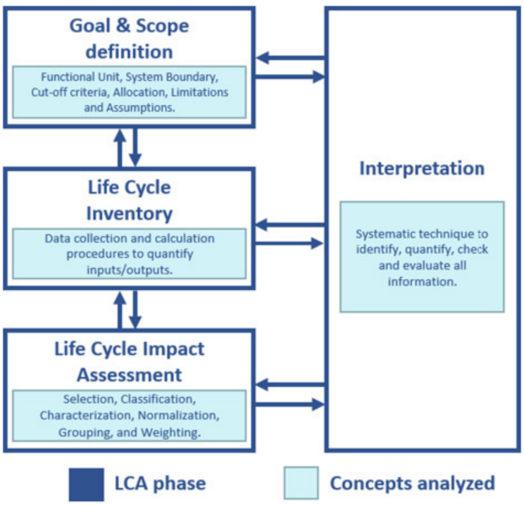


Figure 3.5 Conceptual framework of LCA. Source: Life cycle assessment for structural and non-structural concrete.

3.2. LCA tools for buildings

Hollberg summarized the mainstream LCA tools available on the market in a 2016 study and categorized them into four types: Generic, Spreadsheet-based, Online Component catalogues, and CAD integrated. He pointed out that for building projects, some LCA tools have limitations[35].

For instance, Generic LCA tools like Sphera (Gabi), SimaPro, and OpenLCA are more product-oriented and primarily intended for generating EPD reports. These tools often require manual data input and have limited interoperability with architectural software, making them less practical for building design. This sort of tool additionally requires a high level of specialization on the part of the researchers executing the study, making them less user-friendly for building projects.

On the other hand, Spreadsheet-based or online Component-Catalogs-based LCA tools, such as Athena EcoCalculator, have their own advantages and disadvantages to a greater or lesser extent. Typically, although they still require users to input bill of quantity (BoQ) manually, they have been simplified in terms of all data input compared to generic tools and are overall more relevant to the building project.

The commonality of these three categories of LCA tools remains the inability to provide designers with sufficiently convenient data interactions, avoiding labor-intensive manual data entry, and

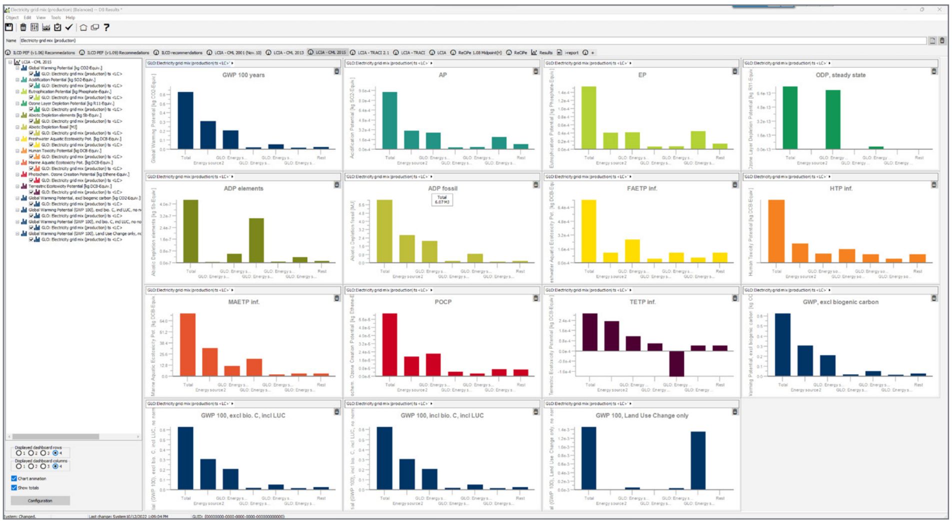


Figure 3.6 Sphera software interface. Source: Sphera.

facilitating LCA comparisons based on variables.

This has led to another category of LCA tools integrated into 3D computer-aided design programs, with Tally and OneClick LCA being prominent examples. These LCA tools are highly tailored to buildings, with more consolidated and holistic databases. OneClick LCA, in particular, covers databases from various regions.

Quantity takeoffs can be automatically generated from geometric models, allowing designers to quickly compare scenarios with different variables. In theory, these tools require geometric models with a wealth of building information, i.e., BIM. In the early stages of model development, when the models lacked maturity, it was impossible to perform LCA comparisons. However, with the gradual improvement of information such as prefabricated modular classes and building assemblies, as shown in Figure 3.7, even in the early design stages, architects can employ such information to make conventional assumptions for rough proposals. A quick comparison of designs based on certain assumptions can happen even when the architectural modeling is relatively rudimentary.

It's worth noting that the issue of lacking design-oriented integrated LCA tools, which can link early geometric models, calculate operational energy consumption, and provide optimization possibilities, as raised by Hollberg in 2016[34], has not been satisfactorily resolved to date. Although some tools such us OneClick LCA and Legep offers a basic framework in this direction, there is still a need for further investigation and validation, especially concerning the assessment of operational energy results and the provision of early preset assembly component information. A matching workflow for this also remains to be developed.

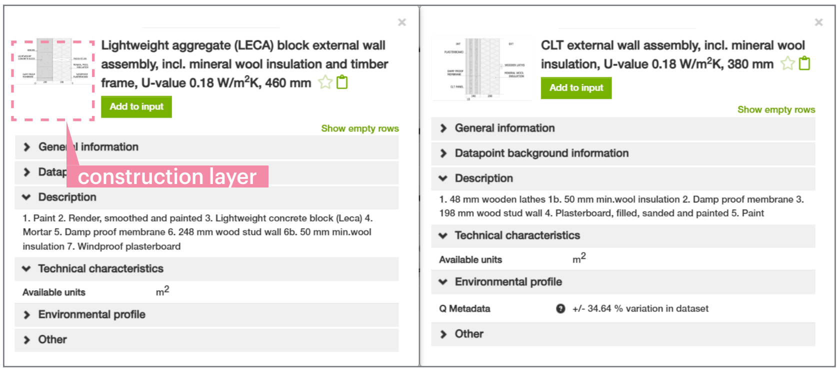


Figure 3.7 Building assembly applied in early design stage for LCA calculations in OneClick LCA. Source: Self-edited image from OneClick LCA.

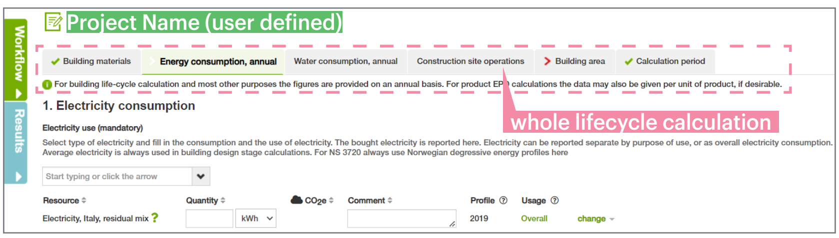


Figure 3.8 Workflow of LCA calculations applied in OneClick LCA. Source: Self-edited image from OneClick LCA.

	Tool Name	Type	Database	Advantage	Limitation	Link
Europe						
Germany	LEGEP	B	Ökobau.dat	• LCC included • Optimization allowed	• Offline • Regionalism	https://legep.de/?lang=en
Germany	Ökobilanz Bau	B	/	• Online • Architectural expertise	• Regionalism	https://www.oekobilanz-bau.de
Germany	OpenLCA	G	Multipule	• Free • LCC included	• Offline • Lack of architectual expertise	https://www.openlca.ORG
Netherlands	GreenCalc+	G	Multipule	• Optimization allowed	• Offline • Regionalism	https://www.nefab.com/en/solutions/optimization-programs/life-cycle-assessment
Netherlands	Ecochain	G	/	• Optimization allowed	• Offline • Regionalism	https://ecochain.com
Netherlands	SimaPro	G	Multipule	• International	• Offline • Lack of architectual expertise	https://simapro.com
Finland	One-click LCA	B	Multipule	• Online & Plug-in • Free • Architectural expertise • LCC included • International • Optimization allowed	/	https://www.oneclicklca.com
Fr	ELODIE	B	/	• Architectural expertise • Optimization allowed	• Offline • Regionalism	https://boutique.cstb.fr
Other						
Ca	ATHENA Impact Estimator	B	Athena Institute	• Free • Architectural expertise • Optimization allowed	• Offline • Regionalism	https://calculatelca.com/software/impact-estimator
US	Sphera (Gabi)	G	Gabi & Third-party	• International • LCC included	• Offline • Lack of architectual expertise	https://sphera.com/life-cycle-assessment-lca-software
US	Tally	B	Gabi	• Plug-in • Architectural expertise • Optimization allowed	• Regionalism	https://choosetally.com
UK	IMPACT (bre)	B	Ecoinvent	• Online • Architectural expertise • LCC included • Optimization allowed	• Regionalism	https://bregroup.com/products/impact/

B: Building/ G: Generic

Table 3.3 Common LCA tools. Source: Self-produced.

Table 3.3 lists the representative mainstream LCA tools available in the market for various regions and provides a comparison of the advantages and disadvantages of each software. It can be observed from the table that there are currently not many building-specific LCA tools available on the market, and most of the software has weaknesses such as the inability to be edited online and locational limitations. Amongst the building-specific LCA software, even fewer are able to support the early building design phase. Although some software can provide optimization of material information selection, such as LEGEP, Tally, and ELODIE, there is not yet any software that explicitly supports preliminary LCA calculations for the early stages of various building configurations.

3.3. Building Information Modeling (BIM)

While the BIM concept has been around since the 1970s[26], it was not widespread because of the limited hardware and software available in the early years. However, with the advancement of computer technology, the concept of BIM, a digital format for storing facility or building information, has gained significant popularity and evolution. As current most accepted definition of BIM: Building Information Modeling, emphasizes that essentially BIM is a technology for modeling information, which comprises all the relevant processes and information that enable a project to be constructed, communicated, and analyzed[26], ultimately producing a gigantic library of information throughout the entire lifecycle of the building. Most importantly, this library of information allows for collaboration and coordination between the multiple disciplines involved, leading a new mode of data flow, as shown in Figure 3.6. The BIM solution definitely improves the work quality, and efficiency, reducing the considerable cost of manual communication and interaction, thereby accomplishing many of the impossible.

BIM Dimension

Presently, BIM technology has expanded the possibilities of use cases in more dimensions as it continuously progresses. Although the application and definition of BIM in 3D is non-controversial,

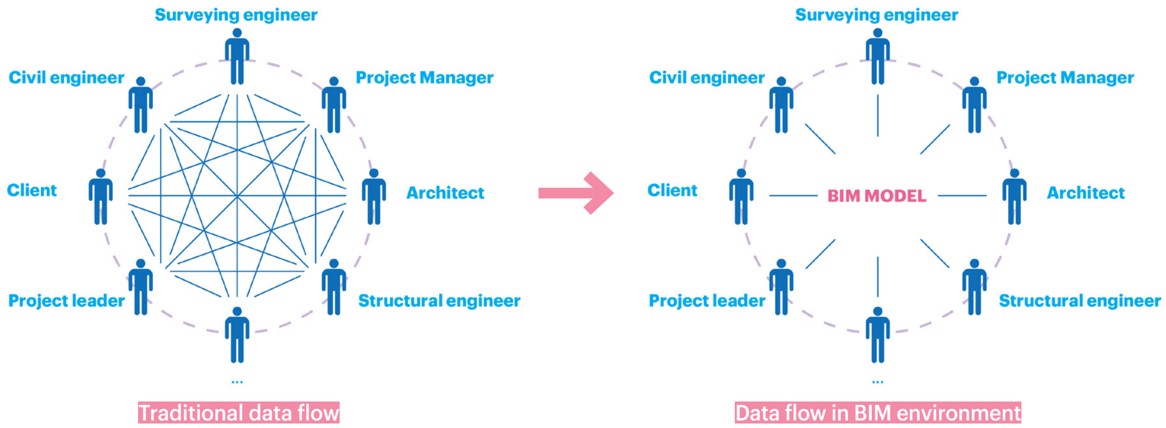


Figure 3.9 Data flow in the traditional and BIM model. Source: Self-produced.

there has been ambiguity and lack of clarification in defining the other dimensions in the past time. However, for most practitioners who apply BIM in realistic projects as well as researchers in academia, the commonly accepted representation of 4D to 7D in a BIM environment are as follows[17]:

- **4D**: Relates to time, specifically planning and scheduling.
- **5D**: Concerns project costs.
- **6D**: Typically involves sustainable strategy throughout the overall lifecycle of the project, such as the consideration of energy consumption early in the design phase.
- **7D**: Relates to operations and facility management, ensuring the building's ongoing optimal serviceability of the building.

These different dimensions of project content generally reach the present various necessities on building projects, but also further accelerate the trend of synchronizing and sharing all the data of each discipline in the 3D BIM model.

Level of development (LOD)

Along with the different phases that a project passes through, the level of development of the BIM model will also be raised to several levels. Should the BIM dimension define the varying service content that an information model should provide, the concept of LOD, proposed by the American Institute of Architects (AIA) in 2008[24], defines how detailed a BIM model needs to achieve for delivering services. According to the latest publication of LOD definitions elaborated by bimforum, LOD has evolved from five levels, ranging from 100-500, with the addition of LOD350, to the current six levels[27].

Distinguishing from what has been interpreted at times as a level of detail, LOD is now normatively defined as a level of model development, referring to the reliability of the output that can be

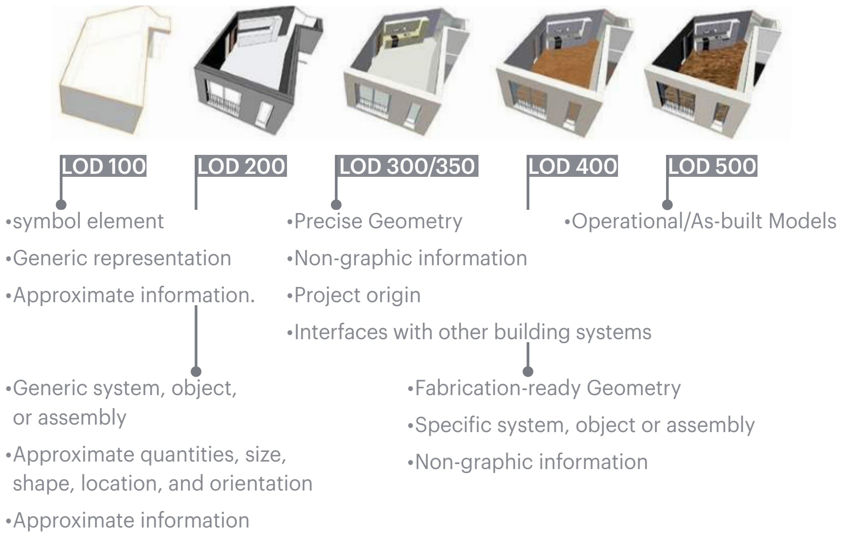


Figure 3.10 BIM model at LOD 100, 200, 300/350, 400, 500. Source: datbim.com.

depended upon for use by all other project stakeholders. In highly collaborative environments, the LOD framework establishes standards for the model that can be shared for communication and collaboration among different disciplines.

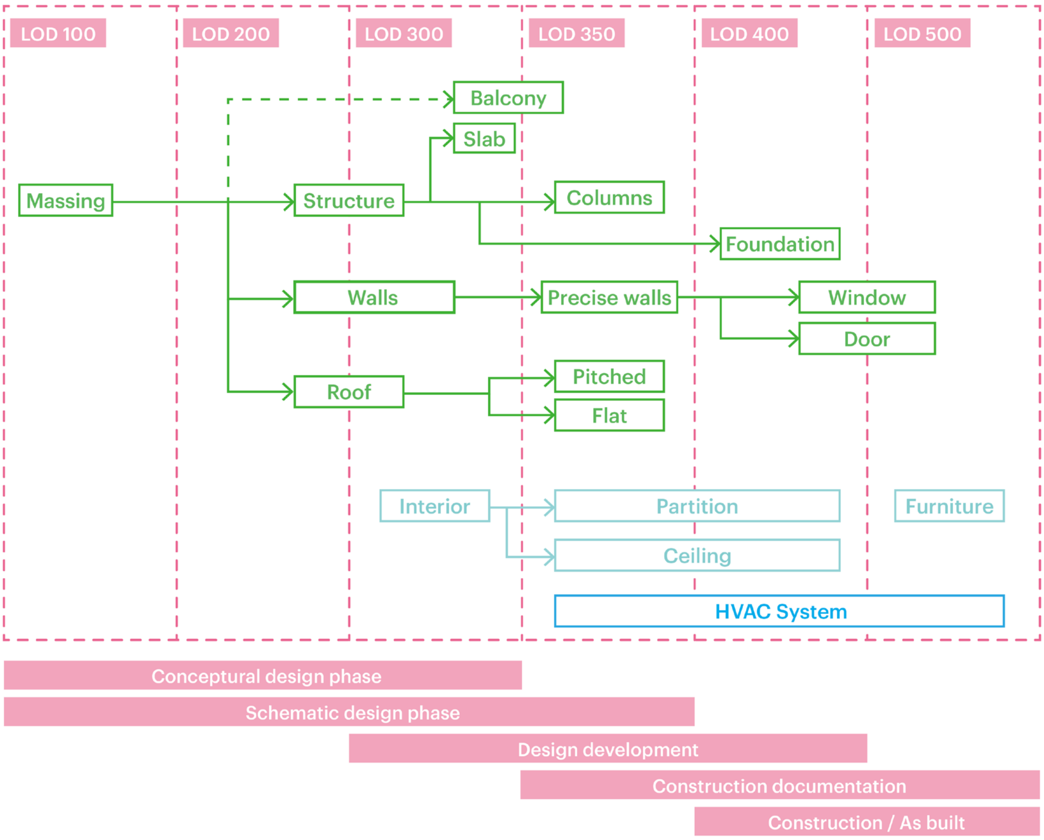


Figure 3.11 Design phase with elements under each level of development of BIM model. Source: Self-produced.

However, for architectural designers, the concept of LOD is not deliberately emphasized during non-deliverable time points. The enrichment of building information for architects depends more largely on the different design phases. The relationship between the definition of the design phase and the LOD is not a one-to-one correspondence. At a given time different elements may be developed to different levels, such as the Schematic Design phase may contain walls at LOD 100, the facade system at LOD 200, or even structure at LOD 300. The author has drawn the following diagram according to the experience of the actual working experience and the LOD specification, to illustrate the relationship between the LOD and the design phases, and the approximate time nodes of the architectural elements appearing sequentially during the progression of the design, as shown in Figure 3.11.

No less important is the clarity on the information capabilities of the BIM model at different LOD levels, namely, how to utilize the model's geometrical data or non-image data at different LOD levels. In the Approved Use Guide provided by the Real Estate Department of the U.S. General Services Administration (GSA), an example of model content and LOD matrix is given[51]. Taking the sustainable requirements in BIM 6D applications as an illustration, the User Guide states that strategic concept proposals should be made from the LOD 100 level of modeling, where the BIM model can provide approximate material quantities at the LOD 200 level. The more maturity the model develops, the increasingly accurate the information needed for sustainable strategy implementation should emerge.

Model Content	LOD 100	LOD 200	LOD 300	LOD 400	LOD 500
3D Model Based Coordination	Site level coordination	Major large object coordination	General object level coordination	Design certainty coordination	N/A
4D Scheduling	•Total project construction duration. •Phasing of major elements.	Time-scaled, ordered appearance of major activities	Time-scaled, ordered appearance of detailed assemblies	Fabrication and assembly detail including construction means and methods (cranes, man-lifts, shoring, etc.)	N/A
Cost Estimating	•Conceptual cost allowance •Assumptions on future content.	Estimated cost based on measurement of generic element (i.e. generic interior wall)	Estimated cost based on measurement of specific assembly (i.e. specific wall type)	Committed purchase price of specific assembly at buyout	Record costs
Sustainable Materials	LEED strategies	Approximate quantities of materials by LEED categories	Precise quantities of materials with percentages of recycled and/or locally purchased materials	Specific manufacturer selections	Purchase documentation
Analysis/ Simulation	Strategy and performance criteria based on volumes and areas	Conceptual design based on geometry and assumed system types	Approximate simulation based on specific building assemblies and engineered systems	Precise simulation based on specific manufacturer and detailed system components	Commissioning and recording of measured performance

Table 3.3 Approved Use Guide. Source: Real Estate Department of the U.S. General Services Administration (GSA).

3.3. BIM-LCA Integration

EOver recent years, there has been a continuous endeavor by scholars in varying directions focusing on BIM-LCA integration as the subject. Some scholars have explored the LCA workflow integrated into the BIM environment in an attempt to identify how environmental impacts can be factored into the complex decision-making environment spanning the entire building lifecycle[43, 75]. Some scholars have analyzed multiple LCA studies seeking to derive empirical values for environmental impacts on specific building types (e.g., per square meter of floor area)[59]. In some cases, studies have aimed at addressing specific comparisons of building materials in the early stages of LCA studies[2, 48], and in some cases, energy simulation comparisons during the operational phase have also been included in the scope of the study for continuity purposes[5, 53].

Empowered by the strengths of BIM technology, researchers in building LCA are becoming increasingly interested in integrating LCA into the building design process expeditiously, allowing for the assessment and improvement of building lifecycle performance in the early design phase[58], as shown in Figure 3.12, thereby avoiding the risk and potentially high cost of drastic changes associated with the implementation of LCA at the later design stage.

The popular goal of BIM-LCA integration studies is through feasible efforts to either develop workflows for monitoring sustainable design decisions by integrating existing applications[7, 29] or

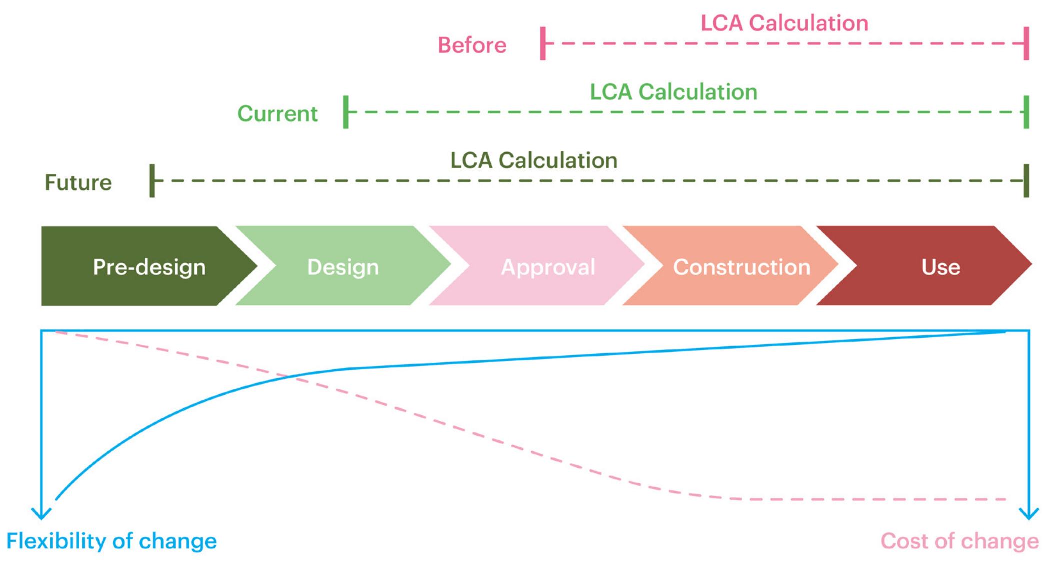


Figure 3.12 LCA integration along with design process. Source: Self-produced.

to provide LCA data to guide decision-making by means of developing simple applications or by executing self-produced code[35, 39, 49]. More specifically, Tam et al. categorized the research topics related to BIM-LCA over the past decade into five groups[66]:

1. **Comparing design alternatives:** This involves using BIM-LCA to compare different design options in terms of construction methods, materials, and structural systems for their environmental impacts.
2. **Identifying hotspots of the environmental impacts of a building:** This can help to provide design guidance and optimize design strategies.
3. **Carrying out parametric modeling for optimal design:** This refers to parametrically modeling building geometry, boundary systems, and so on.
4. **Improving BIM-LCA integration approaches:** This involves solving the issues related to misalignment between BIM data and LCA data.
5. **Conducting sensitivity analysis:** This is carried out to test how design variables impact building environmental performance.

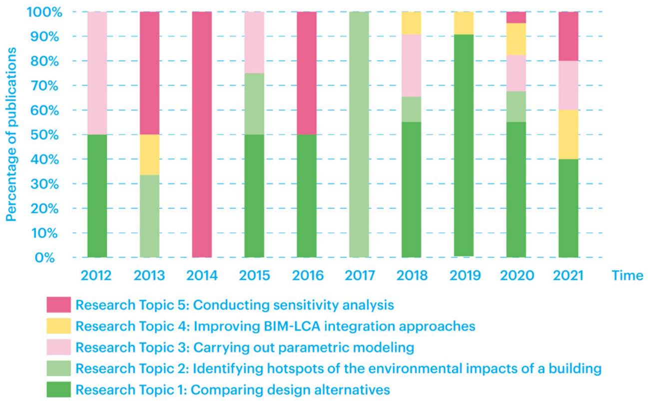


Figure 3.13 Percentage of publications distributed among different research topics from 2012 to 2021. Source: [63].

The authors have also developed Table 3.4 based on studies published in the last decade concerned with the embodied environmental impacts of buildings in BIM environments, with an emphasis on the comparison of the objectives, methodologies (e.g., software used and data exchange formats), database sources, and LOD of the BIM models employed in these studies.

The majority of these studies adopted the approach of extracting material quantities from the BIM model to establish material inventories for the assessment[58]. The authors identified the following issues in these early studies:

1. The information contained in the BIM geometric model was not sufficient to support the execution of a full LCA[25].
2. The manual exporting of the bill of materials by the researcher was time-consuming[39].
3. The system boundaries of LCA and the LOD level of the

BIM model, especially specification on low LOD levels, are not clearly and rigorously defined, resulting in non-interoperable integration methods.

4. The presentation and readability of the LCA conclusions and data in visual display still remain to be improved.

Such challenges could lead to undesirable consequences, which include the inability to efficiently evaluate multiple options and compare the outcomes in a short period, the inability to purposefully optimize the unsatisfactory options, the lack of compatibility and fragmentation of methodological frameworks between different studies, and the fact that architectural designers still need a certain threshold to understand the LCA results.

With the development of visual programming tools, the efficiency of data exchange between BIM and LCA has been improved[60]. BIM plug-ins available in LCA software such as OneClick LCA are even more powerful for quickly exporting the designer's customized material quantity-takeoff with a single click. The popularity of parametric design has also assisted to an insignificant extent in optimizing design decisions, and even multi-objective optimization studies based on LCA results have emerged[13].

It indicates that the current research approach is distinguished from the previous BIM-LCA research in that it should break down the disciplinary barriers and provide user-friendly as well as reliable LCA results that can be interpreted and communicated efficiently in order to support early architectural decision-making. The new tools developed should be more dynamic, and integrated into the building design process, enabling the comparison of multiple alternatives to optimize the performance of the building, evaluating the range of LCA results rather than exact value in early design stages with a unified structure of BIM and LCA data[66]. Such tools and methods can fundamentally improve the popularity and applicability of LCA in the architectural design process.

Table 3.4 Existing BIM-LCA studies. Source: Self-developed.

Year	Author	Paper Title	Software Use
2014	Jalaei and Jrade	An Automated BIM Model to Conceptually Design, Analyze, Simulate, and Assess Sustainable Building Projects	Revit, Ecotect, IES-VE, Excel, ATHENA Impact Estimator
2014	Wiberg *et al.*	A net zero emission concept analysis of a single-family house	Revit, Excel, SIMIEN, SimaPro 7.3, Polysun
2015	Ajayi *et al.*	Life cycle environmental performance of material specification: a BIM-enhanced comparative assessment	Revit, Green Building Studio, ATHENA Impact Estimator, Excel
2015	Georges *et al.*	Life cycle emissions analysisof two nZEB concepts	Revit, Excel, SIMIEN, SimaPro 7.3
2015	Lee *et al.*	Green template for life cycle assessment of buildings basedon building information modeling: focus on embodied environmental impact	Revit
2016	Hollberg and Ruth	LCA in architectural design—a parametric approach	Grasshopper, Rhinoceros, eLCA
2016	Peng	Calculation of a building's life cycle carbon emissions based on Ecotect and building information modeling	Revit, Ecotect, Excel
2017	Abanda *et al.*	Integrating BIM and new rules of measurement for embodied energy and CO2 assessment	Revit, Navisworks, Excel
2017	Najjar *et al.*	Integration of BIM and LCA: Evaluating the environmental impacts of building materials at an early stage of designing a typical office building	Revit, Tally, Green Building Studio
2018	Bueno *et al.*	Comparative analysis between a complete LCA study and results from a BIM-LCA plug-in	Revit, Dynamo, Excel
2018	Nizam *et al.*	A BIM based tool for assessing embodied energy for buildings	Revit, Tally
2018	Rock *et al.*	LCA and BIM: Visualization of environmental potentials in building construction at early design stages	Revit, Dynamo, Excel
2019	Cavallier *et al.*	Continuous BIM-based assessment of embodied environmental impacts throughout the design process	Revit, Rhinoceros, Excel
2019	Naneva A	The Potential of Digitalization for Sustainability: A Building Process Perspective	Revit, Dynamo, Excel
2019	Rezaei *et al.*	Integrating building information modeling and life cycle assessment in the early and detailed building design stages	Revit
2022	Kamari *et al.*	A BIM-based LCA tool for sustainable building design during the early design stage	Revit, Self developed plug-in

Database	interaction	Life-cycle stage	LOD	Service life
EcoScorecard©[1], ATHENA Impact Estimator	gbXML, Revit API (C#)	A1–A4	Not specified	Not specified
Ecoinvent Version 2.2	gbXML	A1-A3, B4	Not specified	60 years
ATHENA Impact Estimator	gbXML	A, B, C, D	200	30 years
Ecoinvent Version 2.2	gbXML	A1-A3, B1, B4	Not specified	60 years
Korea life-cycle inventory (Adapted from ISO standard)	Not specified	Not specified	300	40 years
ÖKOBAUDAT	Grasshopper plug-in	A1–A3, B4, B6(water deducted), C3, C4	Not specified	50/100 years
ICE database	Not specified	A, B, C(not clear)	Not specified	50 years
ICE database	gbXML	A1-A3	Not specified	Not specified
GaBi database	Tally plug-in	A1-A3, B, C	Not specified	50 years
ReCiPe 2008	Dynamo	A, B, C(not clear)	Not specified	40 years
ICE Database	Tally plug-in	Not specified	Not specified	60 years
Ecoinvent	Dynamo	A1-A3	200	60 years
KBOB, Swiss Building Database, BauteiKatalog		A1–A3, B4, C3 and C4	100-400	60 years
KBOB	Dynamo			
Ecoinvent 3.3	Not specified	A, B, C(not clear)	100-300	60 years
ÖKOBAUDAT (EN 15804), GNF	Revit API (C#)	A1-A3	100-200	Not defined

3.3. What architects can learn from BIM-LCA integration?

To date, despite the efforts in BIM-LCA-related research to enhance the effectiveness of the involvement and contribution of LCA in the early architectural decision-making stages, BIM models used to evaluate comparisons of material combinations for different building components, as proposed in the methodology of Rock et al. still typically operate at LOD 200 level[58]. Additionally, studies conducted using LOD 100-200 stage BIM models, as declared by Kamari et al., are often focused on the material environmental impacts of one single building proposal in terms of morphology[39].

The workflows and research objectives of the existing studies, namely testing different material combinations on building components to provide arguments in favor of optimizing material choices through hotspot and sensitivity analyses, have not yet addressed the potential of LCA to contribute to the genuine early architectural design phase, specifically the phase of decision-making regarding massing and morphology of a building.

When the level of detail of the digital model remains at LOD 100, deliberation on the building massing can often be extensive. For architects, the conventional aspects that need to be taken into account in determining the building's overall massing include the context, orientation, functional requirements, required floor area, and so on. Architects, then based on these constraints and their own judgment, will select the optimal massing proposal in the early design stage.

With the pursuit of sustainable goals in recent years, more architects also adopted sustainable strategies such as optimizing the surface area of volumes based on energy efficiency, maximizing daylighting hours based on solar orientation, or optimizing the layout of building clusters based on wind conditions. It indicates that many of these sustainable strategies, to varying degrees, will influence the form of the building as well. However, there is still a lack of reflection and investigations exploring how building massing is directly or indirectly influenced from an LCA perspective.

In the application of 6D BIM, sustainable strategies are executed along the whole life cycle, being planned from the very start of the project[52]. The earlier multidisciplinary collective has been deliberated, the more synthesized and sophisticated architectural decisions can be made. Examining whether different building morphologies signify different embodied environmental impacts is a strategic step in fully integrating LCA into the early building design stage. This eliminates the limitations of early-stage LCA in previous studies where it could have only a monolithic effect on design modifications in terms of materials.

It is recognizable that the building LCA is a calculation of all possible environmental impacts throughout the life cycle, focusing mostly on materials in the early stages, resource consumption in the operational phase, and waste disposal during the demolition phase.

Comparing the LCA of different volume scenarios cannot fundamentally alter many of the objective requirements of the building. For example, residential buildings have constraints on volume depth to achieve natural ventilation, and public buildings have requirements for higher-quality public spaces (e.g., open and high-ceilinged space). It can be stated that early decision-making in architecture is a complex, multifaceted, and synthetic process. The impact of LCA is not absolutely dominant.

The idea of the early comparison of LCA for multiple volume scenarios in the BIM environment was intended to offer an additional perspective and to facilitate the integration of subsequent LCA calculations, leading to a seamless, scientific design pipeline. Once the data presentation of LCA no longer has profound professional barriers, the BIM-LCA software becomes more user-friendly, and the exchange of LCA-BIM data becomes smoother and more efficient, it is the ultimate goal to broaden the accessibility of LCA by enabling the architects to design with a life-cycle perspective from the very beginning.

4 | New methodology: LCA tools for comparing building massing

This chapter primarily explains the approach of how the massing design process of a building can be influenced from the LCA perspective in the early stages of architectural design. It also elaborates on the tools developed during the exploratory process for calculating LCA results. However, due to the complexity of the form-finding process in the early stages of a building, it is crucial to strictly define the timing of LCA's intervention.

As pointed out in the previous chapter, many of the design parameters are objective constraints that cannot be altered, such as required gross floor area, building's typological characteristics (e.g., restrictions on volume depth for better ventilation and lighting in residential buildings), orientation, and so forth. LCA is limited in its usage and directivity, which needs to be combined with other design parameters from non-LCA perspectives to assist the designer in making a decision.

Therefore, the methodology and workflow proposed in this chapter is a early massing design process for buildings based on integrating sustainable ambitions as much as possible. There are major explanations on how to incorporate LCA, in what manner, and at which time point should the LCA be stepped in. The new design methodology will synthetically integrate objective design parameters, exemplary parameters that selected as particularly relevant in the current scenario, potential sustainable strategies screened by the authors, and LCA outputs, to clearly define the sequencing in considering different design parameters in the massing-finding stage. This is to present a complete application paradigm for the new BIM-LCA integrated workflow.

The aim is to clarify how architects can bring the material perspective and life cycle thinking into the design decision-making process as early as possible, in pursuit of better sustainability, and to make comparatively unbiased decisions from a multidisciplinary perspective in the early design process, where offers more flexibility and lower cost of changing. Simultaneously, the new BIM-LCA integration method also facilitates architects' consistent participation in subsequent LCA, increasing the accessibility of LCA.

In the workflow developed by the authors, LCA serves as a tool which can evaluate environmental impact to assist the architect in decision-making related to sustainable aspects which is not able to independently support the designer in the generation of diverse architectural massings. Consequently, the LCA-assisted decision-making aspect should arise after an initial shortlisting of alternatives that comply with other parameters and requirements.

The architect begins with the production of varying volumetric options based on the known project conditions and the architect's judgment (e.g., coupled with promising sustainable strategies). At this stage, the LOD level of the BIM model stays at 100, which is a phase lacking data on specific building elements and materials.

Accordingly, the second step in this new BIM-LCA integration method is to efficiently upgrade the LOD-100-BIM model to a level close to LOD 200 through automated parametric modeling. All parameters in this automated modeling process can be customized and adjusted as needed.

Once the BIM model, which can be used for the rough material's quantity take-off, has been obtained, the key step in the workflow, LCA calculation, will be detailed in section 4.2. It begins with the identification of LCA-related parameters, including the life-cycle stage, system boundaries, impact indicators, etc. Following this, LCA results for the three structural systems (reinforced concrete structure, steel structure, and timber structure) will be generated by calculating their overall environmental impact. Ultimately, the range of LCA results obtained for each massing option will be presented, along with additional LCA data from hotspot analysis for further comparison.

The fourth step focuses on data analysis based on the existing LCA data, creating automated GUI dashboards to produce LCA reports for each massing alternative where clarity and readability are guaranteed.

Finally, architects can assess the strengths and weaknesses of different massing options from an LCA perspective, conduct comparative analysis, and facilitate optimization and decision-making.

4.1. Phase 1: Generation of massing alternatives

4.1.1. Define design parameters

In most well-industrialized regions, the building design process has been broken down into five steps, from conceptual design at the beginning, schematic design to design development, construction design, and final execution. Each stage brings separate rules and limits. Yet not all of the constraints need to be considered at the beginning, given that this study investigates the feasibility and implementation of LCA in comparing massing alternatives, the design parameters will mainly be emphasized before jumping into the schematic design phase, which is associated with the general configuration of the building.

Mandatory parameters

For architecture, massing represents the overall logic coupled with the feeling of forms and spaces. Mandatory parameters and constraints form the foundation that supports the reasonable operation of design solutions. Design problems are often multi-dimensional and highly interactive[45], therefore mandatory parameters can be drawn from multiple sources. However, limited mandatory parameters are imposed to a certain extent to be complied with. The author classifies them into three categories, including:

1. The typological parameters associated with the functionality of the building itself (e.g. the spacing between regular residential blocks ought to not be too small to avoid impacting natural lighting, the general deepness of public buildings tends not to be too small to impact the evacuation of occupants, etc.)
2. Program requirements (e.g. specific functional configurations and area requirements).
3. Local regulations in the project location.

These three categories of mandatory design parameters can be expanded to numerous depending on the complexity of the project. In this methodology, the author takes an example of the regular residence to illustrate the objective parameters that will be employed at first in this methodology, as listed in Table 4.1. In other future studies, as building functions alter, the parameters specified at this stage will be adapted accordingly.

Mandatory Parameters		
Residential building (Regular)		
Typology	Program	Local Regulations
•Maximum depth of individual volume	•GFA (gross floor area) •Area above ground •Area below ground	•Required setback of the property line •Maximum height •Minimum storey height •Minimum spacing between blocks •...(More according to specific local code)

Table 4.1 Mandatory parameters adopted in the methodology. Source: Self-developed.

Optional parameters

The constraints listed alone are incomplete to support the generation of massing alternatives, and the design requires additional parameters. Despite the fact that the scope of the selected inputs is sharply circumscribed, the possibilities of parameters are still diverse. In addition to mandatory parameters, subjectively determined parameters play another significant role in evaluating the quality of an early massing proposal, or in developing an appropriate starting point for massing generation. Unlike mandatory parameters, not all optional parameters need to be considered.

Optional parameters can be approached from various perspectives, such as social-economical, natural-geographic, urban, environmental, technical, cultural, and aesthetic categories that Abyzov has argued[3]. They can also be characterized in two broad groups in terms of whether they can be quantified or not. Different categories can lead to a wide range of specific design parameters.

The selection of optional parameters can differ greatly in accordance with each design methodology. In this methodology, the emphasis is on choosing specific, quantitative parameters with quantifiable evidence to facilitate decision-making, rather than utilizing qualitative parameters related to aesthetic preferences that demonstrate the architect's own design sensitivities. In line with the goal of better environmental performance, the author selects the optional parameters related to sustainability for preliminary massing optimization and filtering at this stage. The choice of these quantifiable parameters will be limited to those directly relevant to the geometric aspects of the building massing. It should be noted that the parameter selection here can be substituted in different contexts.

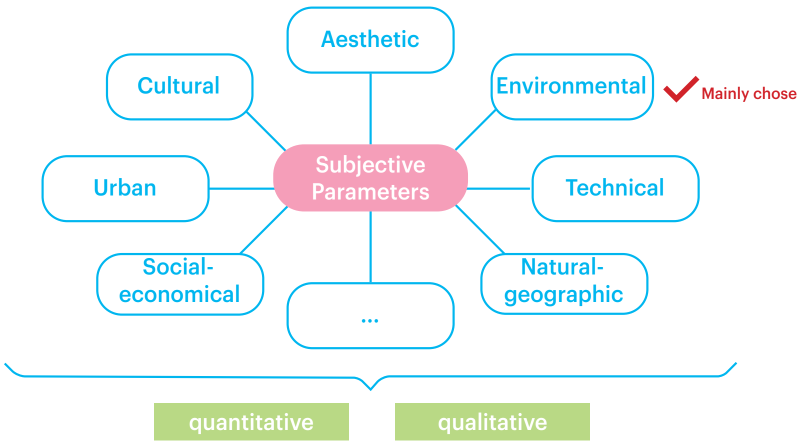


Figure 4.1 Catogery of optional parameters. Source: Self-produced.

Environmental parameters

As Clarence reviewed Barnabas's book said "If we follow Calder's logic that "form follows fuel," it seems that architects and builders will have to reinvent their various modes of intervention within the built environment during the post-carbon age[31]." The parameters that the author selected in this methodology reflect more on the consciousness of low-emission pursuit and carbon sequestration. More importantly, as mentioned earlier, it is advisable that these environmental parameters should be capable of establishing a direct correlation with the geometric inputs of the building volume. As shown in Table 4.2, the author enumerates the possible environmental parameters and indicates whether there is a direct association with the building massing. For instance, taking green systems as an example, especially the measure of implementing roof green systems with rooftop photovoltaic panels, can be directly linked to the geometrical dimensions of the roof area.

	Environmental parameter	Geometrical direct link	Potential Benifit for LCA	Potential drawback for LCA
Climate	Sun hours	Overall massing surface area	Lower heating needs	Higher cooling needs
	Solar orientation	\	Lower heating needs	Higher cooling needs
	Natural ventilation	\	Lower cooling needs	\
Greenery	Vertical green wall	Facade area	Sequestration, Lower cooling needs	Increase maintenance impacts
	Green roof	Roof area	Sequestration, Lower cooling needs	Increase maintenance impacts
Techinical	Roof PV panel	Roof area	Lower environmental impact	Increase embodied impacts
	Glass PV panel (for facade)	Facade area	Lower environmental impact	Increase embodied impacts
Others	View analysis	\	\	\
	Noise analysis	\	\	\
	...			

Table 4.2 Relationship between possible environmental parameters and geometrical dimension of massing. Source: Self-developed.

In addition to design strategies that focus on optimizing the building envelope in later stages, the integration of greenery systems with buildings for better thermal performance and the integration of renewable energy production (e.g. PV systems) have become mainstream in recent years. It is not only because of its great potential to improve the urban environment, such as promoting air quality, water storage management, and dense vegetation but also its potential to minimize the urban heat island effect and decrease carbon emissions, thus reducing energy consumption[55, 63, 69]. The implantation of the greenery system is even included in the passive house design strategy due to the additional benefits in terms of insulating impact in winter and shading in summer[15,54].

Furthermore, many researchers have suggested the potential of greenery systems in carbon sequestration at varying intensities[64, 72], in particular, the performance of green roof systems on carbon capture is much more remarkable than that of vertical green wall systems[9], along with the quantitative carbon sequestration figures derived from practical case studies. In addition, the integrated application of roof composite systems, combining PV panels and green roof systems, has also gained wider recognition in recent years.

Since both roof PV panels and green roofs have the same direct geometrical association with the roof area, they have been together selected in this methodology as subjective environmental design parameters for generating massing alternatives in order to co-benefit the final LCA results. Although there does exist a broader range of sustainable design strategies that deserve to be accounted for as subjective parameters as shown in Table 4.2, a green roof system with PV panels serves more as a starting point to demonstrate how the entire workflow functions.

4.1.2. Generation of massing alternatives

After identifying the subjective and mandatory design parameters in this methodology, before proceeding to the LCA study, the architect should perform the initial generation of the volumetric proposal based on all available quantifiable parameters known at this point in time.

Architects should begin by clarifying the maximum three-dimensional design envelope approved within the site based on all objective conditions, including height limits, site boundary setbacks, and neighborhood daylighting demands, etc. Then, considering other mandatory conditions such as storey-height requirements or plot ratio, combined with programmatic requirements for gross floor area, architects can roughly outline various massing options that meet all the fundamental parameters. These massing proposals can either be centralized and singular or be fragmented in different positions on the site, aiming to enable architects establishing the fundamental spatial relationship between the new construction and the site.

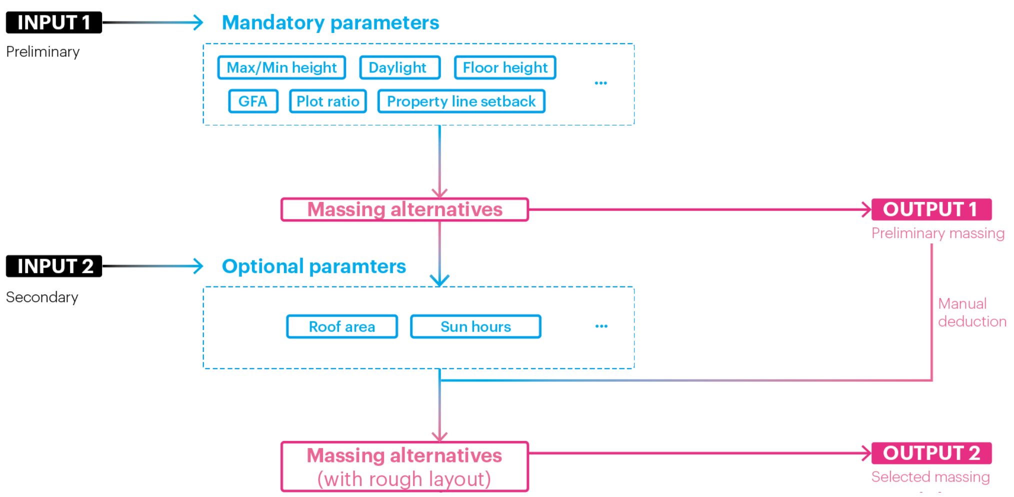


Figure 4.2 Workflow of the massing generation process . Source: Self-produced.

After generating rough massing options, the architect will be required to optimize and select the massing in accordance with optional aspects. In this methodology, the appropriate roof area, as a quantifiable and intuitive piece of evidence, will be considered as one of the filters. More qualitative aspects may also contribute at this stage, depending on the circumstances of the project. For instance, in regions where the climate is relatively cold, or where the heating demand is relatively high in winter, the total sun hours gained by the entire building surfaces can also be considered as one of the quantifiable parameters.

4.1.3. Automation of modeling

Define LOD level

According to the specification of the level of development for building information models published by BIMforum, a BIM model at LOD level 100 contains no precise elementary data beyond the generic representation, suggesting that such a low-LOD-level model is incapable of directly delivering material quantity for LCA calculations[27].

From the previous research, it can be found that quite BIM-based LCA early studies adopted the model with least 200-LOD-level for quantity take-off [5, 58], then classified the building elements for strictly aligning the collected environmental impact profiles of materials to the respective quantities, and the purpose of those research remains in selecting a more appropriate allocation of construction materials for one particular massing option. Instead, in view of the intention herein lies in providing comparative LCA results for multiple massing options at the early decision stage, the model's LOD level remains at LOD 100 as mentioned before. Consequently, in this approach, parametric computer-assisted modeling will be utilized to automatically model some of the building elements in order to quickly obtain the predicted material quality, enhancing the LOD level from 100 to almost 200.

Software selected

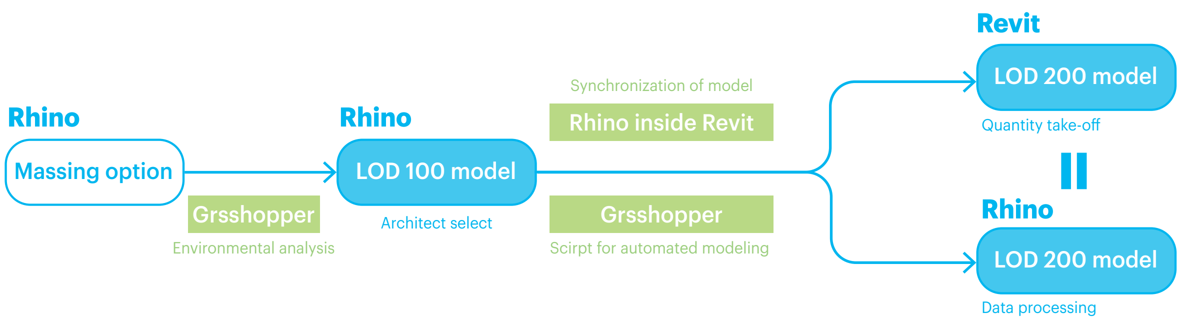


Figure 4.3 Software selection and the utilization in entire workflow . Source: Self-produced.

From previous BIM-LCA integration studies, it can be found that the development of BIM models in relative studies was usually carried out with Revit software[39, 49, 51, 56], benefiting from the built-in technical information directly provided in Revit, such as volume or area of building elements. Only a few researchers performed data collection in Rhino[16, 35].

Nevertheless, Rhino and its accompanying extensive analytic, as well as visualized plug-ins, hold an irreplaceable advantage in terms of the early assessment of multiple options. Grasshopper today represents a much freer and more sophisticated environment, both in terms of interactivity with external databases and in terms of its own ability to process data using Python or C# programming.

Many well-known architectural firms rely on these tools for their early design stages as well. Additionally, with the maturation of the Rhino-inside-Revit plugin, the integration between Rhino and Revit ceased to be an obstacle, enabling a comprehensive LCA evaluation from the beginning of the conceptual phase by pooling the respective strengths of both software.

Thus continuing the parametric supplementation of the building elements by grasshopper, it is possible to retrieve complete parameters and data about each component in real-time under the Revit environment so as to facilitate the subsequent development of BIM work. This has become the final chosen software-related workflow.

Script for automation of modeling

The author has developed a script in Grasshopper to automate the modeling process, aiming essentially to equip the volumetric model with all structural elements, including beams, columns, foundations, floor slabs, and envelopes, promoting the LOD level from 100 to 200. The Script, thus, enables the model to be capable of initially extracting component material quantity for subsequent LCA studies.

The Script for modeling building elements consists of three parts. First is the part of fundamental parameters that can be freely defined or modified by the designer, including grid spacing, floor height, total number of floors, ground-floor height, and column

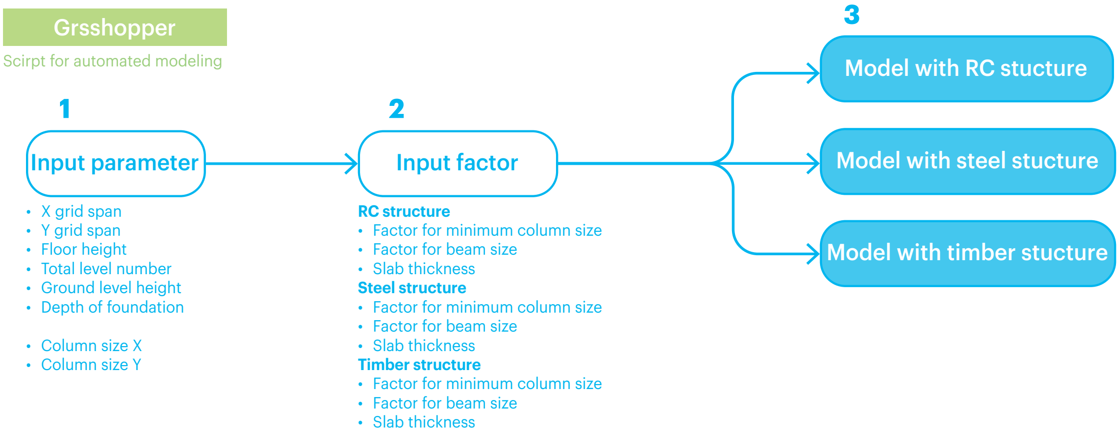


Figure 4.4 Framework of the script for automation of modeling. Source: Self-produced.

dimensions. The second step involves calculating code-compliant beam dimensions based on the input information and conventional structural system size principles[67]. It also verifies column dimensions that designers assigned before to ensure they meet structural requirements. The third part is the specific script for the generation process.

To avoid biased results based on homogeneous structural material due to overly subjective preferences or lack of information, the automatic modeling procedure will provide three structural systems, respectively reinforced concrete, steel, and timber structures. The applied structural dimensional parameters for each will also be consistent with the conventional strength of the material[67].

The author argues that the aim of presenting three structures and subsequent quantity take-off is to establish a more holistic environmental potential for each option, indicating both the reality of the probable results as well as the extreme range, as opposed to focusing on one structural form with single specific values for environmental impacts at the early design stage.

The automated modeling process will ultimately provide LOD 200 models for three different structural systems. In these models, except for the floor slabs in the steel mode, where the concrete material is still adopted, the main beams, columns, and slabs will correspond to the respective structural systems, while the envelope can be customized by the architects as per regional contexts. Each massing option will thus result in three models for different structural systems, which will be used for subsequent LCA calculations.

Define parameters and factors for modeling architectural elements

The axial grid spacing and column dimensions under each structural system are optional self-defined parameters or the default values specified according to the building typology. In most cases, architects can use the typical grid dimensions and column sizes associated with the specific project type. However, in special circumstances, the adjustable parameters provide the flexibility needed for design modifications. The dimensions of the structural beam system are derived based on the criteria provided by rules of thumb for designing a load-bearing structure[66], as shown in Figure 4.5.

It should be specifically stated that since there is a relatively fixed profile of steel column and beam dimensions, for instance, after determining the required depth of the steel beam, the appropriate section profile in compliance with the EN 10365 standard will be adopted by means of a customized battery developed by C#.

Beyond the required factor of calculation pertaining to the three different structures, further inputs and specifications are also required for the model. The first input is the building height and the total number of floors. The ground floor height, separately defined from the other floor heights, is optional. The depth of the foundation should be set by the designer, while the basement parameters are not considered in this version of the schematic automation modeling process.

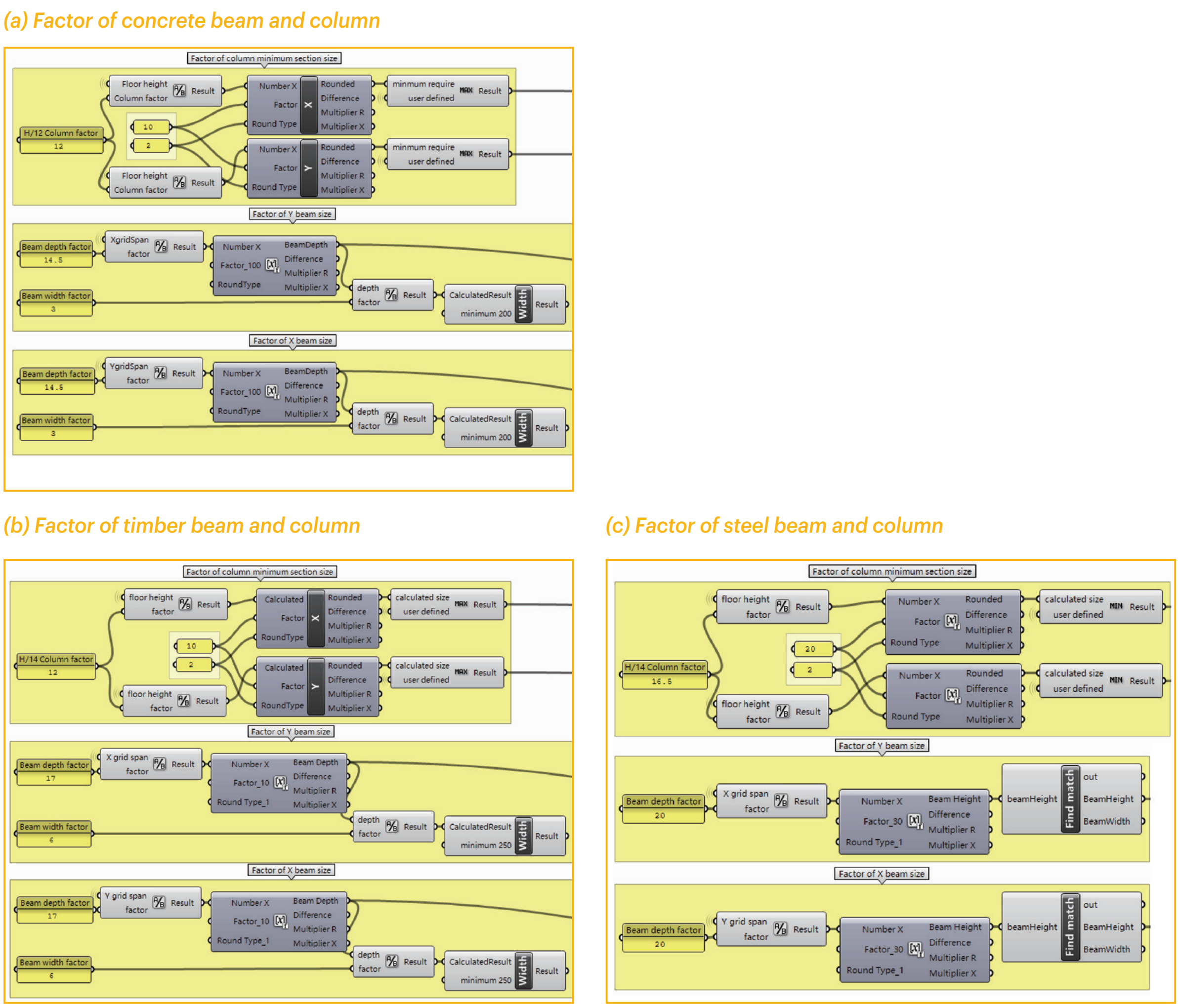


Figure 4.5 Factors applied for each structural system. Source:Self-developed.

Regarding the roof and envelope system with integrated multiple layers, parameters have been simplified with either customized options or, in the absence of a specific preference, have been given the common configuration that follows the building typology by default which will be elaborated on as follows.

Customize the type of each family in Revit

Simply completing the geometric modeling is not sufficient for LCA calculations, it's also necessary to assign the appropriate building materials to each building element. Aided by the Rhino-inside-Revit plug-in, the building components created in the above step can be seamlessly synchronized into the Revit environment. However, based on different modeling logics, as in Rhino, there is no need to strictly classify different building elements into separate families as in Revit, resulting in the necessity to create family types recognized by Revit based on the dimensions of the components calculated in the previous step. Simultaneously, the Rhino-inside-Revit plug-in allows specifying the component materials directly, thereby preparing for the next stage of the bill of material quantities take-off.

The accurate establishment of the family type is essential to guarantee the accurate quantity take-off of the different materials later for LCA calculations, therefore this methodology classifies, on a somewhat simplified basis, the family types into two catalogs, one involving solely a single material, referring to, structural

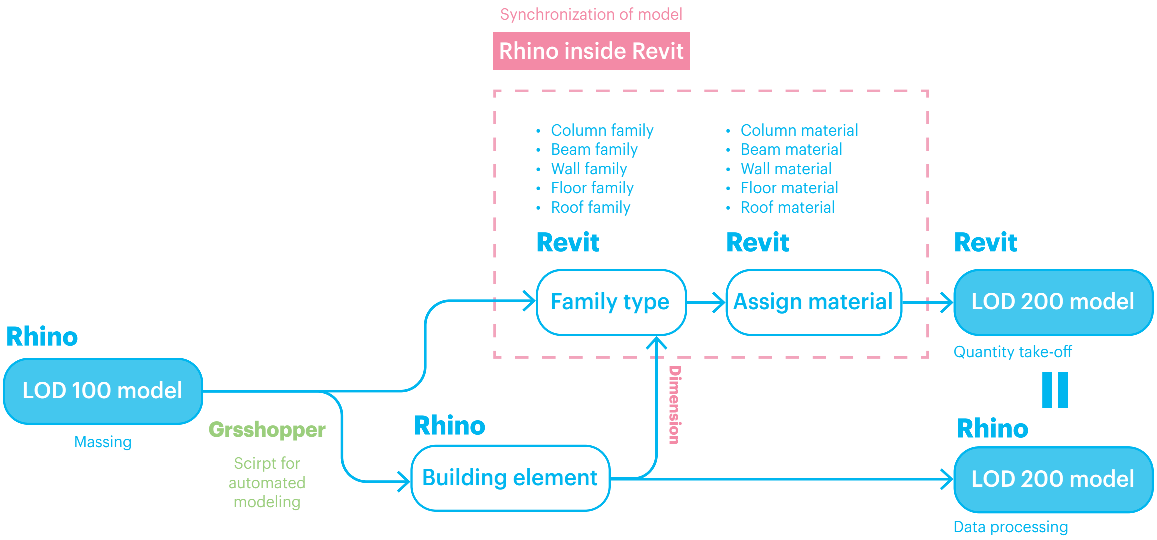


Figure 4.6 Workflow of customize the type of each family in Revit . Source: Self-produced.

elements: beams, columns, structural slabs and foundations. The family types of such elements simply require the corresponding geometric dimensions to be defined.

The accurate establishment of the family type is essential to guarantee the accurate quantity take-off of the different materials later for LCA calculations, therefore this methodology classifies the family types into two catalogs, as depicted in Figure 4.6. The first one involves solely a single material, referring to, structural elements: beams, columns, structural slabs and foundations. The family types of such elements simply require the corresponding geometric dimensions to be defined.

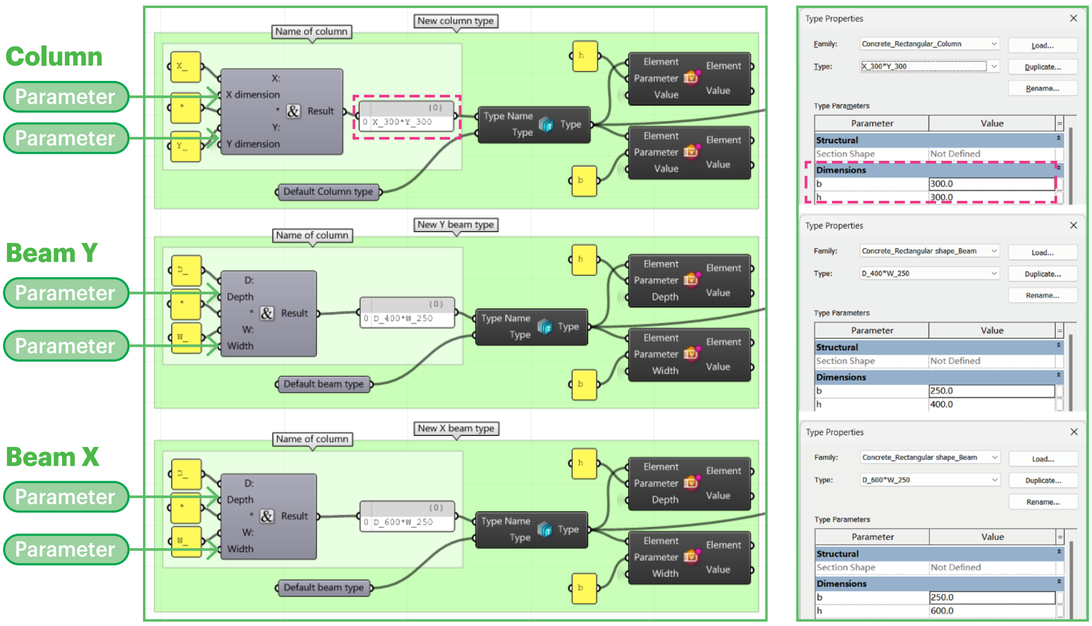
Take beams and columns as an example, synchronous types of families, based on pre-defined parameters, will be built by the 'Duplicate-Type' function in Rhino and Revit simultaneously, as shown in Figure 4.7.

The other catalog involves multiple layers of stacked materials, which are, for instance, the facade wall system and the green roof system. The family types of these assemblies require a relatively delicate layer-by-layer specification of the material composition, as shown in Figure 4.8. They could be customized by designers or be directly adopted with default values, which largely depend on the circumstances and preferences of designers or on the material performances which, in particular, thermal performances.

In the case of green roof systems, green roofs generally consist of several components, from bottom to top: structural slab, waterproof membrane, anti-root barrier, a protection layer, water storage and drainage layer, filtration layer, substrate, and vegetation[14]. Despite the similarity of the constituents, the selection of construction materials differs widely. For instance, the water storage and drainage layer can be composed of granular materials or high-strength synthetic materials such as polyethylene or polystyrene.

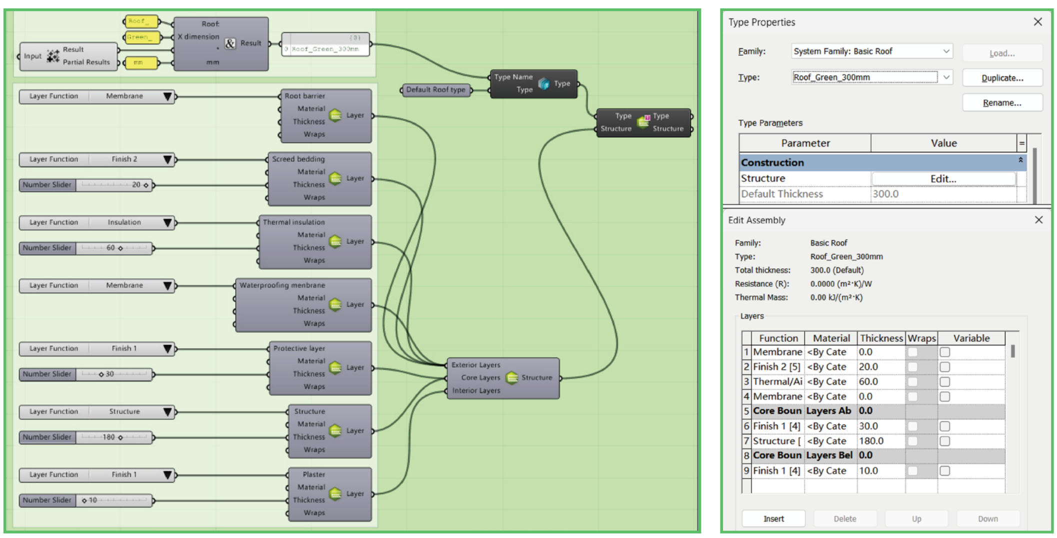
As such, a simplified type of family build-up will only encompass the specific material and thickness of the protection layer and all layers below. It is notable that the specified layer in the family type only regulates the construction sequence and the possible choice of material type, regardless of the possible subsequent environmental impact depending on different products.

Instead of resizing the elements straightforwardly by modifying the element parameters, new types with customized profile thicknesses should be constructed by accessing the compound structure layer and reconstructing it layer by layer in parallel, as



(a) New column and beam type created in Grasshopper (b) Real-time synchronisation in Revit

Figure 4.7 Synchronisation of family types with customized paramters: Column and Beam. Source: Self-produced.



(a) New roof type created in Grasshopper (b) Real-time synchronisation in Revit

Figure 4.8 Synchronisation of building family types with customized paramters: Roof. Source: Self-produced.

 shown in Figure 4.8.

Parameter driven instance

Designers first have to distinguish between the roof surface and the overall volume on different layers in Rhino and pick as reference the correct layer at the input stage, as shown in Figure 4.9.

Taking the most common beam and column structure system as an example, under the premise of complying with building height limitations, users can customize the storey height and the total number of storeyss to establish appropriate levels, which are built simultaneously in Revit and controlled by a Boolean toggle.

Generation of architectural elements is carried out using the 'Add-Component-Family' function by Rhino inside. Even though 'Add-Geometry-Direct-Shape' can also load the same geometric data

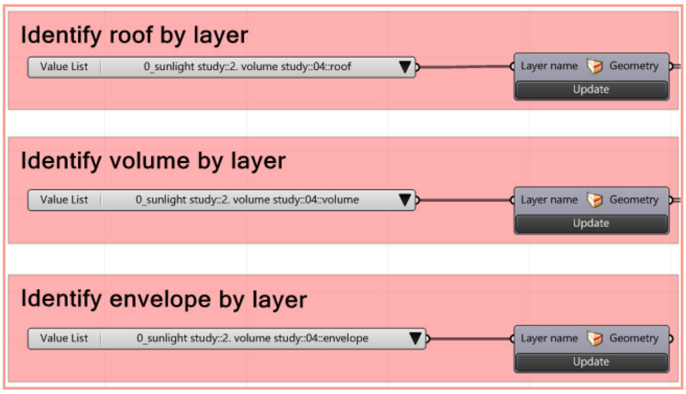


Figure 4.9 Identify respective layer as reference in Grasshopper. Source: Self-produced.

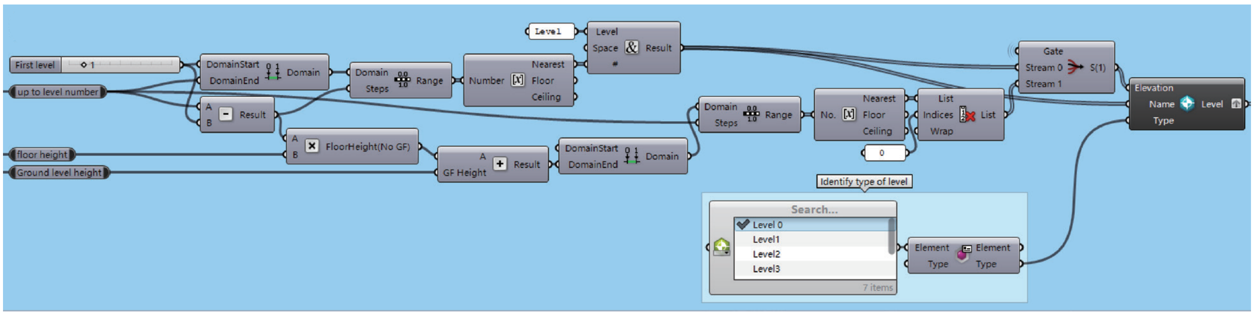
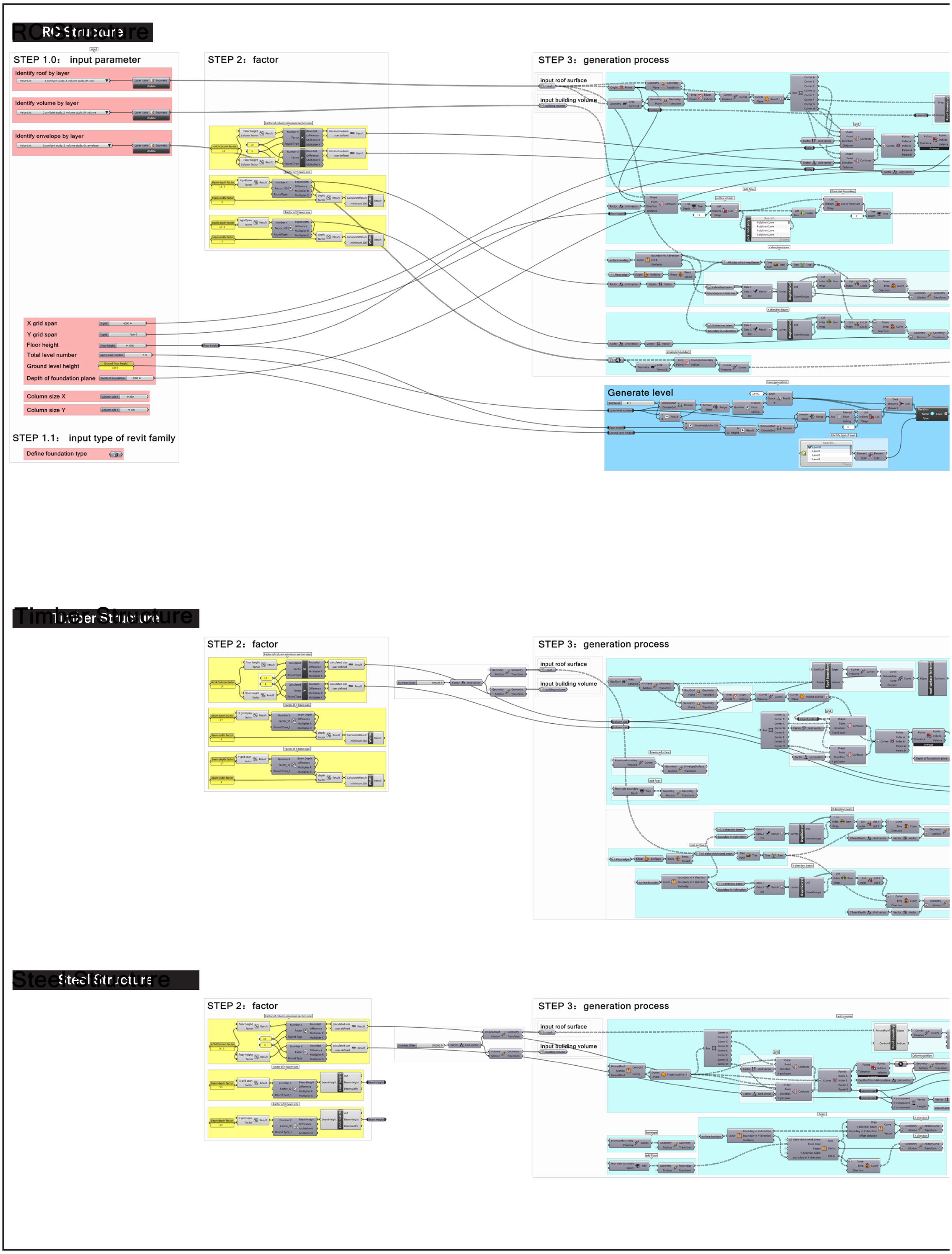


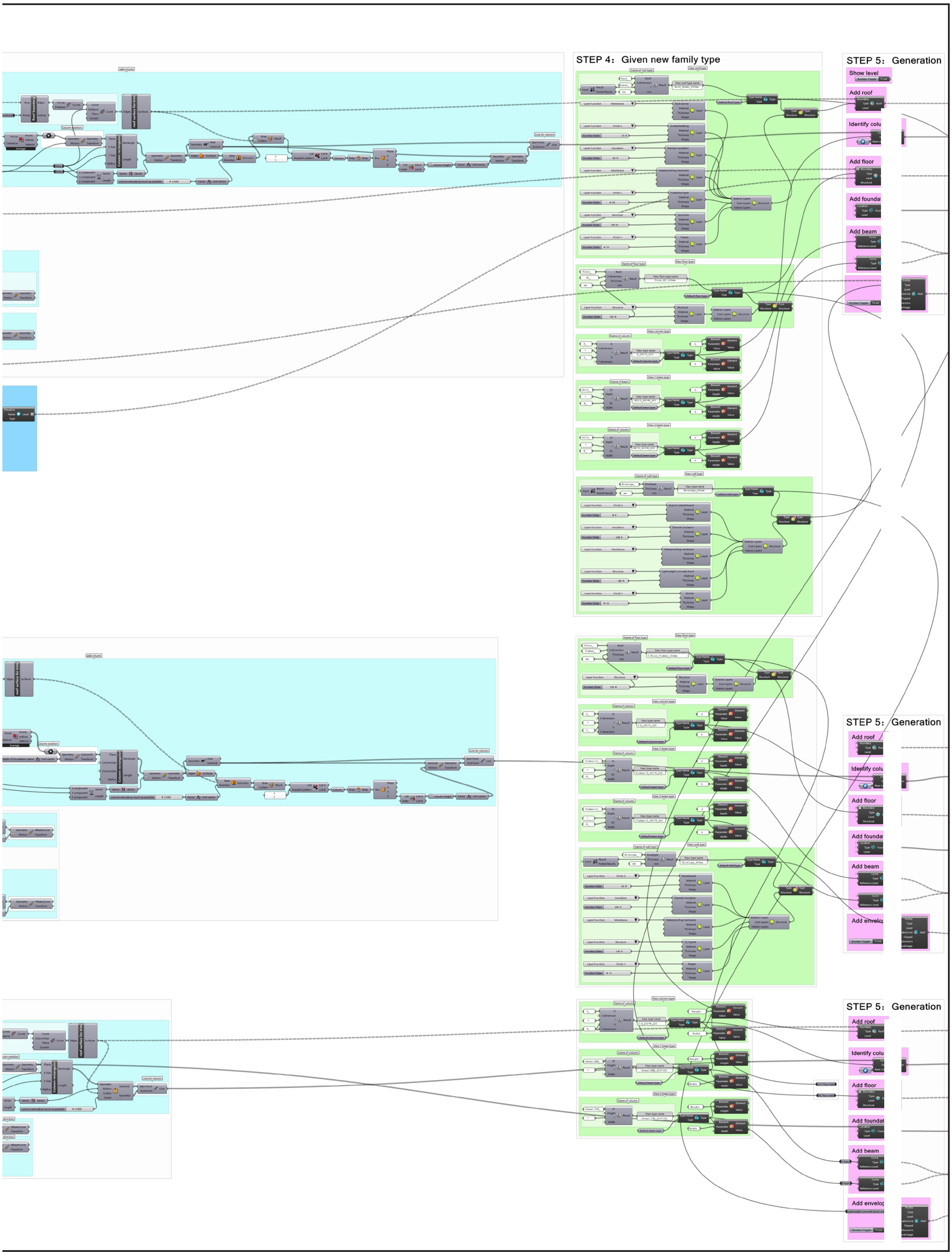
Figure 4.10 Establishment of level system in Grasshopper. Source: Self-produced.

from Rhino into Revit, yet the added objects cannot contain all the organizational information of loadable family/type[57].

The instance added by means of 'Add-Component-Family' allows real-time access to the parameters, such as area or volume, for LCA calculations by the 'Inspect-Element' function. Thus, the entire script of automated element generation which promotes the BIM model from LOD 100 to LOD 200 is composed of three individual parts for three structural systems, however, they share the same level system which ensures that all instances are built in the Revit environment reflecting in real-time. The entire script is shown as follows in Figure 4.10.

Figure 4.11 The entire script of automation of modeling. Source: Self-produced.




STEP 4：Given new family type
STEP 5：Generation
Show level
Add roof
Add floor
Add beam
STEP 5：Generation
Add roof
Add floor
Add beam
STEP 5：Generation
Add roof
Add floor
Add beam

4.2. Phase 2: LCA Calculation

The goal of conducting LCA is stated in this study, providing a life cycle perspective to aid decision-making in the selection of massing alternative options and giving early 'hot spot' analysis to enable architects to establish an awareness of the environmental impact of buildings earlier are the main objectives. The early implementation of LCA into the BIM workflow also leads to accelerated development of thorough holistic life cycle management.

The functional unit specified in this study is an entire building, and the conventional 60 years is taken as the study period, notwithstanding that the assessment of the operational phase is deducted herein. The physical system boundaries were varied according to the project but comprised at least the primary building structure, enclosure, and foundation. The system boundary in terms of life-cycle focuses on the A1-A3 stages, which is the production phase of the building materials. Additionally, materials such as steel, which has a high recycling rate at Stage D, or wood, which has additional carbon storage capacity, will be calculated separately.

The selection of impact indicators is aligned with the goal, and, although multiple indicators are weighing the impact of materials on separate aspects of the environment, this study chose the relatively most commonly tracked global warming potential as a single indicator, as it was one of the most standardized indicators established for evaluation. Although it would be advantageous to cover a wider spectrum of impact factors, this can be progressively developed in future studies.

4.2.1. Quantity take-off

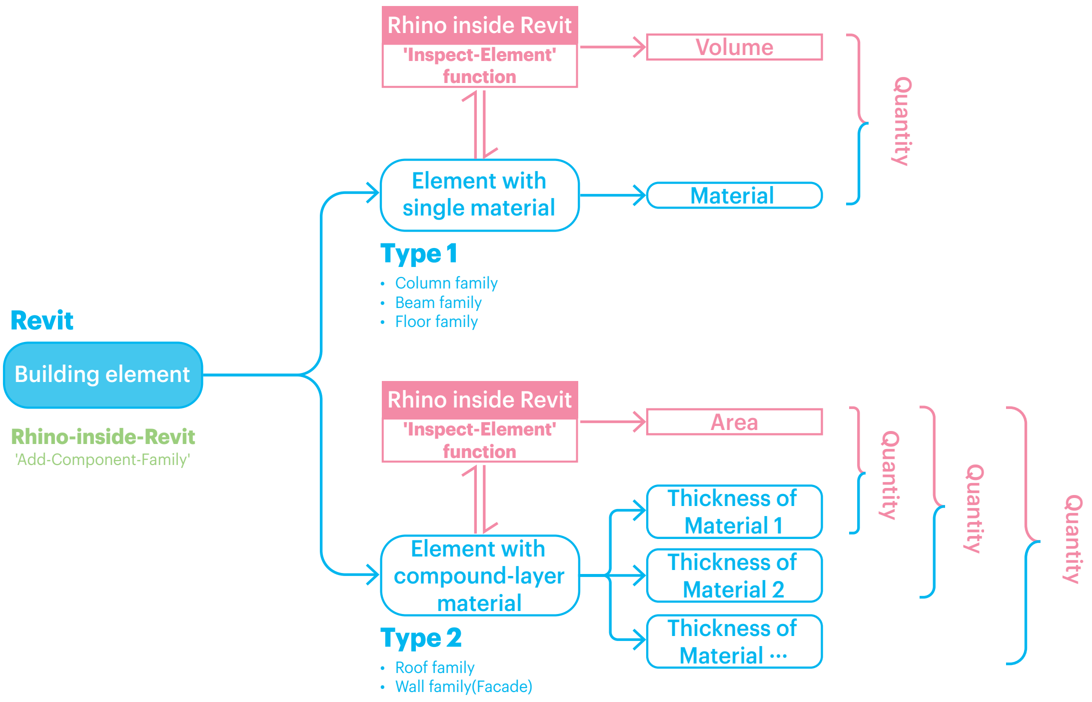


Figure 4.12 How to have the quantity take-off in the methodology. Source: Self-produced.

Since the automatic modeling has been carried out through the Rhino-inside-Revit plug-in, the instances essentially exist in Revit, allowing the calculation of the volume and the area of each building element by leveraging the features of Revit in terms of hosting information.

In this study, the selection of area or volume is largely determined by the properties of the material itself and the units commonly used in its LCA report. For instance, the membrane material is more widely evaluated in area units due to its thinness, while ready-mixed concrete, on the other hand, is generally estimated with volume units. For monolithic material elements, it is sufficient to simply access the volume, but for envelope systems with composite layered structures, separate extraction for each material layer is necessary. The quantity take-off for LCA calculations is therefore divided into two main catalogs, which remain the same for all three different structural options.

Simultaneously, the study also provides in parallel the results calculated from the quantified mass per unit area of the gravity frame obtained from other studies[21], whose conclusions are informative and close to practical needs, given that such studies were statistically grounded on real cases and conducted as a result of machine learning. Although the LCA calculations will still rely on material data derived from previous automated modeling, additional volume and mass estimates are available to avoid the impracticability of the results.

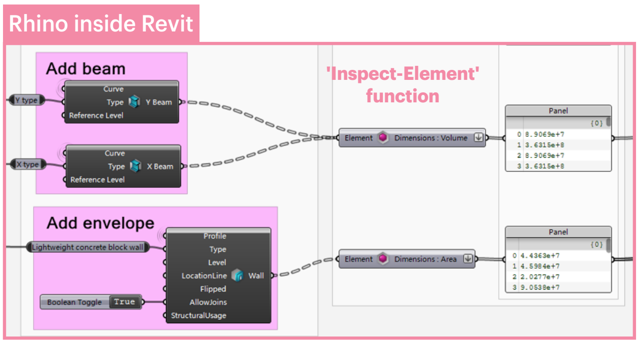


Figure 4.13 Inspect instance information. Source: Self-produced.

4.2.2. LCA data

C25/30	General information and Data background						Technical Characteristics				Environmental Profile (GWP： kg CO2e/ m^3)						Resource
	Commercial Name	Manufacturer	EPD number	EPD program	Year	Standard	Technical specification	Density	Default thickness	Unit	A1-A3	A4	Transportation distance (km)	C2	C3	D	Link of EPD
1	ZA000495	UNICAL SPA, Orbassano plant	EPDITALY0385	EPD Italy	2022	EN15804+A2	C25/30, S4, D32, low carbon	2400.0 kg/m^3	_	m^3	132.00	Concrete mixer truck, appr. 8 m3, 100% fill rate: 0.13 kg CO2e / tonkm	100	_	_	_	https://www.epditaly.it/wp-content/uploads/2016/12/Report-Calcestruzzo_EPD_EA8006.pdf
2	ZA000551-xpav	UNICAL SPA, Orbassano plant	EPDITALY0386	EPD Italy	2022	EN15804+A2	C25/30, S5	2400.0 kg/m^3	_	m^3	216.00	Concrete mixer truck, appr. 8 m3, 100% fill rate: 0.13 kg CO2e / tonkm	100	_	_	_	https://www.epditaly.it/wp-content/uploads/2016/12/Report-Calcestruzzo_EPD_EA8011.pdf
3	EcoPact AN XC2 C25/30	Holcim Aggregati Calcestruzzi Srl	EPDITALY0391	EPD Italy	2022	EN15804+A2	C25/30, S4, D31,5-32,5	2400.0 kg/m^3	_	m^3	209.00	Concrete mixer truck, appr. 8 m3, 100% fill rate: 0.13 kg CO2e / tonkm	40	_	16.7 kg CO2e / kg	-3.82 kg CO2e / kg	https://www.epditaly.it/wp-content/uploads/2016/12/Report_EPD_ECAN304B3C_2023-02-23_02-11-32.pdf

C30/35	General information and Data background						Technical Characteristics				Environmental Profile (GWP： kg CO_{2e}/ m^3)						Resource
	Commercial Name	Manufacturer	EPD number	EPD program	Year	Standard	Technical specification	Density	Default thickness	Unit	A1-A3	A4	Transportation distance (km)	C2	C3	D	Link of EPD
1	dryCrystal RCK37	Colabeton	EPDITALY0108	EPD Italy	2020	EN15804+A2	C30/37, XC4, S4, D25, CEM IV 32.5 N	2400.0 kg/m^3	_	m^3	276.00	Concrete mixer truck, appr. 8 m3, 100% fill rate: 0.13 kg CO2e / tonkm	25	_	_	_	https://www.epditaly.it/wp-content/uploads/2016/12/Report-EPD-Colabeton-Mediglia.pdf
2	ZA000531-xpav	UNICAL SPA, Orbassano plant	EPDITALY0386	EPD Italy	2022	EN15804+A2	C30/37, Sr 150, D32, XC4	2400.0 kg/m^3	_	m^3	241.00	Concrete mixer truck, appr. 8 m3, 100% fill rate: 0.13 kg CO2e / tonkm	100	_	_	_	https://www.epditaly.it/wp-content/uploads/2016/12/Report-Calcestruzzo_EPD_EA8011.pdf
3	EcoPact AN XC2 C30/37	Holcim Aggregati Calcestruzzi Srl	EPDITALY0390	EPD Italy	2023	EN15804+A2	C30/37, S4, D31,5-32,5	2400.0 kg/m^3	_	m^3	226.00	Concrete mixer truck, appr. 8 m3, 100% fill rate: 0.13 kg CO2e / tonkm	40	11.3 kg CO2e/ m^3	16.6 kg CO2e/ m^3	-3.8 kg CO2e/ m^3	https://www.epditaly.it/wp-content/uploads/2016/12/Report_EPD_ECAN374B3C_2023-02-23_02-15-25.pdf

CLT	General information and Data background						Technical Characteristics				Environmental Profile (GWP: kg CO_{2e} / m^3)							Resource
	Commercial Name	Manufacturer	EPD number	EPD program	Year	Standard	Technical specification	Density	Default thickness	Unit	A1-A3	A4	Transportation distance (km)	C2	C3	D	Biogenic CO_2 storage (A1)	Link of EPD
1	Pannello MHM	FBE	S-P-03663	International EPD System	2020	EN15804+A1	CLT, glulam and LVL	450.0 kg/m^3	_	m^3	273.00	Trailer combination, 40 ton capacity, 100% fill rate: 0.0383 kg CO2e / tonkm	210	_	_	_	717.0	https://api.environdec.com/api/v1/EPDLibrary/Files/8b9056bb-ae03-4c90-c7f8-08dafef7b801/Data
2	Rubner-XLAM	Rubner Holding	EPD-RUB-20180060-IBB1-EN	IBU	2018	EN15804+A1	CLT, glulam and LVL	461.0 kg/m^3	_	m^3	181.17	Trailer combination, 40 ton capacity, 100% fill rate: 0.0383 kg CO2e / tonkm	340	_	759.0	-410.0	845.17	https://oneclicklcaapp.com/app/sec/util/getEpdFile?resourceId=ibuCrossLaminatedTimberRubnerHoldingXlam&profileId=RubnerHolding2018
3	binderholz Brettsperrholz BBS, CLT BBS, X-LAM BBS	Binderholz Bausysteme (Austria)	EPD-BBS-20190021-IBB1-DE	IBU	2019	EN15804+A1	CLT, glulam and LVL	470.88 kg/m^3	100mm	m^3	103.96	Trailer combination, 40 ton capacity, 100% fill rate: 0.0383 kg CO2e / tonkm	560	0.548	766	-412.00	761.00	https://oneclicklcaapp.com/app/sec/util/getEpdFile?resourceId=ibuBinderholzBrettsperrholzBBSXLAMCLT_fixApr2022&profileId=BinderholzBausysteme2019
4	X-LAM • Cross Laminated Timber	Artuso Legnami S.r.l.	S-P-01408	International EPD System	2018	EN15804+A1	CLT, glulam and LVL	400.0 kg/m^3	200mm	m^3	160.0	Trailer combination, 40 ton capacity, 100% fill rate: 0.0383 kg CO2e / tonkm	280	_	_	_	520.0	https://api.environdec.com/api/v1/EPDLibrary/Files/dd02e37b-6c9d-4347-928c-690f08e79282/Data

Figure 4.14 Sample page of material life-cycle inventory. Source: Self-produced.

LCI, or life cycle inventory, is mainly concentrated on the cradle-to-gate phase of buildings in this study. To be precise, the system boundaries in this study are defined as the A1-A3 stages, which focus on the embodied environmental impacts in the early stages of building project. Although there is some research started to target the data collection in the quantitative building demolition phase [36] with the intention of integrating associated data into the earlier LCA studies, it was not included in this study due to the inadequate variety and amount of cases yet.

Although there are many databases available for construction materials, they vary considerably by region, and several do not provide free student-accessible versions. Consequently, this study was undertaken by self-collecting materials' EPD to establish a database for reference purposes to perform the assessment, by searching in reputable EPD libraries, such as EPD Italy, International EPD System, IBU, etc.

The EPD selection is based on the search for manufacturers within an appropriate transportation distance region, centered on the site where the case application is located, considering the efficiency of material's transportation in spite that stage A4 where environmental impact is tied to locality has not be included into the system boundary. A statement should be drawn that the selected EPD is grounded on certain criteria, taking the study case in the next chapter as an example, the insulation material is required to comply with proper Lambda value, whereas materials failing to meet the requirements will not be adopted.

The final database is stored in Excel to facilitate data retrieval and processing in Grasshopper. By accessing a fixed cell range in a spreadsheet named after a material category, all possible values of the GWP for that material can be obtained. In particular, it should be emphasized that the unit of measurement of GWP values may be varied for different materials, e.g. waterproofing membranes are measured in $kgCO_2eq/m^2$, while other materials such as concrete or CLT are measured in $kgCO_2eq/m^3$.

C40/45	General information and Data background						Technical Characteristics				Environmental Profile (GWP： kg CO2e/ m³)						Resource
	Commercial Name	Manufacturer	EPD number	EPD program	Year	Standard	Technical specification	Density	Default thickness	Unit	A1-A3	A4	Transportation distance (km)	C2	C3	D	Link of EPD
1	Ordinario 30R404C9	Unical, plant Cervia	EPDITALY0081	EPD Italy	2019	EN15804+A2	C32/40, S4, D32, XC2	2400.0 kg/m³	–	m³	393.00	Concrete mixer truck, appr. 8 m3, 100% fill rate: 0.13 kg CO2e / tonkm	100	–	–	–	https://www.epditaly.it/wp-content/uploads/2016/12/Report-Calcestruzzo_EPD_El40002-
2	R40C4D31S4XC4/XC3/XC2/XC1	Betonrossi S.p.A.	EPDITALY0393	EPD Italy	2023	EN15804+A2	C40, S4, D31, XC4/XC3/XC2/XC1	2400.0 kg/m³	–	m³	285.40	Concrete mixer truck, appr. 8 m3, 100% fill rate: 0.13 kg CO2e / tonkm	80	11.7 kg CO2e/ m³	4.01 kg CO2e/ m³	0.225 kg CO2e/ m³	https://www.epditaly.it/wp-content/uploads/2016/12/EPD_Betonrossi_rev.03
3	dryCrystal RCK45	Colabeton	EPDITALY0108	EPD Italy	2020	EN15804+A1	C45, XC4, S5, D15, CEM IV 42.5 R	2400.0 kg/m132	–	m³	381.00	Concrete mixer truck, appr. 8 m3, 100% fill rate: 0.13 kg	25	–	–	–	https://www.epditaly.it/wp-content/uploads/2016/12/Report-

Waterproofing	General information and Data background						Technical Characteristics				Environmental Profile							Resource	Note
	Commercial Name	Manufacturer	EPD number	EPD program	Year	Standard	Technical specification	Density	Default thickness(mm)	Unit	A1-A3 (GWP: kg CO_2eq / m²)	A1-A3 (ADPF: MJ)	A4 (GWP: kg CO_2eq / m²)	Transportation distance (km)	C2 (GWP: kg CO_2eq / m²)	C3 (GWP: kg CO_2eq / m²)	D (GWP: kg CO_2eq / m²)	Link of EPD	
1	Flagon® TPO EP/PV-F	Soprema	S-P-01603, ver. 5	International EPD System	2019	EN15804+A1	Plastic membranes	1.4 kg/m²	1.5	m²	0.0653	1.5953	0.0106	40	0.000688	0.00483	-0.0306	https://api.environdec.com/api/v1/EPDLibrary/Files/9fc6d418-c600-459a-9c28-d4f3033d4a4e/Data	8% recycled content
2	VINITEX® MP	Soprema	S-P-01963	International EPD System	2020	EN15804+A1	Plastic membranes , fire resistance class = E	1.8 kg/m²	1.5	m²	0.0659	1.5364	0.00382	40	0.000635	0.00432	–	https://api.environdec.com/api/v1/EPDLibrary/Files/06d9f87a-5ff9-438e-ba11-a334d9a13c6d/Data	
3	TEXSALON® MAT-FB	Soprema	S-P-01962	International EPD System	2020	EN15804+A1	Plastic membranes, UV resistant, fully-adhered	1.5 kg/m²	1.5	m²	0.0653	1.5953	0.0106	40	0.000688	–	–	https://api.environdec.com/api/v1/EPDLibrary/Files/710d4c8b-8260-483a-8367-c8e92b949924/Data	8% recycled TPO

Figure 4.15 Sample page of material life-cycle inventory: WaterProofing. Source: Self-produced.

4.2.3. LCA results and analysis

Since the study focuses on the environmental impact of the production phase, the LCA calculation is relatively straightforward, using the collected information in the EPD of the material multiplied by the corresponding unit volume or area of the respective material needed in the project. It is essential to be aware that there are a few materials evaluated in different units, such as steel, which is standardized in weight, requiring conversion efforts.

The computation is performed in Grasshopper using C# for customization. Each category of materials has collected various EPDs from different manufacturers, then all have been recorded in different spreadsheets within Excel. Users can identify the specific cell values for the GWP of each material by utilizing the sheet name in Excel as an identifier. This allows the users to obtain the data list of GWP values for each material in that category. By inputting the material information retrieved from Excel as list items, sorting

```
C30_35_GWP.Sort();

double minC30 = C30_35_GWP[0] * C30_35_Volume;
double maxC30 = C30_35_GWP[C30_35_GWP.Count - 1] * C30_35_Volume;

C30_35Range = Tuple.Create(minC30, maxC30);
```

Figure 4.16 Sample algorithms of LCA calculation. Source: Self-produced.

their magnitudes then multiplying them with the volume or area of the material respectively to get the maximum and minimum values of embodied carbon emissions of the material, which are output as a tuple.

The final range of overall buildings is summed by the results of all calculations. Components with benefits within the system boundary (A1-A3) need to be calculated separately, e.g. the biogenic carbon storage of timber frames is excluded from the total carbon emissions from the production phase. The carbon sequestration later will be included. The reason of this is that, although the widespread conclusion in comparative LCA-based material studies is that timber structures tend to contribute least in terms of embedded carbon emissions[6, 30, 33], primarily because of the carbon sequestration biological characteristics of timber during the growth cycle, it should not be overlooked that timber structures may present a considerably higher carbon footprint under a hypothetical worst-case scenario where harvested trees are not replanted thus sequestration is subsequently ignored and

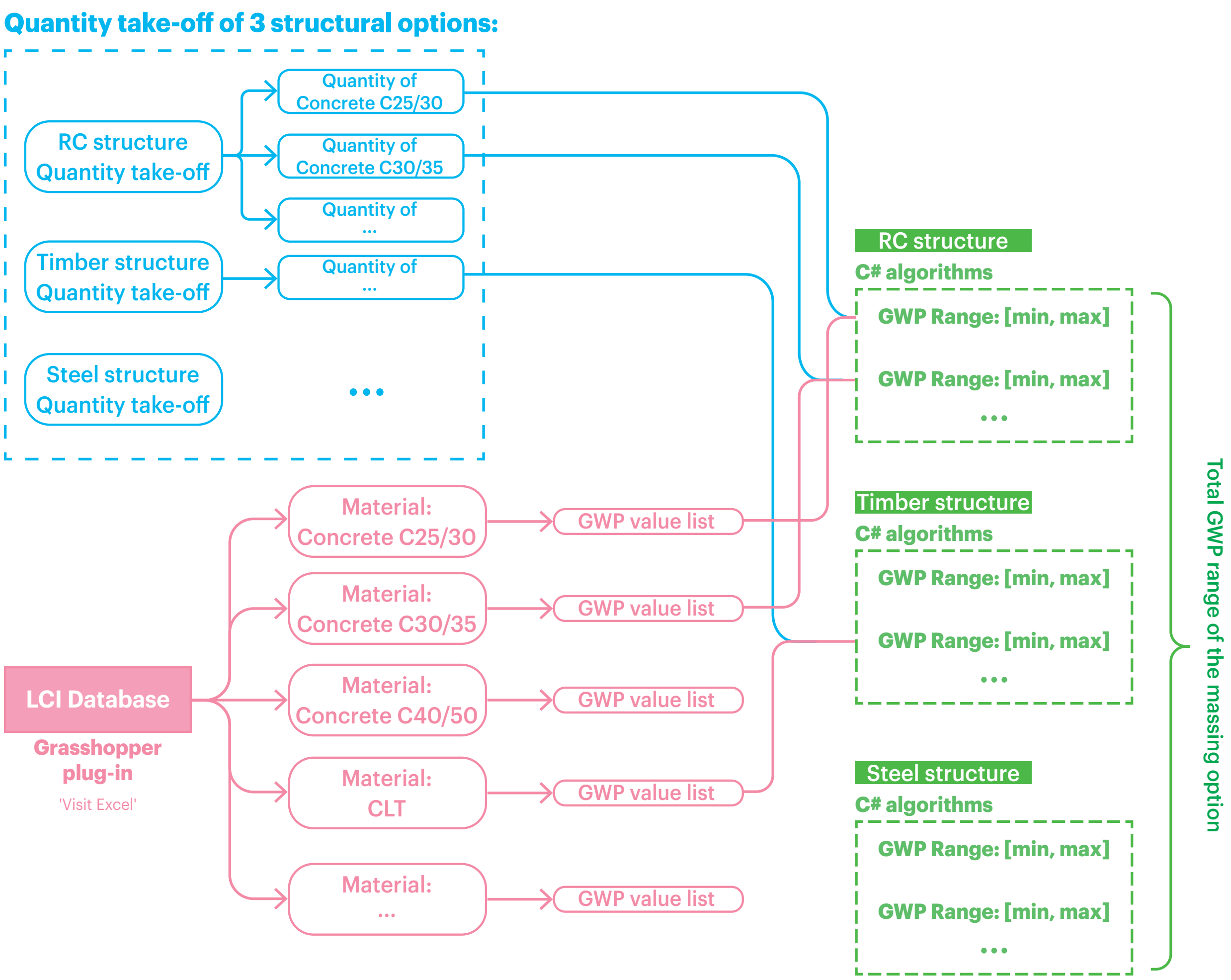


Figure 4.17 Framework of LCA calculation for each massing option. Source: Self-produced.

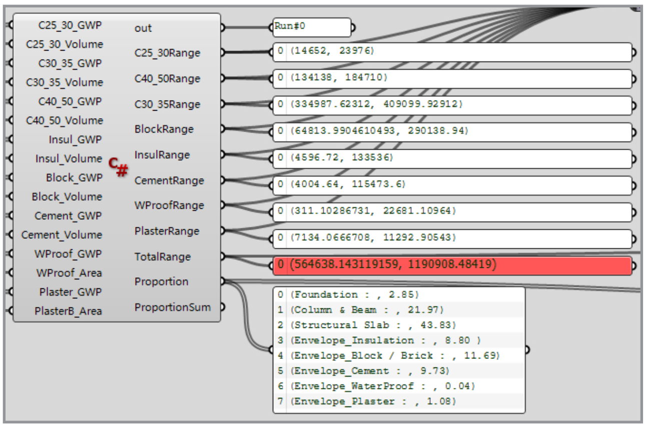


Figure 4.18
Customized C#
battery for calculation:
RC structure.
Source: Self-produced.

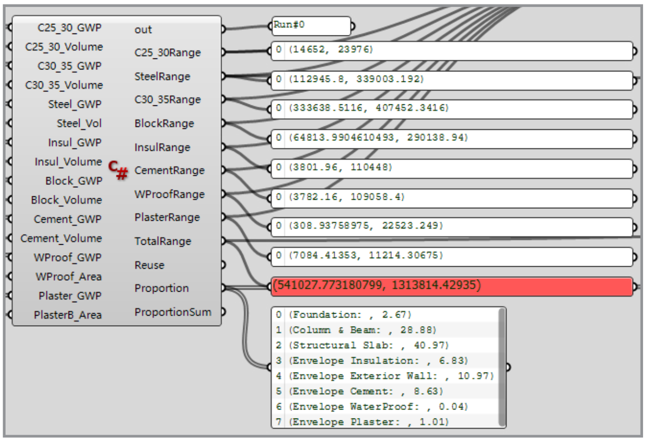


Figure 4.19
Customized C#
battery for calculation:
Steel structure.
Source: Self-produced.

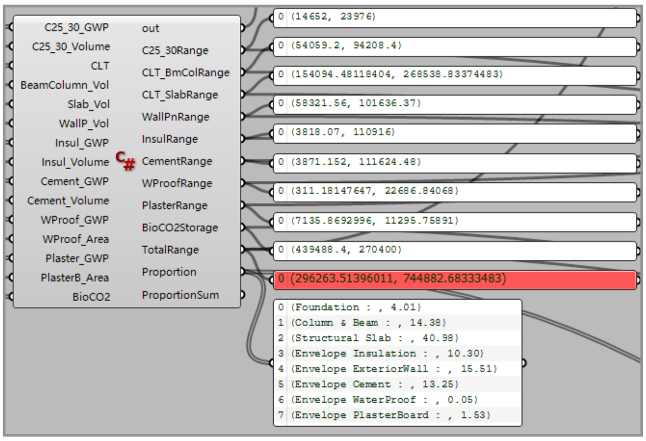


Figure 4.20
Customized C#
battery for calculation:
Timber structure.
Source: Self-produced.

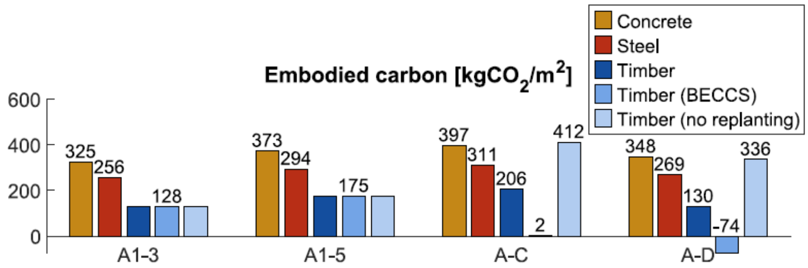


Figure 4.21 Comparison of embodied carbon. Source: [31].

biogenic carbon is released at end-of-life[32], as shown in Figure 4.21. As a result, the environmental impact conclusions at different stages will be discussed separately in this study.

The study also provides the "hot-spot" analysis of embodied carbon emissions so as to allow decision-makers a better understanding of the relationship between the materials and the design. The correspondence between material categories and building components is made one-to-one which means that the same materials applied to multiple elements will be indicated separately to facilitate the percentage calculation. The intrinsic positive environmental benefits per massing alternatives, such as the carbon sequestration potential from the green roof system, will also be computed and represented in the subsequent visualization boards.

4.3. Phase 3: Decision model and visualized dashboard

In addition to the direct data computed above, the study aims to provide more visual expression to intuitively compare the performance of the carbon assessment results for each option. The decision-making modeling is a multi-faceted and complex process, and the purpose of it is to filter out some of the scenarios with too disparate LCA results instead of arbitrarily eliminating all options that perform poorly. Although a better environmental potential in the initial phase implies a greater possible final LCA result of that option, the underperformance in this phase leaves the designer to bridge the gap through the implementation of a more cautious design strategy if the option displays other promising qualities. Thus, the dashboard introduced as follows is constructed to present all relevant data together.

4.3.1. Visualization

With the aid of the Human UI plug-in developed by the Design Computation Leadership Team at NBBJ, automated dashboards can be rendered as a standalone user interface in the Windows environment. The window is controlled by a Boolean toggle, and the dashboard generated for each volumetric proposal consists of four pieces. The correspondent button controls the automatic saving of the window information in a self-defined folder as a picture after.

The generation of automated reports does not require the user to provide any additional input as it is a program completely grounded on LCA values for visual representation. The data processing is still implemented utilizing C# for basic functions such as sums, conversions, comparisons, etc. The layout and graph design of each independent window, instead, is carried out through the functions of HumanUI. Figure 4.22 shows the script for generating one report as an sample.

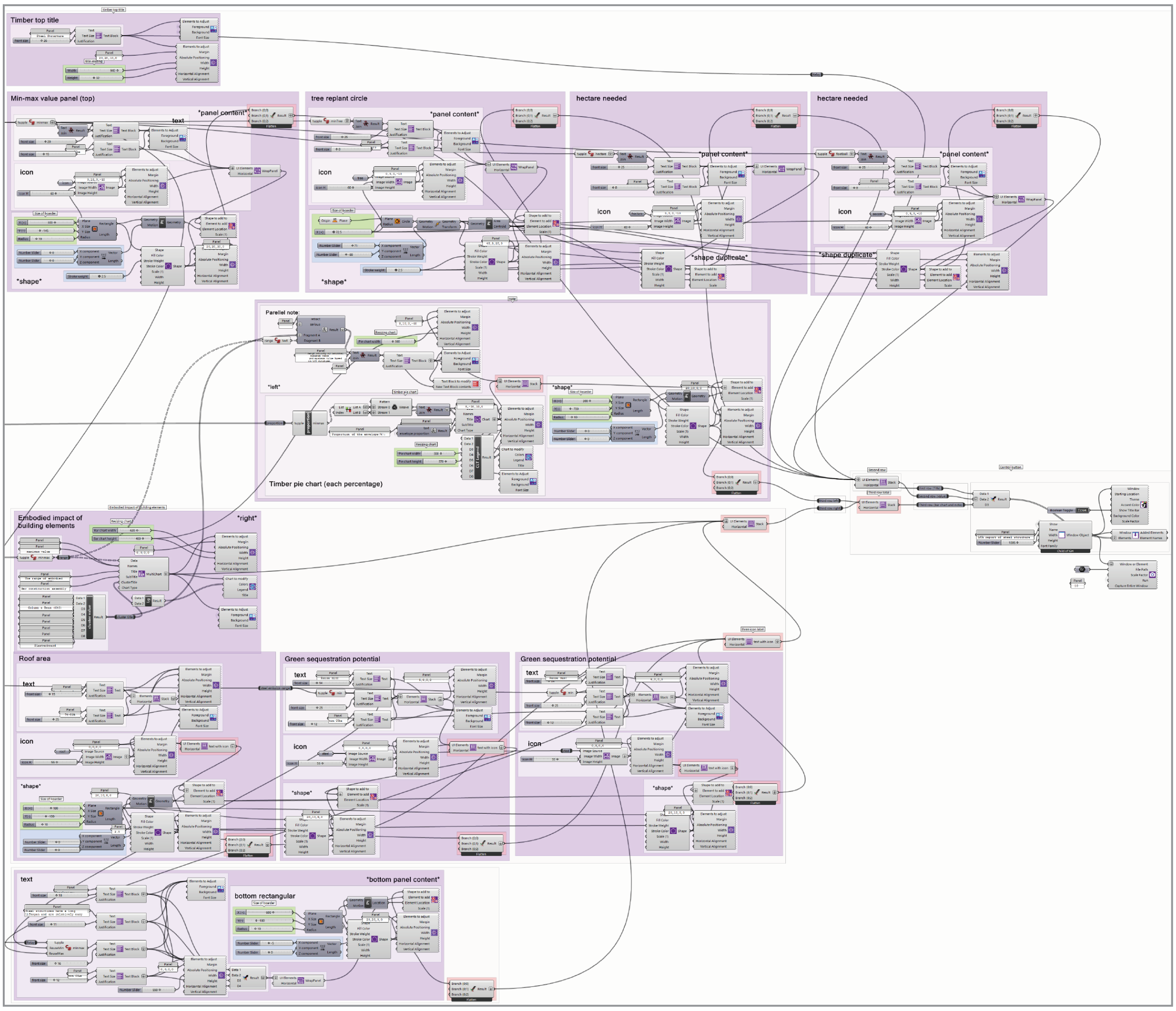


Figure 4.22 Sample algorithm of visualization for one dashboard. Source: Self-produced.

The first window presents general information, which is aligned across different structural systems in relation to the properties of the volumetric options themselves, such as the combined total range of GWP values, the envelope area, the green roof area, and the sequestration potential from the green roof systems. This panel is dedicated to the comparison of the alternative options.

Upon launching the general assessment report, the total carbon emissions range for each option will be specified in the top left-hand corner of the report, as shown in Figure 4.23. This range encompasses the three possible structural systems, and more detailed ranges for each of the three are displayed in the bar charts below. The bottom right corner of the report highlights the maximum and minimum carbon emissions per square meter on average.

Additionally, the report provides estimates for the potential carbon sequestration and annual electricity generation from the photovoltaic panel within the purple blocks on the right side, which are based on the roof area per option. The bottom modules contain the total embodied carbon emissions and the per unit area average for the massing option, after offsetting some of the embodied carbon emissions by the carbon sequestration from the green roofs, in a 20-year scenario. Ideally, the positive benefits of electricity generation should also be included. However, the author has not been successful in accessing the proportion of either clean energy or fossil fuel usage for electricity generation. There is no plausible data available for quantifying the avoided impact of electricity generation. Therefore, it has not been included in this study, and this could be improved in the future study once more accurate and public source related are available.

The remaining three panels are LCA reports separately for the

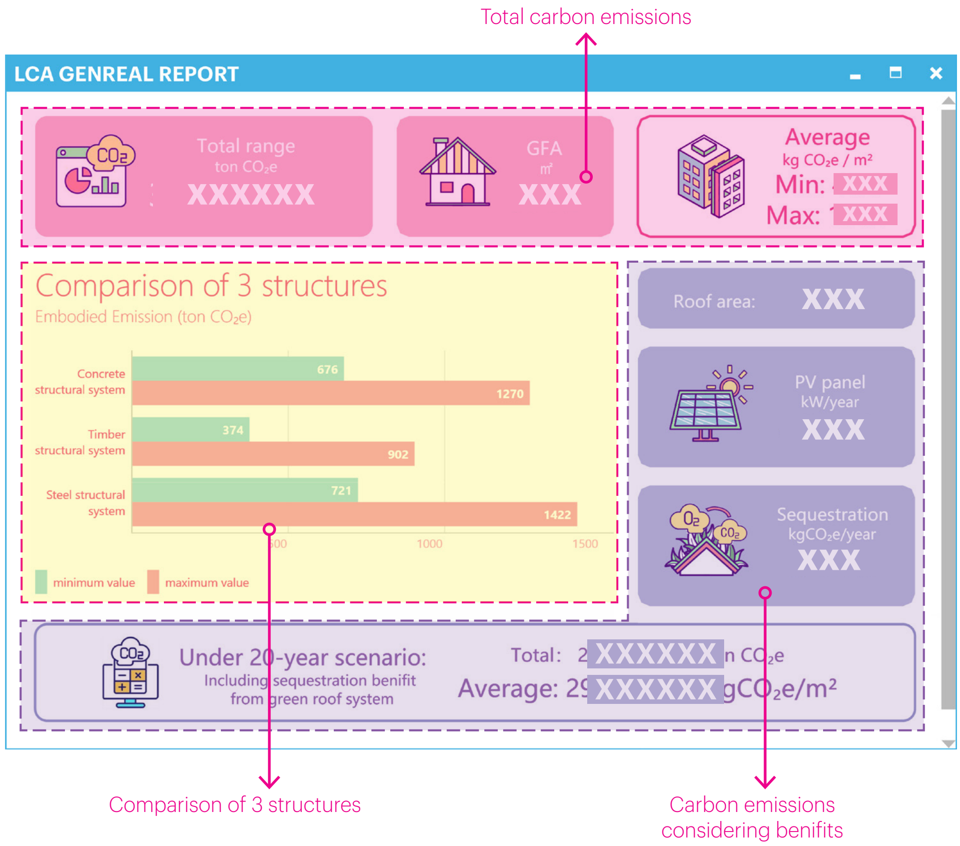


Figure 4.23 Sample of general dashboard. Source: Self-developed.

three specified structural systems of each option. These three reports concentrate respectively on single structural systems in order to facilitate designers to optimize further once they determine the structural preference.

The report contains a range of GWP values for each assembly and hot-spot analysis within A1-A3 stages, excluding carbon benefit. As depicted in Figure 4.23, the top left corner of the report specifies the range of possible emissions under such a structural system. To convey the significance of the statistics effectively, the three figures on the upper right-hand side of the report represent the

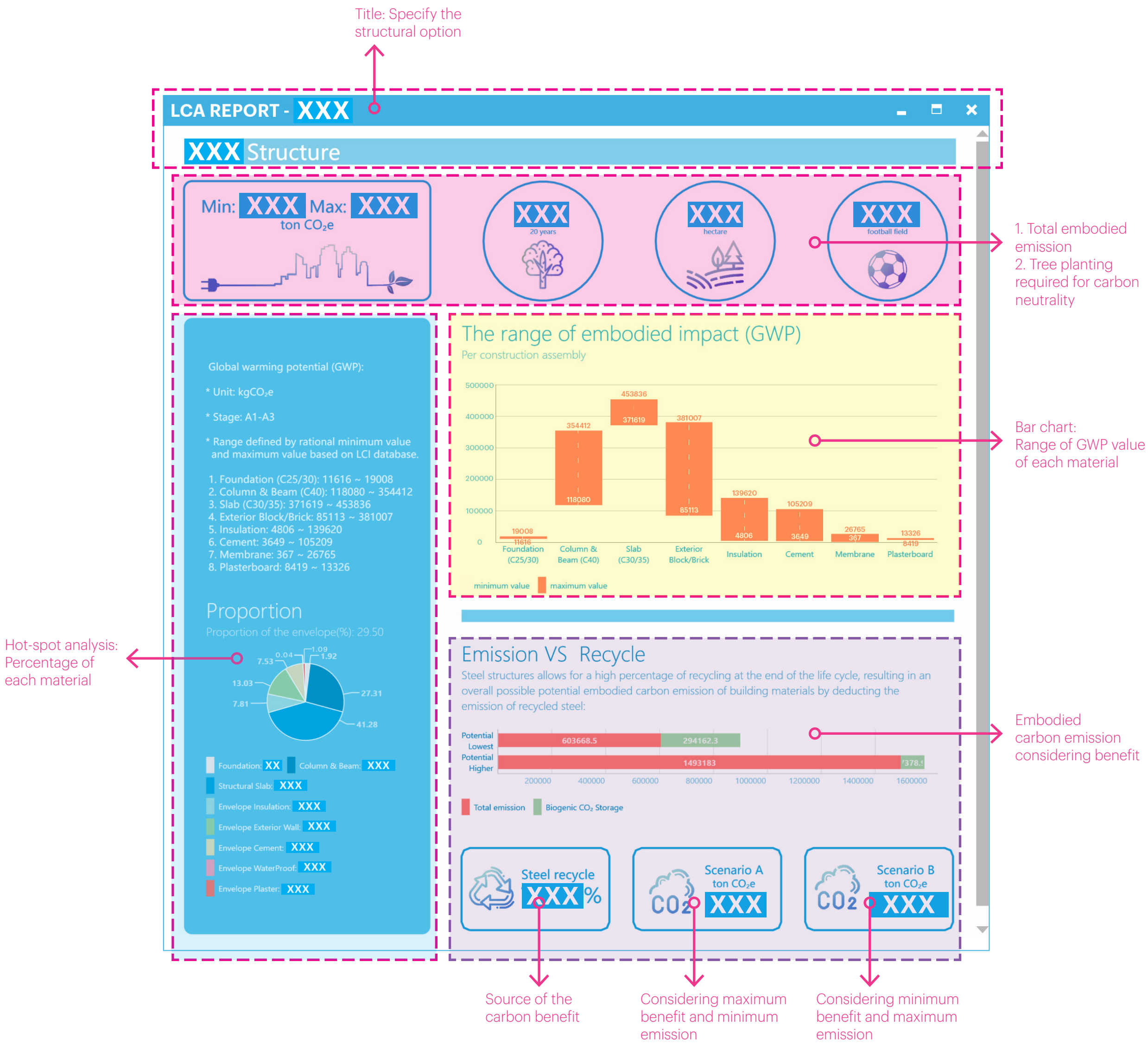


Figure 4.24 Detailed report of each structural option. Source: Self-developed.

approximate number of trees to be replanted over two decades, with the maximum emission as the carbon neutral target, along with the required hectare of land for that amount, and the equivalent amount of soccer pitches. This approach enables designers, who may lack specialized knowledge, to comprehend the meaning behind the figures in a more straightforward and intuitive manner, giving a glimpse of the resulting environmental impact.

The enumeration of values and the pie chart on the left side of the report indicate the total amount and percentage of carbon emissions per construction element, providing a "hot-spot" analysis. Meanwhile, the bar chart on the right side offers a more precise visualization of the detailed carbon emission ranges for each assembly. A longer bar signifies greater differentiation of the material or product in question and calls for more cautious selection by the designer.

Detailed report has a separate illustration of the probable final total emissions to be achieved after considering the carbon benefits. To be more specific, for wood structures, the carbon benefits means the potential of biogenic carbon storage from A1 stage based on a proper replanting scenario. For steel and concrete structure, the author introduce the avoided impact from recycling potential in D stage here just for comparison, displaying a more positive LCA results. The recycling percentage of steel and the value of the avoided impact has been obtained from the collected EPD.

The bottom half of the section contains specific annotations found only in each detailed report. It provides an optimistic estimation of overall carbon emissions by considering the recycling potential to reduce emissions offered by the materials themselves. For instance, it takes into account the biogenic carbon storage properties of timber frames under a guaranteed proper replanting scenario, the high recycling capacity of steel frames, and the potential negative emission contribution from the reuse of aggregates in concrete frames. Scenario A presents the results of the most optimistic scenario, which involves the lowest environmental impact configuration with the lowest carbon emissions and the highest recycling or sequestration potential. Scenario B, on the other hand, illustrates the potential total carbon emissions achieved when material selection is emission-maximized but environmentally benefits-minimized.

4.3.2. Decision model

The decision model is a summary of the entire methodology. It aims to provide a clear sequential mapping of the entire design process specifying where LCA should be integrated and when it should be intervened in the comparison of early massing proposals.

The decision model outlines the parameters that designers need when generating massing options, as mentioned earlier. Once the objective parameters are fulfilled, subjective judgments can be made by the architect to choose the design aspects to be applied for further optimization or for generating specific volume options. For instance, in this method, the emphasis is placed on appropriately optimizing roof area for the integration of sustainable strategies such as green roof systems and solar photovoltaic panels as an subjective goal.

The intervention of LCA occurs after two rounds of massing screening, which means architects have some alternative options that meet certain criteria and require further decision-making. Rapidly upgrade the volumetric model to supplement the architectural elements with the tool developed by the authors, the designer can then quickly obtain the bill of material quantities. In parallel with the development of the early building design, the establishment of a project-based LCI database is a high priority, in order to build up a scientifically reliable database for the subsequent calculations and studies of the LCA. The source of

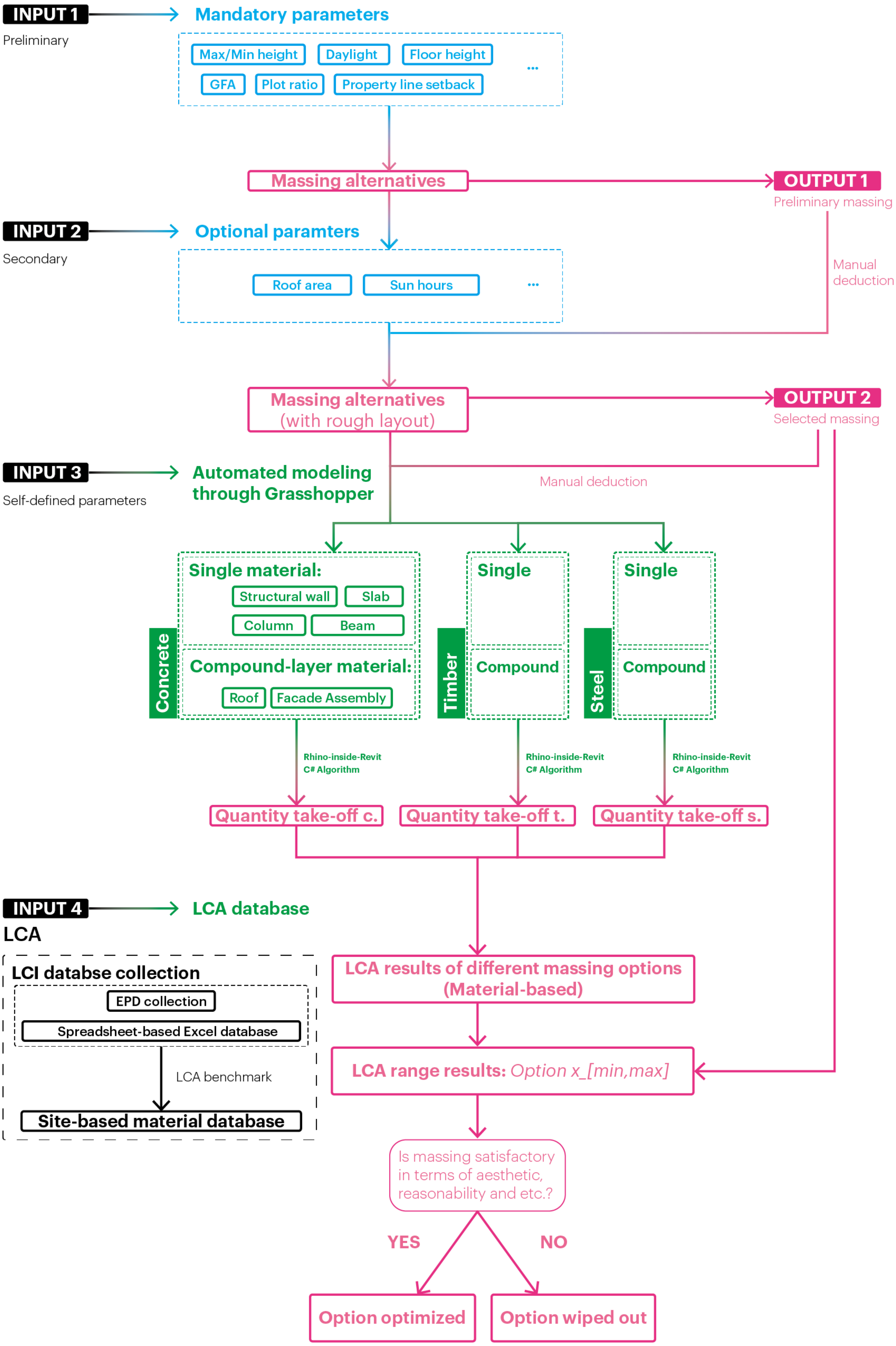


Figure 4.25 Decision model. Source: Self-produced.

information for the database is not explicitly limited, either it could be based on available licensed LCI databases or through self-collection of material EPDs.

Unlike conventional LCA, the LCA utilized for early assessment in this method provides a range of possible values rather than precise results. This range encompasses the maximum or minimum LCA results that may occur under three different structural scenarios of each massing option. Thus, the final step of this desicion model is about calculation, analysis and comparison. As a quantitative data reference, LCA results can help designers to either directly select the best solution, or clarify the optimization direction of the solutions that do not perform well under the LCA perspective.

The final decision is still based on the designer's comprehensive evaluation of the totality of the situation, which, in conjunction with LCA, drives the entire early architectural design process towards a more scientific and synthesized process with a more multidisciplinary perspective and involvement of multiple inputs.

5 | Case study and implementation

The applied case study is the design of a residential building located in Via Lamarmora, Milan.
Figure 5.1 shows the mapping of project location.

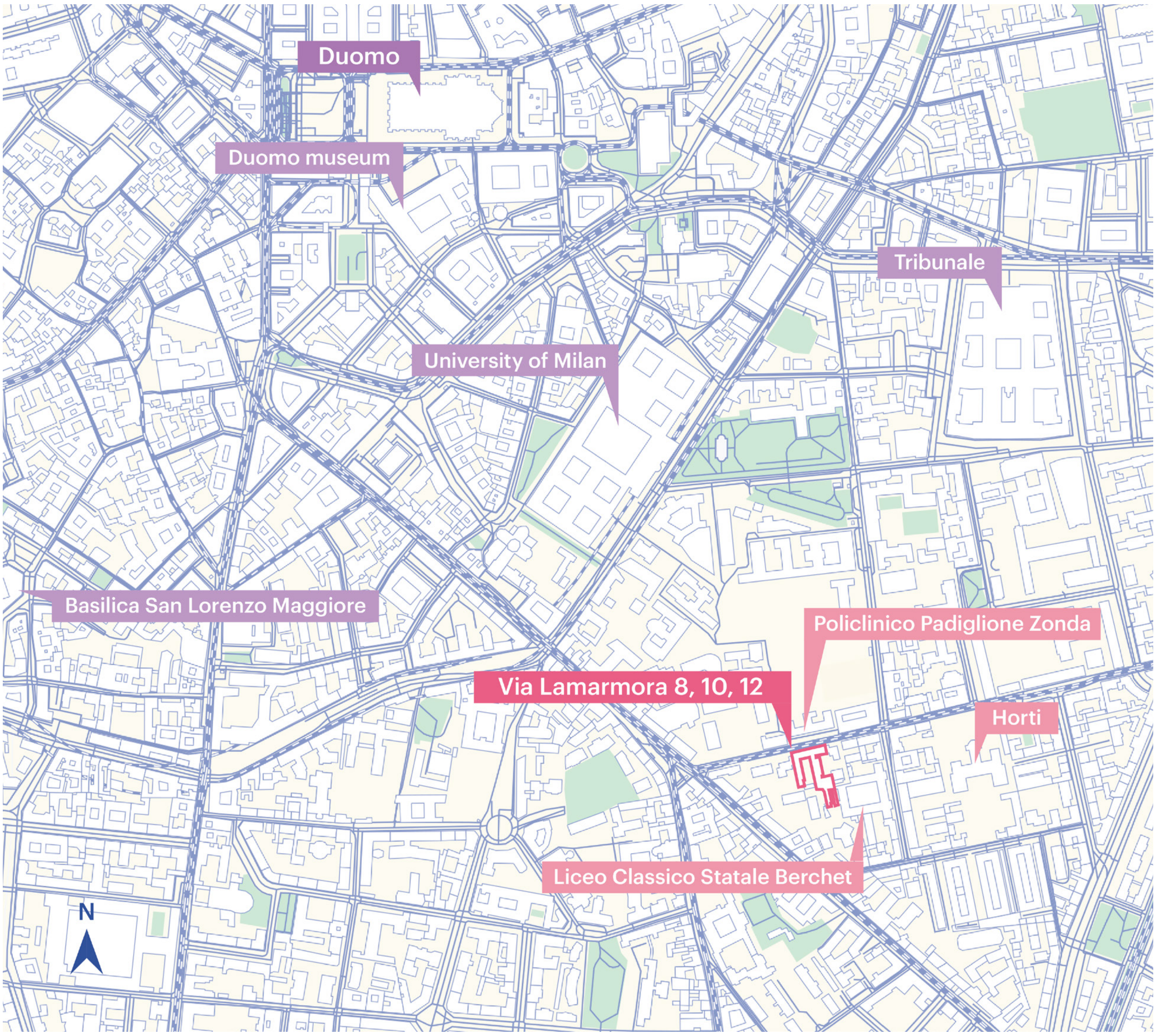
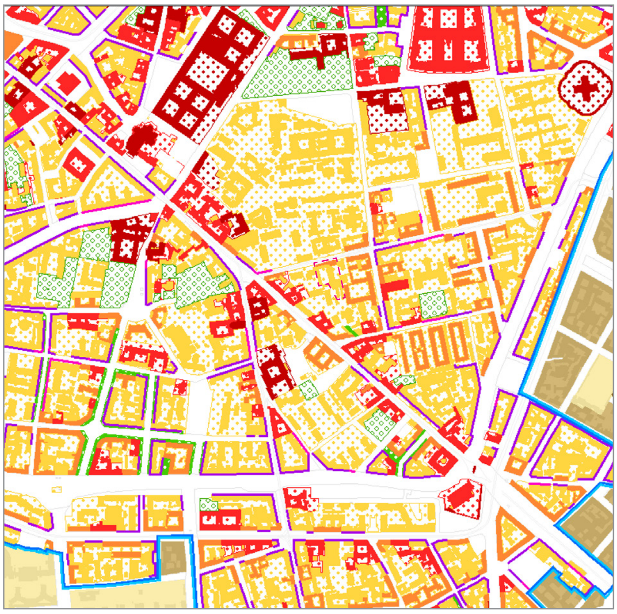


Figure 5.1 Location of the project. Source: Self-produced.

Figure 5.2 Existing situation of the project. Source: Google map.

The project entails a new construction, subject to restrictions imposed by the Municipality of Milan to preserve the architectural heritage. According to these regulations, the original street facade must be preserved without any alterations, as depicted by the regulations in Figure 5.2. However, modifications to the original footprint of the existing buildings are permissible.

The program requires the development of a residential building covering a minimum gross floor area of 8,000 to 9,000 square meters within the site, aiming to ensure pleasant livability. The design is subject to height limits, site boundary setbacks, and



PGT - Piano delle Regole - Analisi Naf

Complessi edilizi con valore architettonico intrinseco (Art. 18.2.c)

- Complessi edilizi moderni d'autore, con carattere monumentale o di emergenza
- Complessi edilizi moderni d'autore
- Tessuto edilizio con valore storico-testimoniale

Immobili con valore estetico-culturale-ambientale (Art. 18.2.d)

- Immobili con valore estetico-culturale-ambientale

Immobili non ricadenti nelle precedenti categorie (Art. 18.2.e)

- Immobili non ricadenti nelle precedenti categorie

PGT - Piano delle Regole - Indicazioni Morfologiche

NAF - Nuclei di antica formazione: Tipologie di intervento

- Interventi di manutenzione ordinaria, straordinaria e restauro (Art. 19.2.a)
- Interventi di manutenzione ordinaria, straordinaria e restauro (Art. 19.2.a)
- Interventi di manutenzione ordinaria, straordinaria, restauro e risanamento conservativo (Art. 19.2.b)
- Interventi di manutenzione ordinaria, straordinaria, restauro, risanamento conservativo, ristrutturazione edilizia e, in tal caso, col mantenimento della sagoma, del sedime e della facciata prospettante lo spazio pubblico (Art. 19.2.c)
- Interventi di manutenzione ordinaria, straordinaria, restauro, risanamento conservativo e ristrutturazione edilizia e nuova costruzione (Art. 19.2.d)
- Mantenimento o ripristino delle cortine edilizie (Art. 19.3.a)
- Completamento del fronte continuo (Art. 19.3.a)
- Recupero e realizzazione di corti, cortili e giardini (Art. 19.3.b)

Figure 5.3 Local regulations of Milan. Source: PGT - Piano delle Regole - Analisi Naf, PGT - Piano delle Regole - Indicazioni Morfologiche.

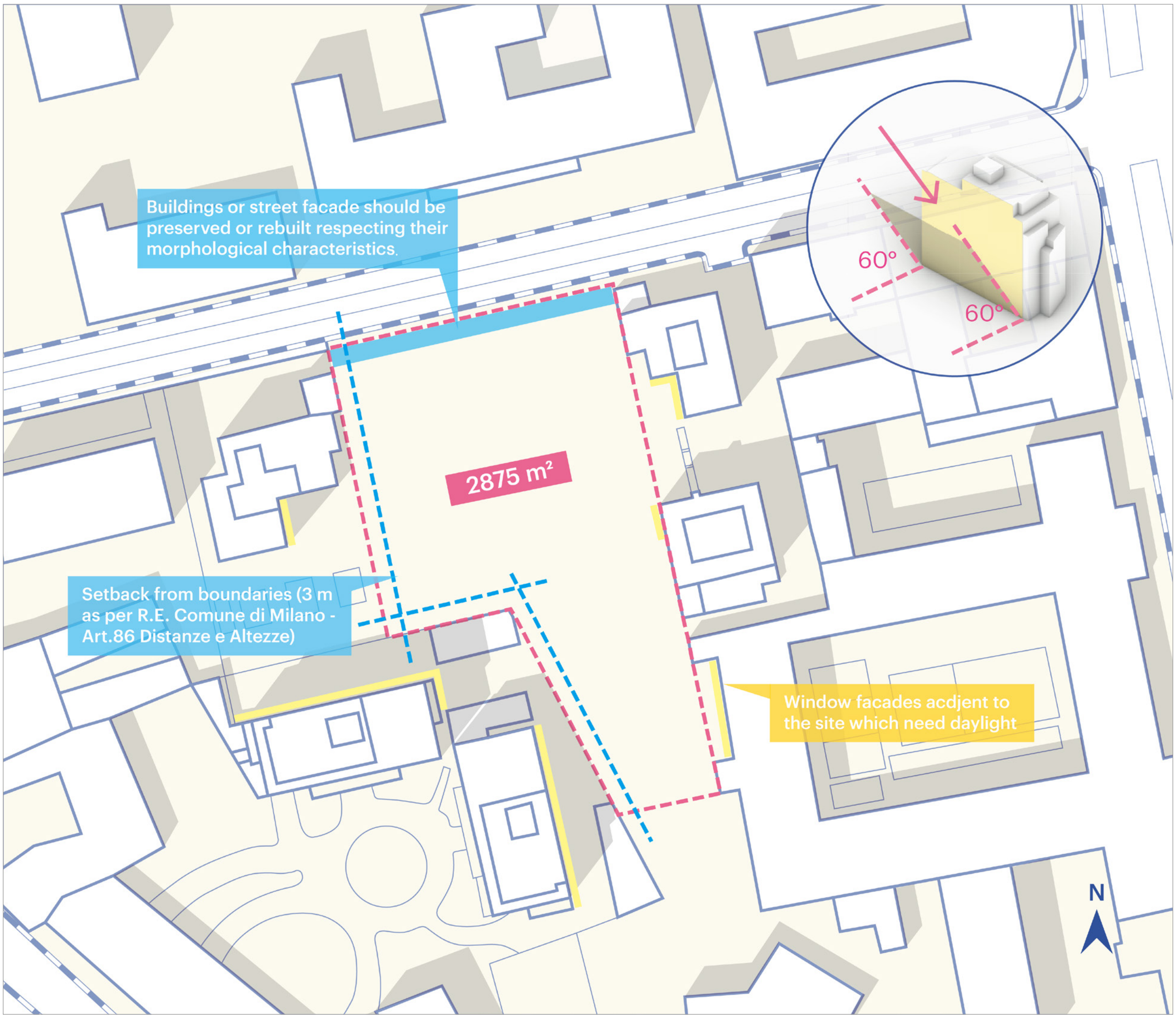


Figure 5.4 Mandatory parameters of design. Source: Self-produced.

1	Height limits	28.6m	26m for volume adjacent to the street side
2	Site boundary setback	3m	/
3	Plot area	2875 m²	/

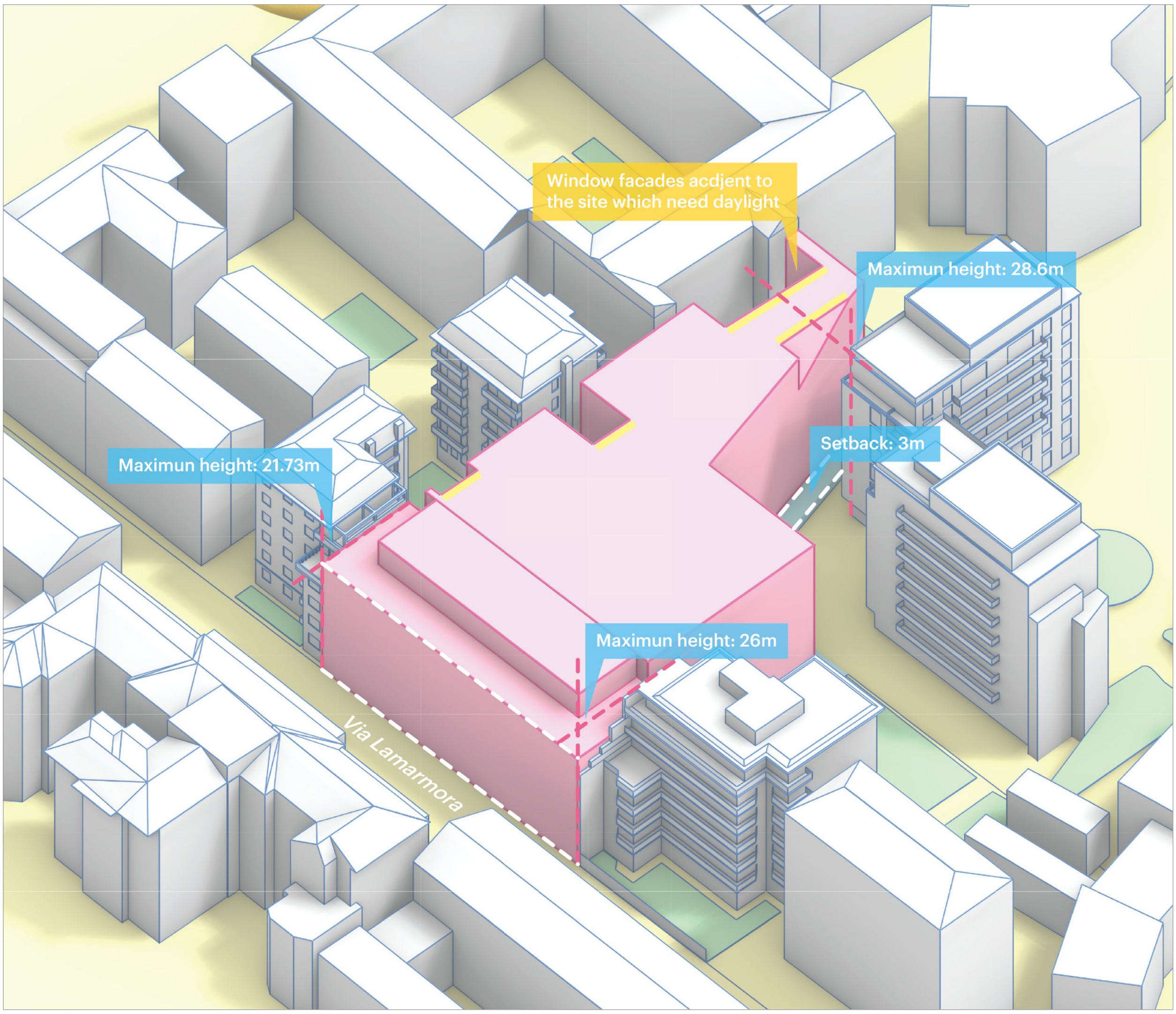


Figure 5.5 Maximum envelope of the project. Source: Self-produced.

minimum daylight requirements that need to be met, as shown in Figure 5.4. Additionally, the surrounding buildings predominantly consist of residential structures with a high demand for daylight, which imposes further constraints on the design process.

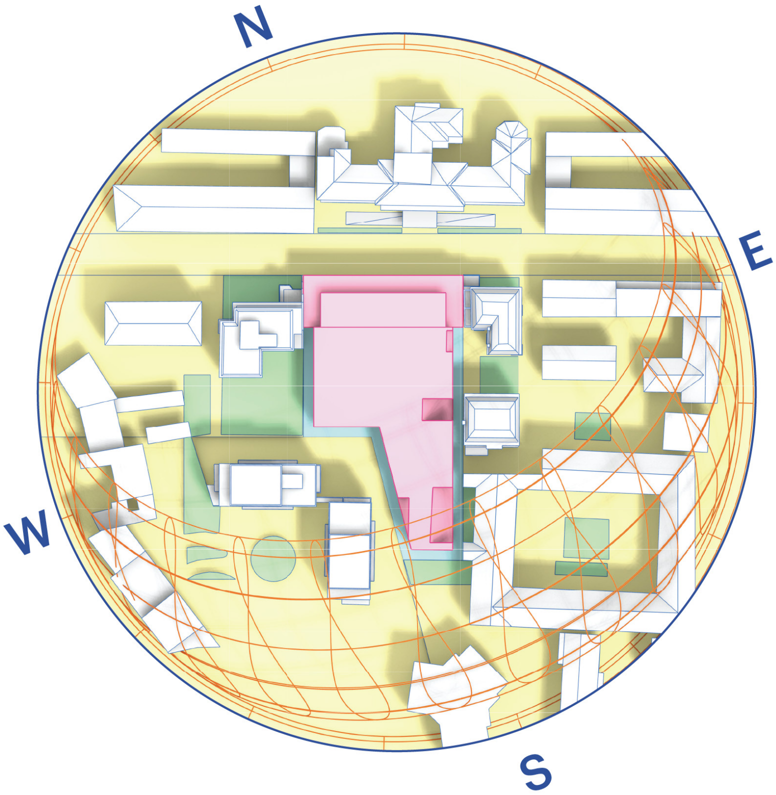


Figure 5.6 Solar orientation. Source: Self-produced.

As illustrated in Figure 5.4, the plot area measures 2,875 square meters, with the solid yellow line representing the window planes of the four residential buildings adjacent to the site. As per the regulations outlined in R.E. Comune di Milano - Art. 86 Distanze e Altezze, the volumetric envelope of the new construction must not exceed an inclined plane rotated by 60 degrees, starting from the horizon line of the facade positioned on the solid yellow line.

Furthermore, the building height limit is 26m for constructions alongside the street, while constructions on the southern part of the site can reach a height of up to 28.6m. The minimum spacing between detached buildings is 10m. Under these specifications, the maximum volumetric range within the site, as depicted in Figure 5.5, ensures that none of the generated massing options exceeds this three-dimensional constraint.

5.1. Volumetric options

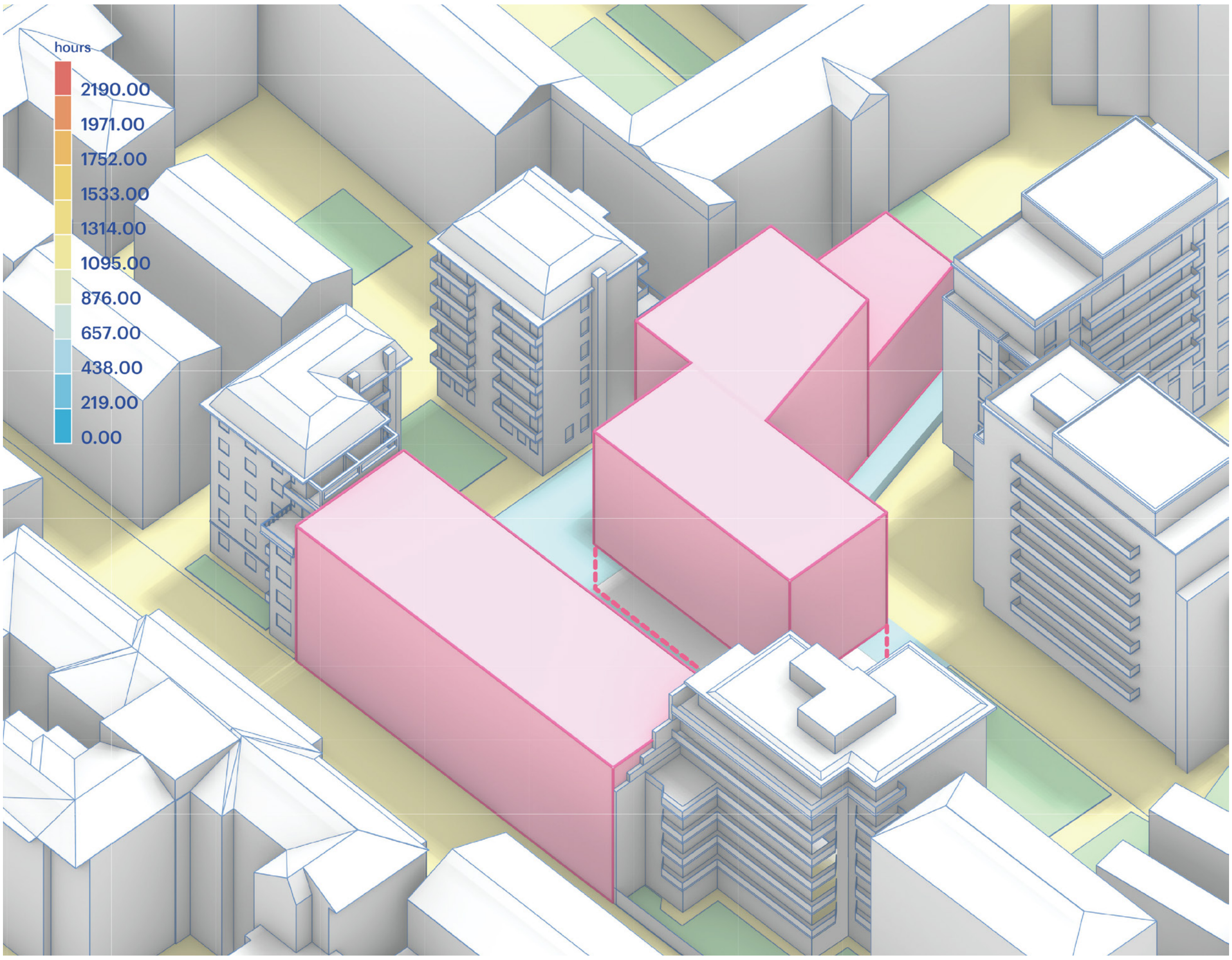
To generate massing options, subjectively defined sustainable design parameters, as mentioned in the previous chapter, play a crucial role in the selection of volumetric options. During this volumetric optimization phase, the primary objectives are to optimize the green roof area and sun exposure hours, allowing the proposals to present similar sustainable performance.

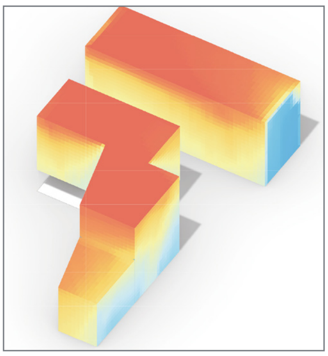
Given that the street frontage of the project has to be preserved by regulation, it would be first and foremost reasonable to align a rectangular volume on the north side of the site, which is tied directly to the adjacent residential buildings to the east and west. However, for better ventilation performance, it is not advisable to further extend the depth of the north-side volume to a depth of more than 15 meters (the depth of the existing volume). Taking these considerations as a start, the author develops three volumetric concepts.

Massing option A: Firstly, the author generates further massing that are detached from the northern block according to the regulation that the detached building spacing needs to be more than or equal to 10 m. Thus, Massing Option A has a detached irregular volume within the remaining space along the site boundary.

Massing option B: Massing Option B continuously seeks to further fragmentation to ultimately generate three separate volumes, compared to Option A.

Massing option C: Massing Option C, on the other hand, differs from the previous two scenarios. It





Option A		
1	Roof area	1574m²
2	Sun hour (envelope)	6,678,934 h
3	GFA	8,992m²
4	Average	742.8 h/ m²

Figure 5.7 Massing option A. Source: Self-produced.

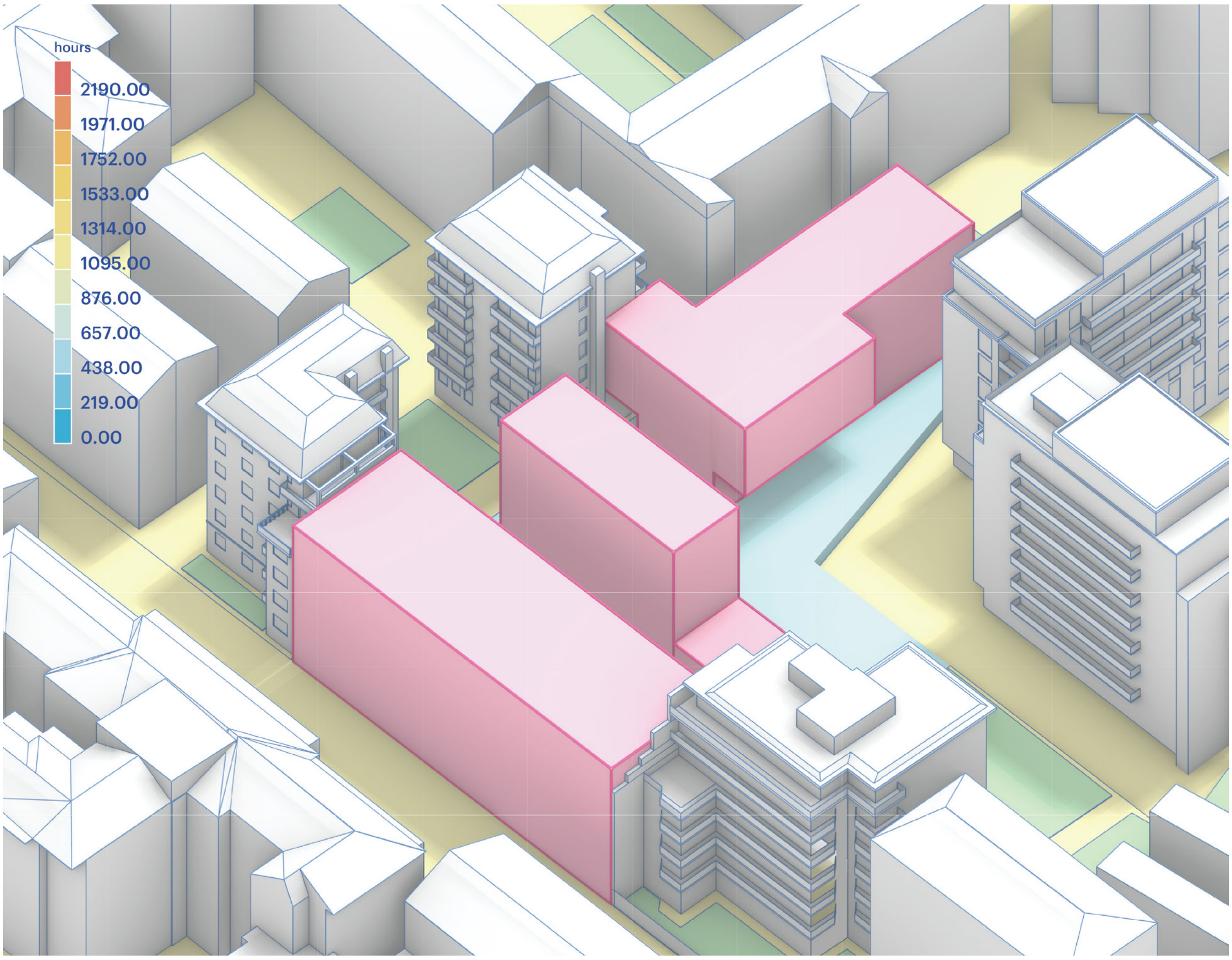
considers establishing a direct connection with the north-side volume along the street, resulting in a linear, elongated massing from south to north.

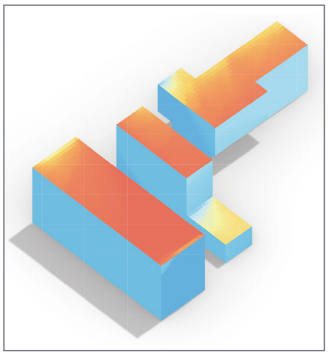
Each of the three options results in a distinctively geometric spatial configuration within the complex surroundings. The requirement to achieve a GFA in the range of 8,000 to 9,000 square meters is strictly followed during the generation of the options. Furthermore, by pursuing optimization goals for subjectively defined parameters, the relative topical detail of the massing has been appropriately adjusted. For instance, in order to maximize daylight exposure, a partial volume of Option A has been elevated from the ground floor, while Option B remains at ground level.

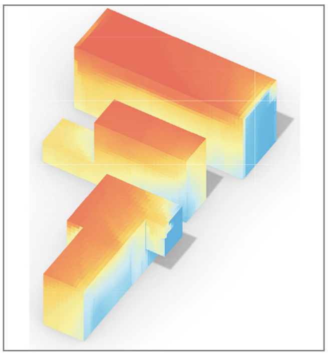
Thus these three options demonstrate similar performance in terms of green roof area, all-year direct sun hours, satisfying the basic requirements of GFA range (8000m^2-9000m^2). Architects can further evaluate the advantages and disadvantages of each volume option from the LCA perspective, distinguishing it from the conventional decision-making process.

Options A and B exhibit similar average annual sun hours per square meter, considering the entire envelope, while option C has a slightly lower value. The gross floor area for all three options falls within the range of 8,000 to 9,000 square meters, with approximate roof areas. The Rhino models for each option were maintained at LOD 100, serving as source material for conducting an early life cycle assessment of the three proposals.

It is worth noting that basement development was not considered in this case study since the project program involves specific expectations for the basement, which remain consistent across all options. As a result, the applied case test simplified the calculation of the basement to focus on comparing the different environmental impacts associated with the above-ground building formation variations.

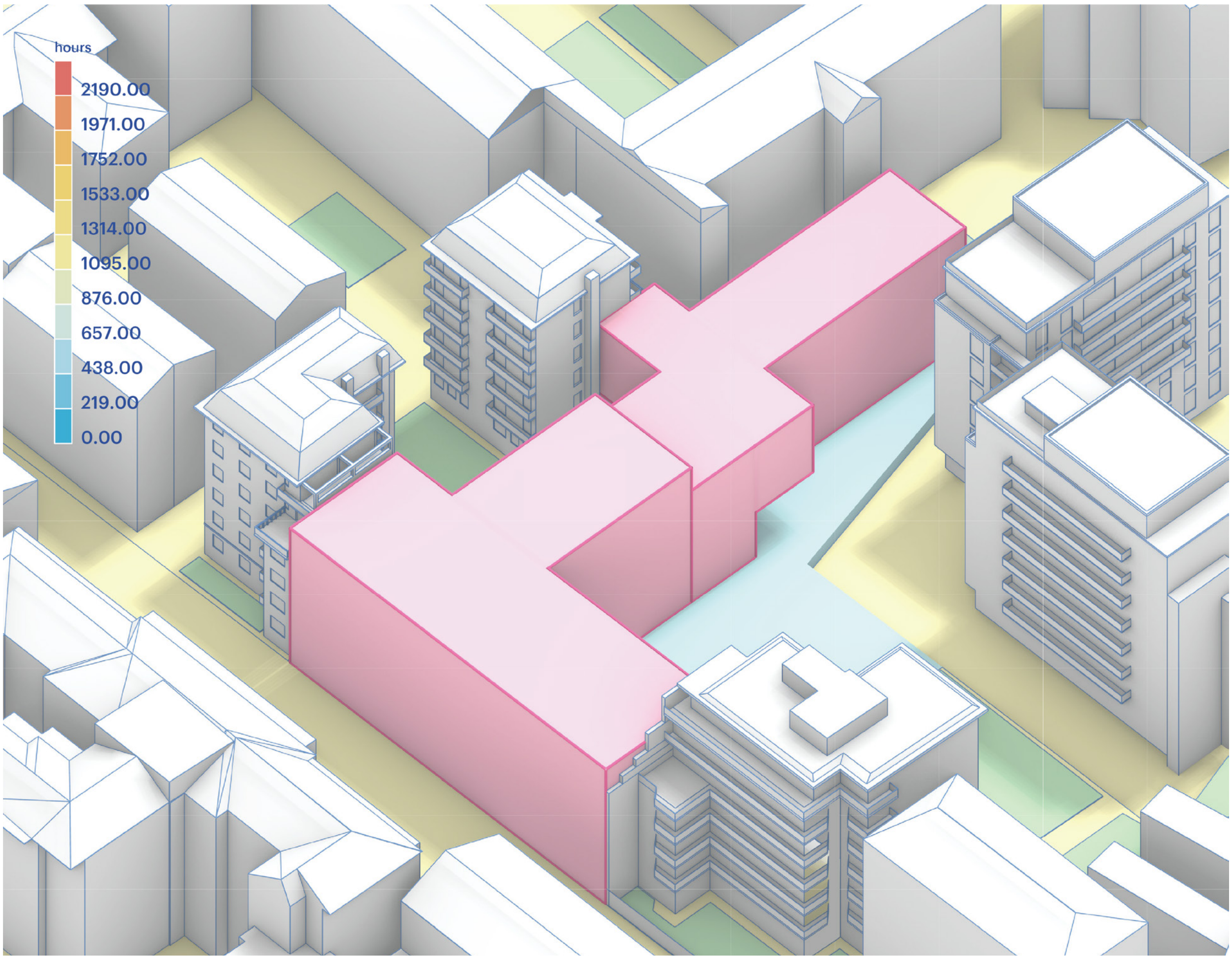


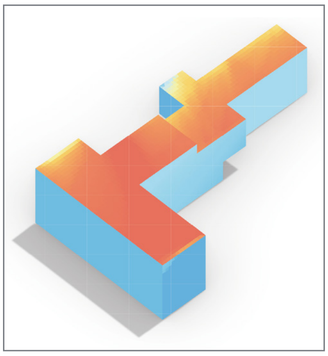


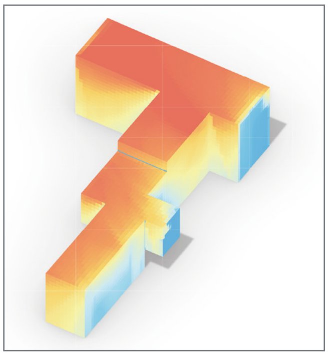


Option B		
1	Roof area	1556m²
2	Sun hour (envelope)	6,071,710 h
3	GFA	8,036m²
4	Average	755.6 h/ m²

Figure 5.8 Massing option B. Source: Self-produced.







Option C		
1	Roof area	1586m²
2	Sun hour (envelope)	5,665,813 h
3	GFA	8,253m²
4	Average	686.5 h/ m²

Figure 5.9 Massing option C. Source: Self-produced.

5.2. Perform LCA

By opening the pre-created volumetric proposal in Rhino inside the Revit environment, an early LCA report can be generated by executing the created algorithm. The building components are automatically built in Revit, promoting the LOD level from 100 to 200. The visualization script enables the designer to review the run results step by step. It is possible to conduct tests of each volumetric scenario individually, either within the same Revit file or separate Revit files. Whenever a new proposal is evaluated, the last generated architectural components will be automatically overwritten within the same file, mitigating the risk of potential component overlapping errors.

5.2.1. Scenario assumptions

In this test of the case, the user-defined axial grid spacing followed the conventional layout of 6m* 7.2m, based on normal loading conditions. However, as the exact same axial layout may not always be suitable for different massing options, the grid spacing will be allowed to be slightly adjusted to ensure feasible structural solutions. The floor height has been set at 3.3 meters, consistent with the height of the ground floor.

For concrete structure and steel structures, the construction layers of the green roof system follow this sequential order: root-proofing membrane, bedding screed, insulation layer, waterproofing

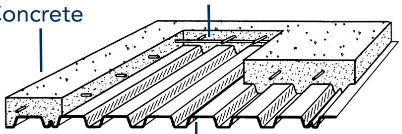


Figure 5.10 Typical composite floor slab in steel strcuture. Source: alphasteel.com

membrane, protective layer, structural layer, and interior plaster finishes, resulting in a total roof thickness of 300 millimeters. For the wood frame, the structural layer material is cross-laminated timber.

The external wall system is designed conventionally, comprising an external plasterboard, thermal insulation, waterproofing, masonry block layer, and interior mortar. To comply with the requirements of the latest code 'Allegato C - Requisiti energetici degli edifici' for the overall U-value of the facade, the insulation layer thickness has been defined with a minimum of 248 mm, with Lambda values of less than 0.033 W/(m.K) for the thermal conductivity of the material. The material of the insulation has been selected between EPS and PUR. The masonry block selection encompasses a wide range of options, from lightweight concrete blocks to bricks. This facade system has been applied in both concrete and steel structures. As for the timber frame, a lighter exterior wall system, consisting of timber cladding, insulation, waterproofing, CLT panels, and interior plasterboard, has been proposed, resulting in an overall thickness of 400 mm.

The thickness of the floor slabs was chosen on the assumption of regular normal loads. In both concrete and timber structures, the floor maintains material consistency with the respective structural system, with a thickness of 150mm, as calculated and determined by the common rules of defining the thickness of the slab. However, for the slab of steel structure, it's slightly more complex, consisting of pre-coated steel decking and cast-in-place concrete, as shown in Figure 5.10. The overall thickness is set to 100mm, fitting the needs of a 6-floor-level residential building, where the thickness of the steel deck and the impact measured unit are determined by the collected products. It is also worth noting that the impact calculation methods of the reinforced steel in concrete structure followed the summary table published by university of Bath which specify the value that should be added to the appropriate concrete coefficient for each 100 kg of rebar per m³ of concrete[28].

As the interior partition walls could not be accurately defined at the conceptual early design stage, and considering the flexibility of the housing units' types, these inner partition walls were not included in the automated modeling. Simultaneously, the percentage of openings (40%) on the facade was relatively fixed. Therefore, to proceed with the following LCA, the approximate result of multiplying the facade area with the opening ratio was directly utilized.

It is important to emphasize that both the facade and the green roof system can be highly customizable, but customizability is not the primary focus of this study. In future cases, the selection of materials and construction solutions can be adjusted adaptively to suit the specific circumstances of each project.

5.2.2. LCI database

It is important to emphasize that both the facade and the green roof system can be highly customizable, but customizability is not the primary focus of this study. In future cases, the selection of materials and construction solutions can be adjusted adaptively to suit the specific circumstances of each project.

The LCI database was developed by searching for material

C25/30	General information and Data background						Technical Characteristics				Environmental Profile (GWP： kg CO2e/ m³)						Resource
	Commercial Name	Manufacturer	EPD number	EPD program	Year	Standard	Technical specification	Density	Default thickness	Unit	A1-A3	A4	Transportation distance (km)	C2	C3	D	Link of EPD
1	ZA000495	UNICAL SPA, Orbassano plant	EPDITALY0385	EPD Italy	2022	EN15804+A2	C25/30, S4, D32, low carbon	2400.0 kg/m³	–	m³	132.00	Concrete mixer truck, appr. 8 m3, 100% fill rate: 0.13 kg CO2e / tonkm	100	–	–	–	https://www.epditaly.it/wp-content/uploads/2016/12/Report-Calcestruzzo_EPD_EA8006.pdf
2	ZA000551-xpav	UNICAL SPA, Orbassano plant	EPDITALY0386	EPD Italy	2022	EN15804+A2	C25/30, S5	2400.0 kg/m³	–	m³	216.00	Concrete mixer truck, appr. 8 m3, 100% fill rate: 0.13 kg CO2e / tonkm	100	–	–	–	https://www.epditaly.it/wp-content/uploads/2016/12/Report-Calcestruzzo_EPD_EA8011.pdf
3	EcoPact AN XC2 C25/30	Holcim Aggregati Calcestruzzi Srl	EPDITALY0391	EPD Italy	2022	EN15804+A2	C25/30, S4, D31,5-32,5	2400.0 kg/m³	–	m³	209.00	Concrete mixer truck, appr. 8 m3, 100% fill rate: 0.13 kg CO2e / tonkm	40	–	16.7 kg CO2e / kg	-3.82 kg CO2e / kg	https://www.epditaly.it/wp-content/uploads/2016/12/Report_EPD_ECAN304B3C_2023-02-23_02-11-32.pdf

C30/35	General information and Data background						Technical Characteristics				Environmental Profile (GWP： kg $CO2_e$/ m³)						Resource
	Commercial Name	Manufacturer	EPD number	EPD program	Year	Standard	Technical specification	Density	Default thickness	Unit	A1-A3	A4	Transportation distance (km)	C2	C3	D	Link of EPD
1	dryCrystal RCK37	Colabeton	EPDITALY0108	EPD Italy	2020	EN15804+A2	C30/37, XC4, S4, D25, CEM IV 32.5 N	2400.0 kg/m³	–	m³	276.00	Concrete mixer truck, appr. 8 m3, 100% fill rate: 0.13 kg CO2e / tonkm	25	–	–	–	https://www.epditaly.it/wp-content/uploads/2016/12/Report-EPD-Colabeton-Mediglia.pdf
2	ZA000531-xpav	UNICAL SPA, Orbassano plant	EPDITALY0386	EPD Italy	2022	EN15804+A2	C30/37, Sr 150, D32, XC4	2400.0 kg/m³	–	m³	241.00	Concrete mixer truck, appr. 8 m3, 100% fill rate: 0.13 kg CO2e / tonkm	100	–	–	–	https://www.epditaly.it/wp-content/uploads/2016/12/Report-Calcestruzzo_EPD_EA8011.pdf
3	EcoPact AN XC2 C30/37	Holcim Aggregati Calcestruzzi Srl	EPDITALY0390	EPD Italy	2023	EN15804+A2	C30/37, S4, D31,5-32,5	2400.0 kg/m³	–	m³	226.00	Concrete mixer truck, appr. 8 m3, 100% fill rate: 0.13 kg CO2e / tonkm	40	11.3 kg CO2e/ m³	16.6 kg CO2e/ m³	-3.8 kg CO2e/ m³	https://www.epditaly.it/wp-content/uploads/2016/12/Report_EPD_ECAN374B3C_2023-02-23_02-15-25.pdf

CLT	General information and Data background						Technical Characteristics				Environmental Profile (GWP: kg $CO2_e$ / m³)							Resource
	Commercial Name	Manufacturer	EPD number	EPD program	Year	Standard	Technical specification	Density	Default thickness	Unit	A1-A3	A4	Transportation distance (km)	C2	C3	D	Biogenic CO_2 storage (A1)	Link of EPD
1	Pannello MHM	FBE	S-P-03663	International EPD System	2020	EN15804+A1	CLT, glulam and LVL	450.0 kg/m³	–	m³	273.00	Trailer combination, 40 ton capacity, 100% fill rate: 0.0383 kg CO2e / tonkm	210	–	–	–	717.0	https://api.environdec.com/api/v1/EPDLibrary/Files/8b9056bb-ae03-4c90-c7f8-08dafef7b801/Data
2	Rubner-XLAM	Rubner Holding	EPD-RUB-20180060-IBB1-EN	IBU	2018	EN15804+A1	CLT, glulam and LVL	461.0 kg/m³	–	m³	181.17	Trailer combination, 40 ton capacity, 100% fill rate: 0.0383 kg CO2e / tonkm	340	–	759.0	-410.0	845.17	https://oneclicklcaapp.com/app/sec/util/getEpdFile?resourceId=ibuCrossLaminatedTimberRubnerHoldingXlam&profileId=RubnerHolding2018
3	binderholz Brettsperrholz BBS, CLT BBS, X-LAM BBS	Binderholz Bausysteme (Austria)	EPD-BBS-20190021-IBB1-DE	IBU	2019	EN15804+A1	CLT, glulam and LVL	470.88 kg/m³	100mm	m³	103.96	Trailer combination, 40 ton capacity, 100% fill rate: 0.0383 kg CO2e / tonkm	560	0.548	766	-412.00	761.00	https://oneclicklcaapp.com/app/sec/util/getEpdFile?resourceId=ibuBinderholzBrettsperrholzBBSXLAMCLT_fixApr2022&profileId=BinderholzBausysteme2019
4	X-LAM • Cross Laminated Timber	Artuso Legnami S.r.l.	S-P-01408	International EPD System	2018	EN15804+A1	CLT, glulam and LVL	400.0 kg/m³	200mm	m³	160.0	Trailer combination, 40 ton capacity, 100% fill rate: 0.0383 kg CO2e / tonkm	280	–	–	–	520.0	https://api.environdec.com/api/v1/EPDLibrary/Files/dd02e37b-6c9d-4347-928c-690f08e79282/Data

C40/45	General information and Data background						Technical Characteristics				Environmental Profile (GWP： kg $CO2_e$/ m³)						Resource
	Commercial Name	Manufacturer	EPD number	EPD program	Year	Standard	Technical specification	Density	Default thickness	Unit	A1-A3	A4	Transportation distance (km)	C2	C3	D	Link of EPD
1	Ordinario 30R404C9	Unical, plant Cervia	EPDITALY0081	EPD Italy	2019	EN15804+A2	C32/40, S4, D32, XC2	2400.0 kg/m³	–	m³	393.00	Concrete mixer truck, appr. 8 m3, 100% fill rate: 0.13 kg CO2e / tonkm	100	–	–	–	https://www.epditaly.it/wp-content/uploads/2016/12/Report-Calcestruzzo_EPD_EL40002-
2	R40C4D31S4XC4/XC3/XC2/XC1	Betonrossi S.p.A.	EPDITALY0393	EPD Italy	2023	EN15804+A2	C40, S4, D31, XC4/XC3/XC2/XC1	2400.0 kg/m³	–	m³	285.40	Concrete mixer truck, appr. 8 m3, 100% fill rate: 0.13 kg CO2e / tonkm	80	11.7 kg CO2e/ m³	4.01 kg CO2e/ m³	0.225 kg CO2e/ m³	https://www.epditaly.it/wp-content/uploads/2016/12/EPD_Betonrossi_rev.03
3	dryCrystal RCK45	Colabeton	EPDITALY0108	EPD Italy	2020	EN15804+A1	C45, XC4, S5, D15, CEM IV 42.5 R	2400.0 kg/m132	–	m³	381.00	Concrete mixer truck, appr. 8 m3, 100% fill rate: 0.13 kg	25	–	–	–	https://www.epditaly.it/wp-content/uploads/2016/12/Report-

Waterproofing	General information and Data background						Technical Characteristics				Environmental Profile							Resource	Note
	Commercial Name	Manufacturer	EPD number	EPD program	Year	Standard	Technical specification	Density	Default thickness(mm)	Unit	A1-A3 (GWP: kg CO_2eq / m²)	A1-A3 (ADPF: MJ)	A4 (GWP: kg CO_2eq / m²)	Transportation distance (km)	C2 (GWP: kg CO_2eq / m²)	C3 (GWP: kg CO_2eq / m²)	D (GWP: kg CO_2eq / m²)	Link of EPD	
1	Flagon® TPO EP/PV-F	Soprema	S-P-01603, ver. 5	International EPD System	2019	EN15804+A1	Plastic membranes	1.4 kg/m²	1.5	m²	0.0653	1.5953	0.0106	40	0.000688	0.00483	-0.0306	https://api.environdec.com/api/v1/EPDLibrary/Files/9fc6d418-c600-459a-9c28-d4f3033d4a4e/Data	8% recycled content
2	VINITEX® MP	Soprema	S-P-01963	International EPD System	2020	EN15804+A1	Plastic membranes , fire resistance class = E	1.8 kg/m²	1.5	m²	0.0659	1.5364	0.00382	40	0.000635	0.00432	–	https://api.environdec.com/api/v1/EPDLibrary/Files/06d9f87a-5ff9-438e-ba11-a334d9a13c6d/Data	
3	TEXSALON® MAT-FB	Soprema	S-P-01962	International EPD System	2020	EN15804+A1	Plastic membranes, UV resistant, fully-adhered	1.5 kg/m²	1.5	m²	0.0653	1.5953	0.0106	40	0.000688	–	–	https://api.environdec.com/api/v1/EPDLibrary/Files/710d4c8b-8260-483a-8367-c8e92b949924/Data	8% recycled TPO
4	Mapeplan Plus	Polyglass	S-P-01106	International EPD System	2018	EN15804+A1	PVC waterproofing membrane	1.8 kg/m²	1.5	m²	4.76	116	0.134	300	0.0142	0.00228	–	https://api.environdec.com/api/v1/EPDLibrary/Files/2cf8e037-d09b-458c-b4b7-55605966ff06/Data	

Figure 5.11 Preview of LCI database. Source: Self-produced.

 suppliers located in Milan, with transportation distances typically not exceeding 300km. In order to enhance the diversity of the database, certain materials with transportation distances exceeding 300km were also included, as they demonstrated better environmental performance.

5.2.3. Automated model

Based on the previously mentioned assumptions, figures 5.12-5.15 depict the automated models, with volume as the reference for each option, incorporating three structural scenarios after running the scripts. These figures show the steel, timber, and concrete structural systems simultaneously in both the Rhino and Revit environments, following user-defined intervals and order, from top to bottom.

To verify the effectiveness and feasibility of the tool, in addition to the three architect-defined options, this study also provides a benchmark option that even though does not fulfill the typical residential requirements (e.g., limited depth for ventilation) or objective parameters (such as height limits), but is completely compact and energy-efficient.

The massing option used for proofing is a simple cubic block, measuring 25m in length, 28m in width, and 36.9m in height. The column grid spacing is consistent with the settings of the other three massing options.

Quantity take-off

As explained in the previous chapter regarding the algorithm, the list of materials used and quantity take-off for the three options can be obtained through data processing by accessing the parameters of each instance directly using the Inspect-element function. Although certain building elements might be constructed with the same materials, they were still treated separately in the calculations for the hot-spot analysis.

The building components included in calculations are beams, columns, roof, exterior walls, and foundation. In particular, the exterior wall and roof constructions are composed of compound material systems with layers of various materials. When extracting the bill of quantities of building materials, insulation, plaster, and waterproofing membranes, for instance, which are applied to both facades and roofs, will be combined together in the calculation. Thus, materials are categorized into two types based on the units used for calculating GWP, as shown in Figure 4.12, namely, area-based and volume-based.

In the following, Figures 5.11 to 5.14 show the models of the different structural systems with the LOD level of 200 in Rhino and Revit, respectively, after adding the architectural elements. Tables 5.1-5.4, then enumerate the bill of material quantities and indicate the material types used for the different elements in the table.

Option A

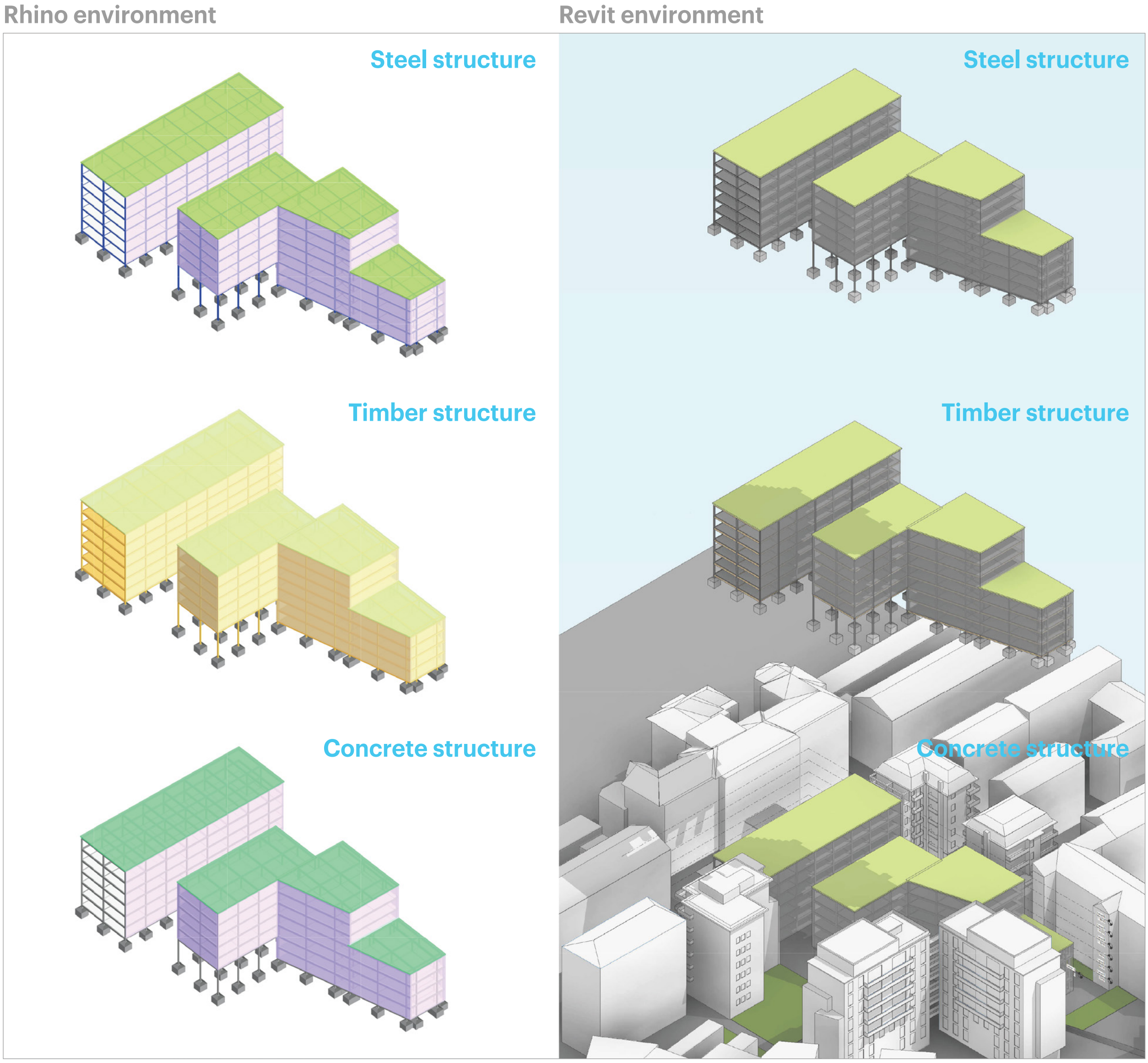


Figure 5.12 Option A. Source: Self-developed.

Concrete structure							
Volume	Foundation (Concrete C20/25)	Beam (Concrete C40/45)	Column (Concrete C40/45)	Structural slab (Concrete C30/35)	Insulation (EPS/PUR)	Block & Brick (Aerated/Autoclaved concrete products, Brick)	Cement mortar
m³	549	401	113	1,649	1,087	716	143
Area	Plaster	Membrane					
m²	5,650	5,650					

Timber structure							
Volume	Foundation (Concrete C20/25)	Beam (CLT)	Column (CLT)	Structural slab (CLT)	Insulation (EPS/PUR)	CLT panel (CLT)	Cement mortar
m³	549	441	112	1,649	896	736	83
Area	Plaster	Membrane					
m²	5,650	5,650					

Steel structure							
Volume	Foundation (Concrete C20/25)	Beam (Hot rolled)	Column (Hot rolled)	Structural slab (Concrete C30/35+Steel deck)	Insulation (EPS/PUR)	Block & Brick (Aerated/Autoclaved concrete products, Brick)	Cement mortar
m³	549	32	12	969.9	1,086	717	142
Area	Plaster	Membrane	Steel deck				
m²	5,623	5,623	8,991				

Table 5.1 Quantity take-off of Option A. Source: Self-developed.

Option B

Rhino environment Revit environment

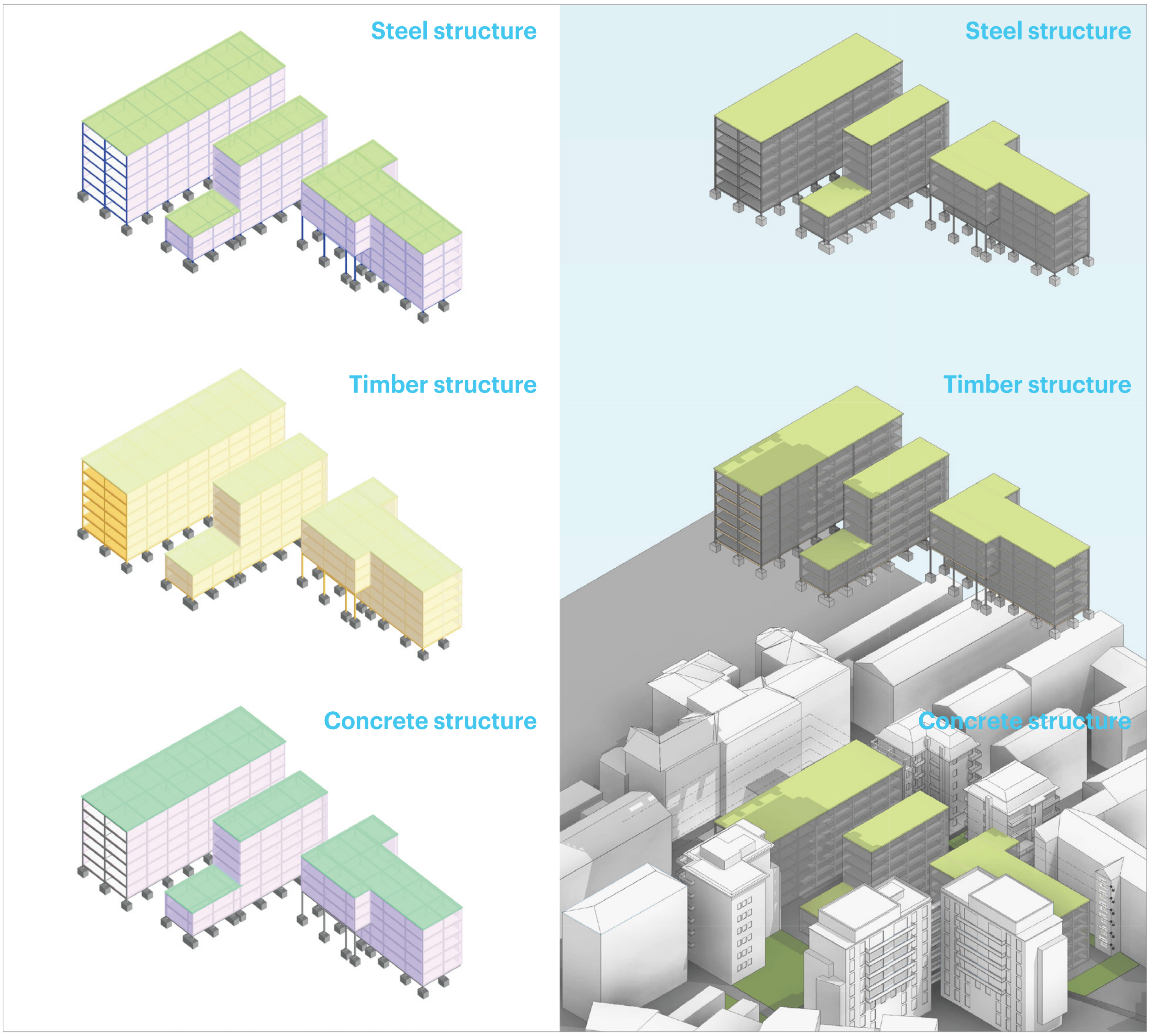


Figure 5.13 Option B. Source: Self-developed.

Concrete structure							
Volume	Foundation (Concrete C20/25)	Beam (Concrete C40/45)	Column (Concrete C40/45)	Structural slab (Concrete C30/35)	Insulation (EPS/PUR)	Block & Brick (Aerated/Autoclaved concrete products, Brick)	Cement mortar
m³	400	368	101	1,506	1,365	918	160
Area	Plaster	Membrane					
m²	6,772	6,772					

Timber structure							
Volume	Foundation (Concrete C20/25)	Beam (CLT)	Column (CLT)	Structural slab (CLT)	Insulation (EPS/PUR)	CLT panel (CLT)	Cement mortar
m³	400	409	101	1,506	1,121	944	84
Area	Plaster	Membrane					
m²	6,773	6,773					

Steel structure							
Volume	Foundation (Concrete C20/25)	Beam (Hot rolled)	Column (Hot rolled)	Structural slab (Concrete C30/35+Steel deck)	Insulation (EPS/PUR)	Block & Brick (Aerated/Autoclaved concrete products, Brick)	Cement mortar
m³	400	31	11	898	1,363	918	158
Area	Plaster	Membrane	Steel deck				
m²	6,739	6,739	8,035				

Table 5.2 Quantity take-off of Option B. Source: Self-developed.

Option C

Rhino environment | Revit environment

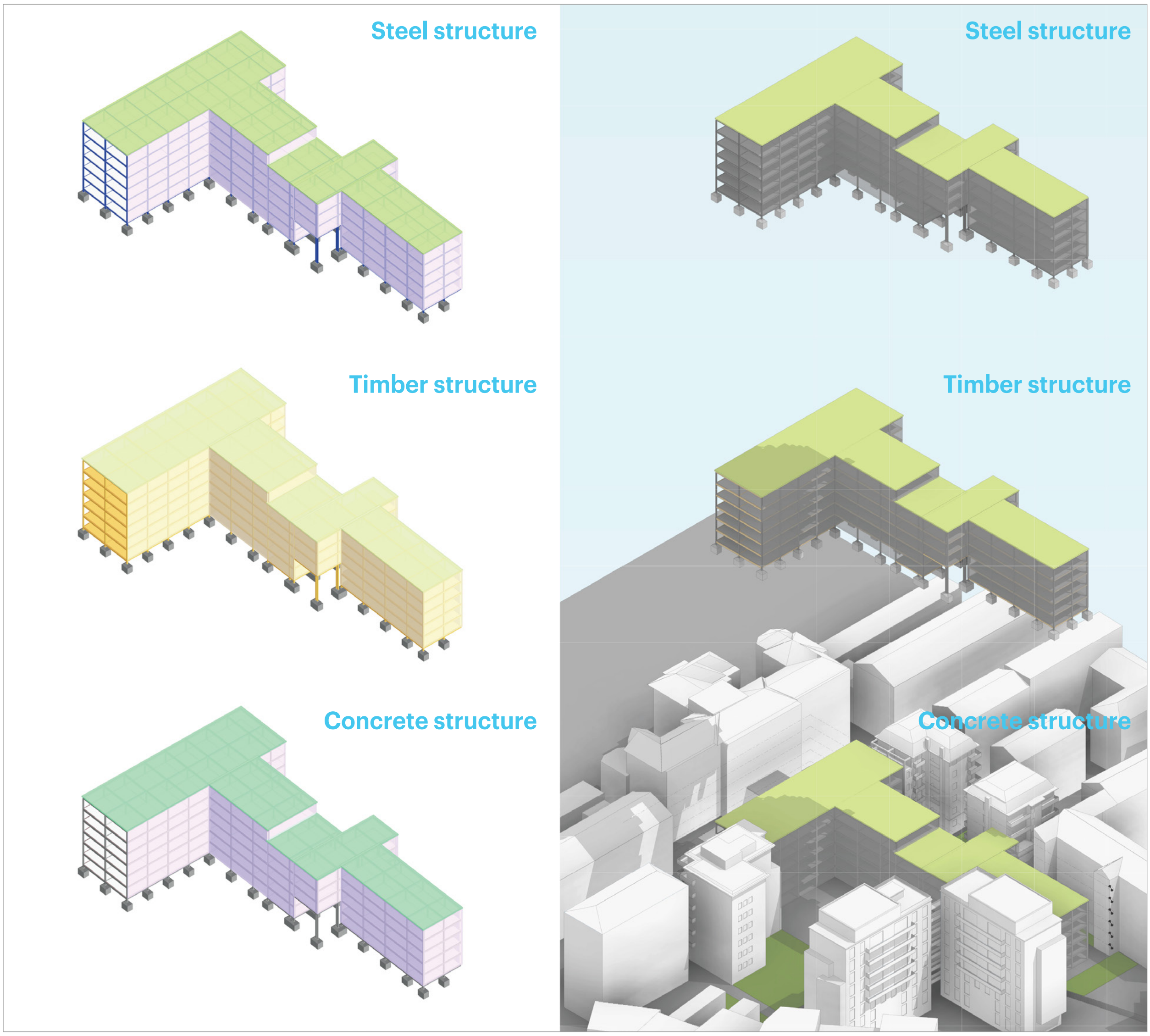


Figure 5.14 Option C. Source: Self-developed.

Concrete structure							
Volume	**Foundation** (Concrete C20/25)	**Beam** (Concrete C40/45)	**Column** (Concrete C40/45)	**Structural slab** (Concrete C30/35)	**Insulation** (EPS/PUR)	**Block & Brick** (Aerated/Autoclaved concrete products, Brick)	**Cement mortar**
m³	362	366	98	1,541	946	613	135
Area	**Plaster**	**Membrane**					
m²	5,091	5,091					

Timber structure							
Volume	**Foundation** (Concrete C20/25)	**Beam** (CLT)	**Column** (CLT)	**Structural slab** (CLT)	**Insulation** (EPS/PUR)	**CLT panel** (CLT)	**Cement mortar**
m³	362	420	98	1,541	783	630	84
Area	**Plaster**	**Membrane**					
m²	5,092	5,092					

Steel structure							
Volume	**Foundation** (Concrete C20/25)	**Beam** (Hot rolled)	**Column** (Hot rolled)	**Structural slab** (Concrete C30/35+Steel deck)	**Insulation** (EPS/PUR)	**Block & Brick** (Aerated/Autoclaved concrete products, Brick)	**Cement mortar**
m³	362	31	11	917.3	944	613	134
Area	**Plaster**	**Membrane**	**Steel deck**				
m²	5,063	5,063	8,253				

Table 5.3 Quantity take-off of Option C. Source: Self-developed.

Subsidiary test

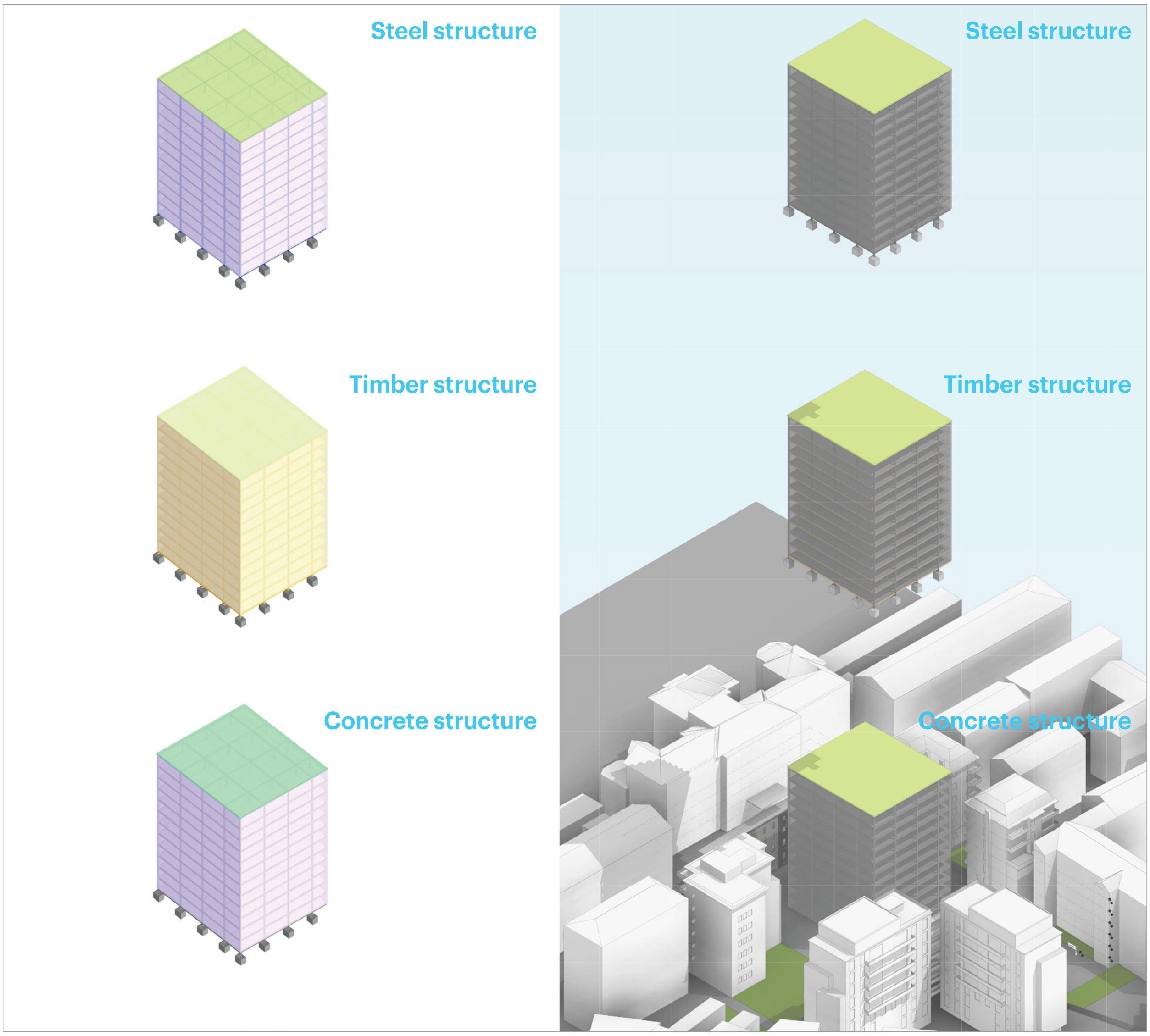


Figure 5.15 Subsidiary test. Source: Self-developed.

Concrete structure							
Volume	Foundation (Concrete C20/25)	Beam (Concrete C40/45)	Column (Concrete C40/45)	Structural slab (Concrete C30/35)	Insulation (EPS/PUR)	Block & Brick (Aerated/Autoclaved concrete products, Brick)	Cement mortar
m³	129	315	70	1,391	1,085	756	99
Area	Plaster	Membrane					
m²	4,928	4,928					

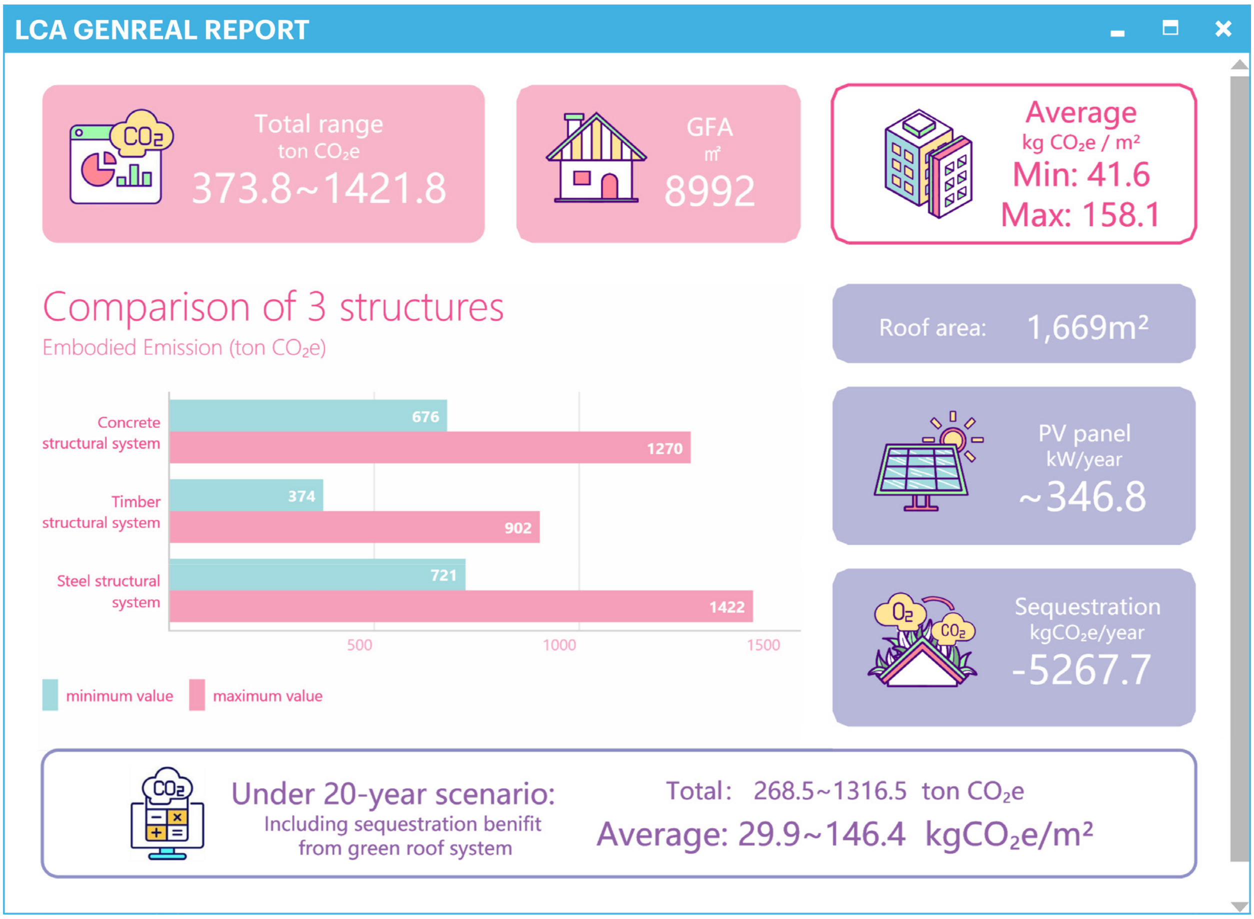
Timber structure							
Volume	Foundation (Concrete C20/25)	Beam (CLT)	Column (CLT)	Structural slab (CLT)	Insulation (EPS/PUR)	CLT panel (CLT)	Cement mortar
m³	129	334	70	1,391	883	777	36
Area	Plaster	Membrane					
m²	4,928	4,928					

Steel structure							
Volume	Foundation (Concrete C20/25)	Beam (Hot rolled)	Column (Hot rolled)	Structural slab (Concrete C30/35+Steel deck)	Insulation (EPS/PUR)	Block & Brick (Aerated/Autoclaved concrete products, Brick)	Cement mortar
m³	129	24	8	760	1,084	756	99
Area	Plaster	Membrane	Steel deck				
m²	4,919	4,919	8,400				

Table 5.4 Quantity take-off of Subsidiary test. Source: Self-developed.

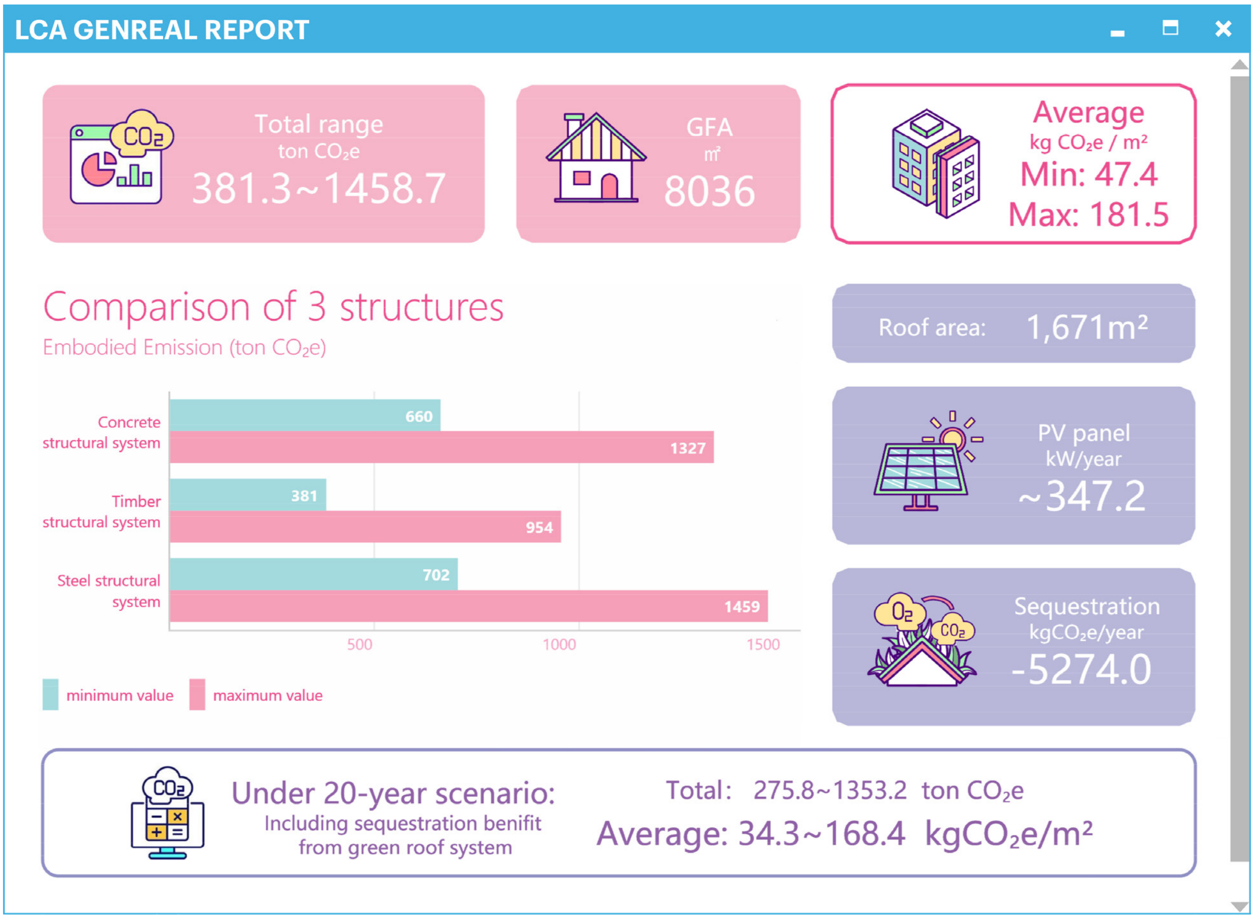
5.3. LCA results and interpretation

5.3.1. Overall dashboard



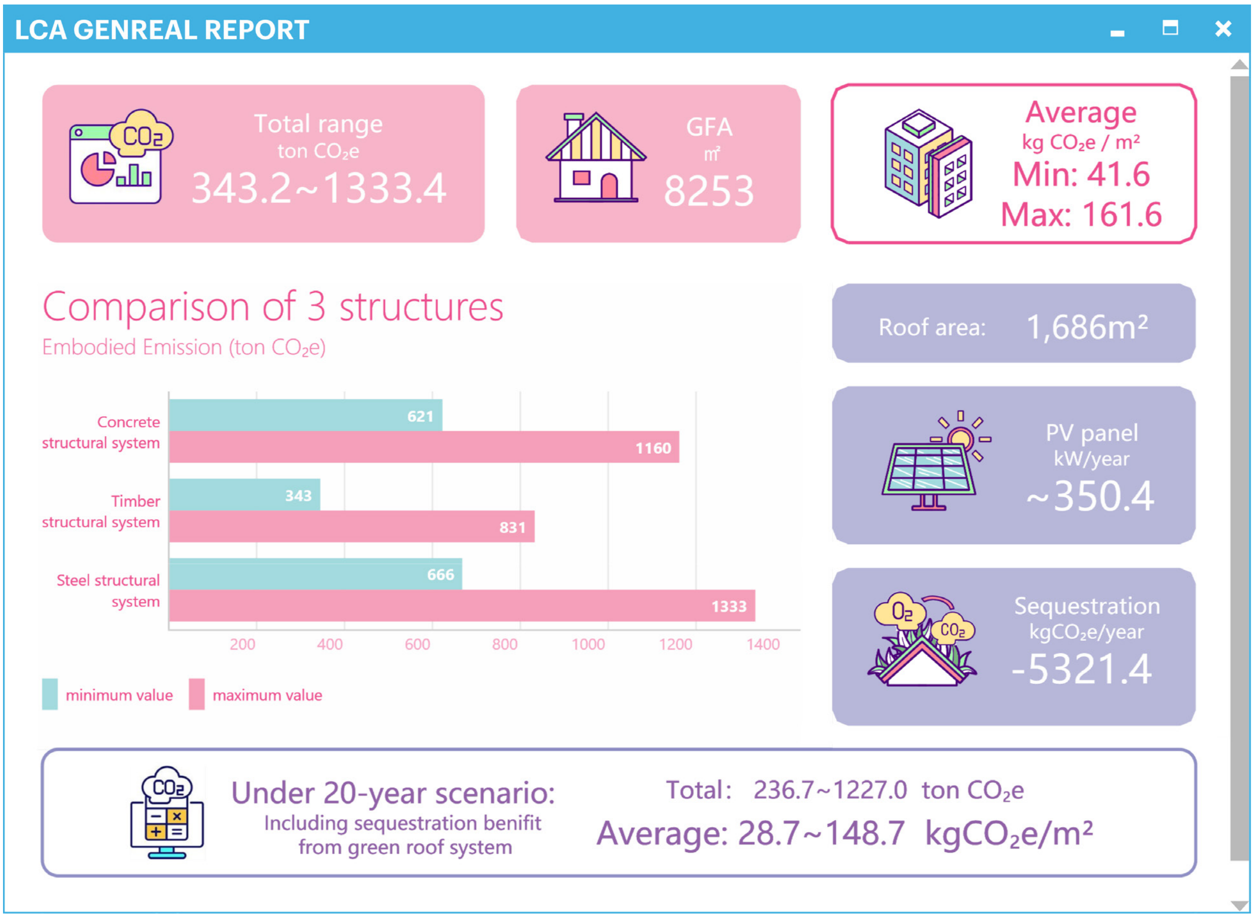
Option A

Figure 5.16 Overall report of Option A. Source: Self-developed.



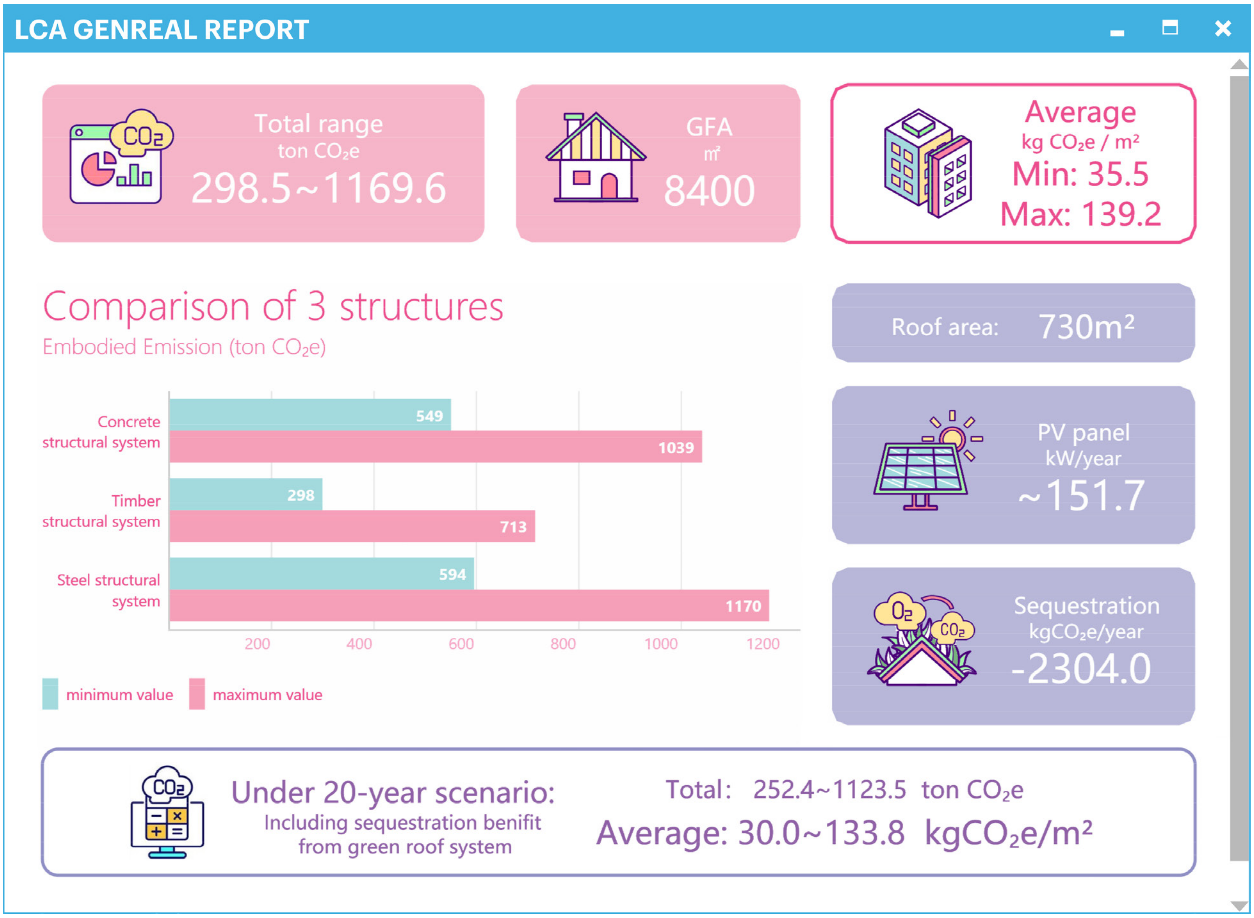
Option B

Figure 5.17 Overall report of Option B. Source: Self-developed.



Option C

Figure 5.18 Overall report of Option C. Source: Self-developed.



Subsidiary test

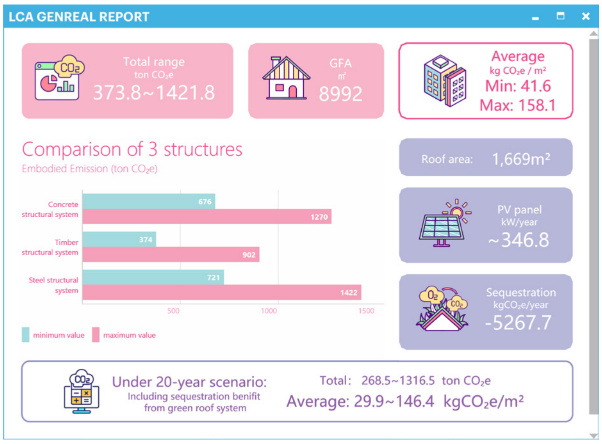
Figure 5.19 Overall report of Option Test. Source: Self-developed.

5.3.2. Overall comparison

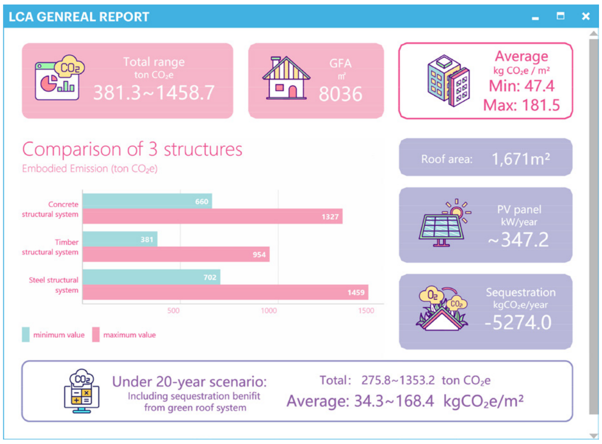
From the comparison of three massing options, as shown in Figure 5.21, it is evident that the one that can contribute to the minimum embodied carbon emissions is Option C under timber structure, at 343.2 tons CO_2e. The one contributing to the maximum emissions appears in Option B under steel structure, at 1458.7 tons CO_2e.

Even though the results of the total emissions suggest that the environmental impacts of Option A might be relatively heavy, when carbon emissions per unit of area are calculated, similar performances can be observed for both A and C, with minimum values of 41.6 kg CO_2e per square meter, indicating that both options A and C under timber structure are in essence comparable in terms of their environmental impacts during the production phase. Instead, Option B has a range of 47.4 to 181.5 CO_2e per square meter, roughly 13.9% to 14.8% larger than the other two options.

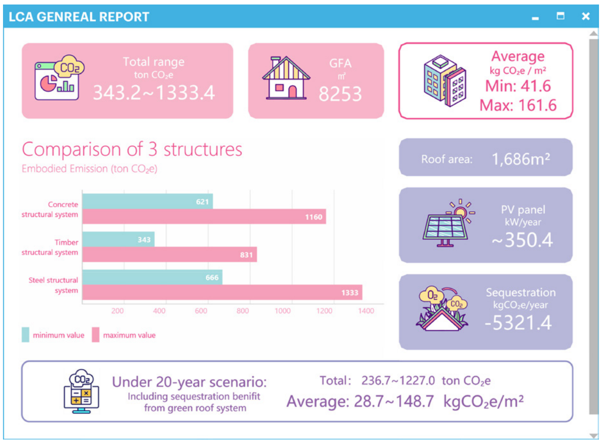
The observation of the bar charts indicates that the timber structure consistently exhibits the lowest emissions among all three structural scenarios for each option, while the steel structure displays the highest carbon emissions when only considering stages A1-A3 in two of the three options. However, the gap between the results of concrete and steel alternatives is not substantial, and in circumstances where more sustainable steel with a high recycling percentage is chosen, the carbon emissions for the steel option tend to be lower than those for concrete as



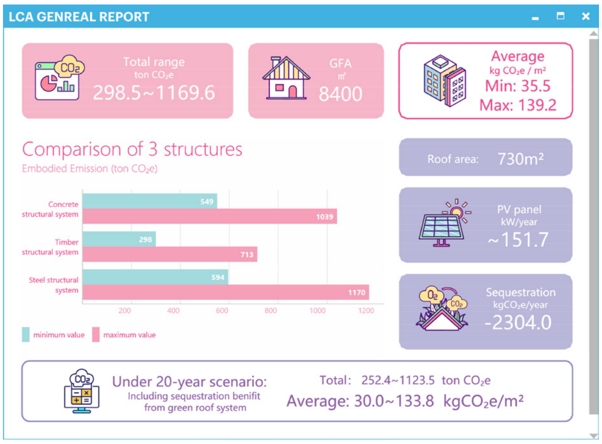
Option A



Option B



Option C



Subsidiary test

Figure 5.20 Overall comparison of all massing option. Source: Self-developed.

explained in the next section. It is essential to emphasize that if the relevant materials under the timber structural system are carelessly selected, there remains a possibility that the final embodied carbon emissions could exceed those of other structural systems, before considering the biogenic carbon storage capacity of wood.

As a control option, the overall report of the subsidiary test, which has a compact and simplistic volume, exhibits a large difference. The average embodied carbon emissions per square meter range from 35.5 to 139.2 kgCO_2e, which is approximately 30% lower on average than the other three massing options. Such a result demonstrates that indeed compact volume may produce lower environmental impacts when the environmental benefits of any additional sustainable measures are not considered, as well as validating the practicability of the tools in this study.

However, the three massing proposals that have been optimized for sustainable strategies such as green roofs during the massing generation phase would carry a carbon benefit, resulting in some positive changes to the embodied carbon emission per unit area.

Due to the similar green roof areas, the carbon sequestration of green roofs as well as the annual average electricity generation after installing photovoltaic systems exhibits similar results. Under the 20-year scenario, the calculation of the average carbon emissions per unit area indicates that Option C performs the best at 28.7 kgCO_2e/m^2, while Option B again performs the worst, sticking at 168.4 kg kgCO_2e/m^2.

In the subsidiary test, where the roof area has not been optimized, a considerable variation of the LCA results under the 20-year scenario is shown here, ranging from 30 to 133.8 $kgCO_2e/m^2$. In this regard, it is noteworthy that when the environmental impact of building materials is not as substantial (e.g. timber), appropriate sustainable implementation measures have the potential to even offset the gap in embodied emissions between the massing alternatives. Both Option A and C benefit from the integration of the green roof system, achieving lower embodied emissions per unit area than the control option of 30 $kgCO_2e/m^2$ at the 20-year scenario assessment, with results of 29.9 $kgCO_2e/m^2$ and 28.7 $kgCO_2e/m^2$ respectively.

This suggests that a relatively complex massing with optimization and careful material selection may have the possibility to present better environmental impact than conventionally compact massing. However, when building materials consist mainly of high-carbon-emission materials like steel or concrete, the impact of sustainable strategies is considerably limited. For instance, the result of 133.8 $kgCO_2e$ per unit area in the subsidiary test option is still about 10-25% lower than the other three proposals.

Overall, based solely on the general assessment report, Options A and C demonstrate equivalent environmental impacts per unit area, while Option B exhibits much higher embodied carbon emissions per square meter. However, Option A provides a larger gross floor area, which presents a slightly advantageous feature over Option C from a commercial and economic standpoint. When considering the long-term perspective and quantifying the carbon benefits of sustainable strategies, Option C with a timber structure performs slightly better, while Option A with either a steel or concrete structure performs better.

5.4. Comparison per structural scenario

The study also provides detailed reports on three specific different structural systems. By examining the report for Option A, it can be observed that, without considering the recyclability or carbon sequestration potential of building materials, the scheme with a timber structure achieves the lowest embodied carbon emissions, while the steel structural system has the highest environmental impact.

Through hotspot analysis, it can be found that similarly, irrespective of the structural type, the proportion of embodied carbon emissions from structural floor slabs has been consistently the largest, fluctuating between 26.57% and 39.54%. Among them, the steel floor slab (steel deck with cast concrete) has significantly the highest emissions, approximately 67.5% higher than the timber one. Following this, beams and columns in steel and concrete structures represent a relatively large proportion as well, 28.5% and 19.44%, respectively.

Furthermore, it can be observed by examining the bar charts that there is also a huge disparity in the range of results for part of the building materials. Plasterboard has the smallest discrepancy between the maximum and minimum values, with the maximum value being only 1.58 times the minimum value, reflecting that the environmental performance of this type of material in the LCI database is relatively homogeneous, suggesting that this material has a minor impact on the overall environmental impact

Option A

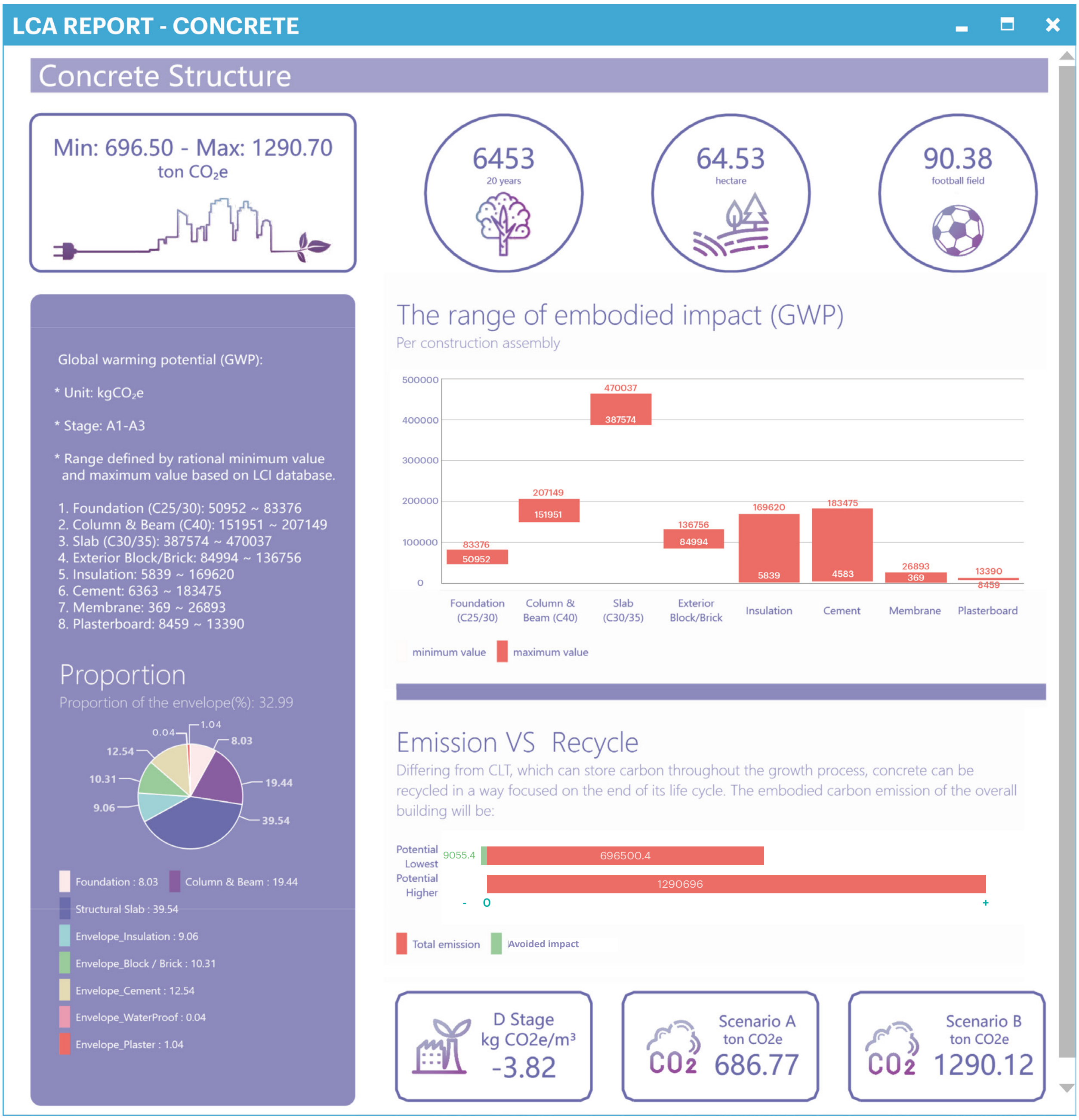


Figure 5.21 Detailed report of Option A with concrete structure. Source: Self-developed.

Option A

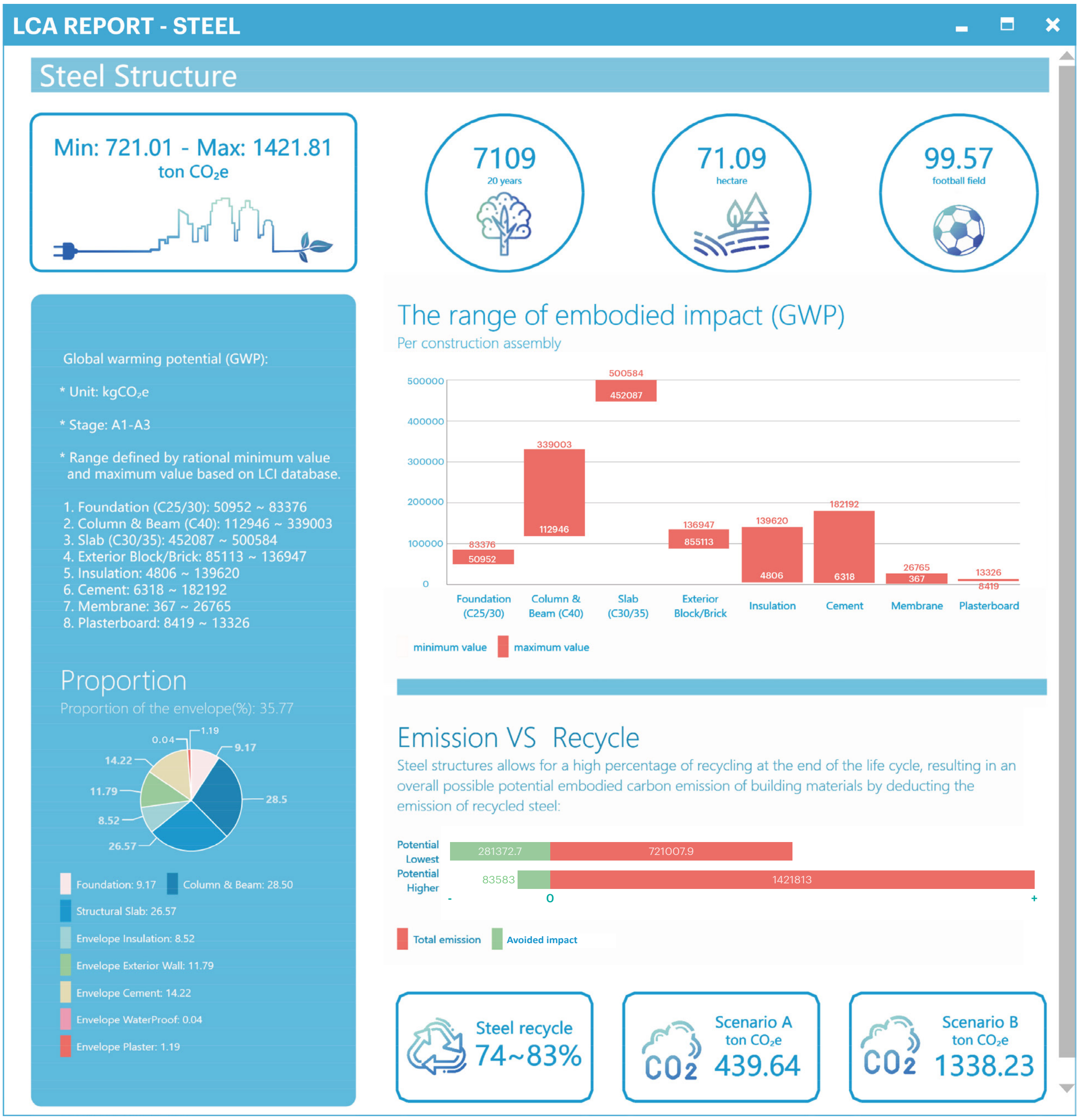


Figure 5.22 Detailed report of Option A with steel structure. Source: Self-developed.

Option A

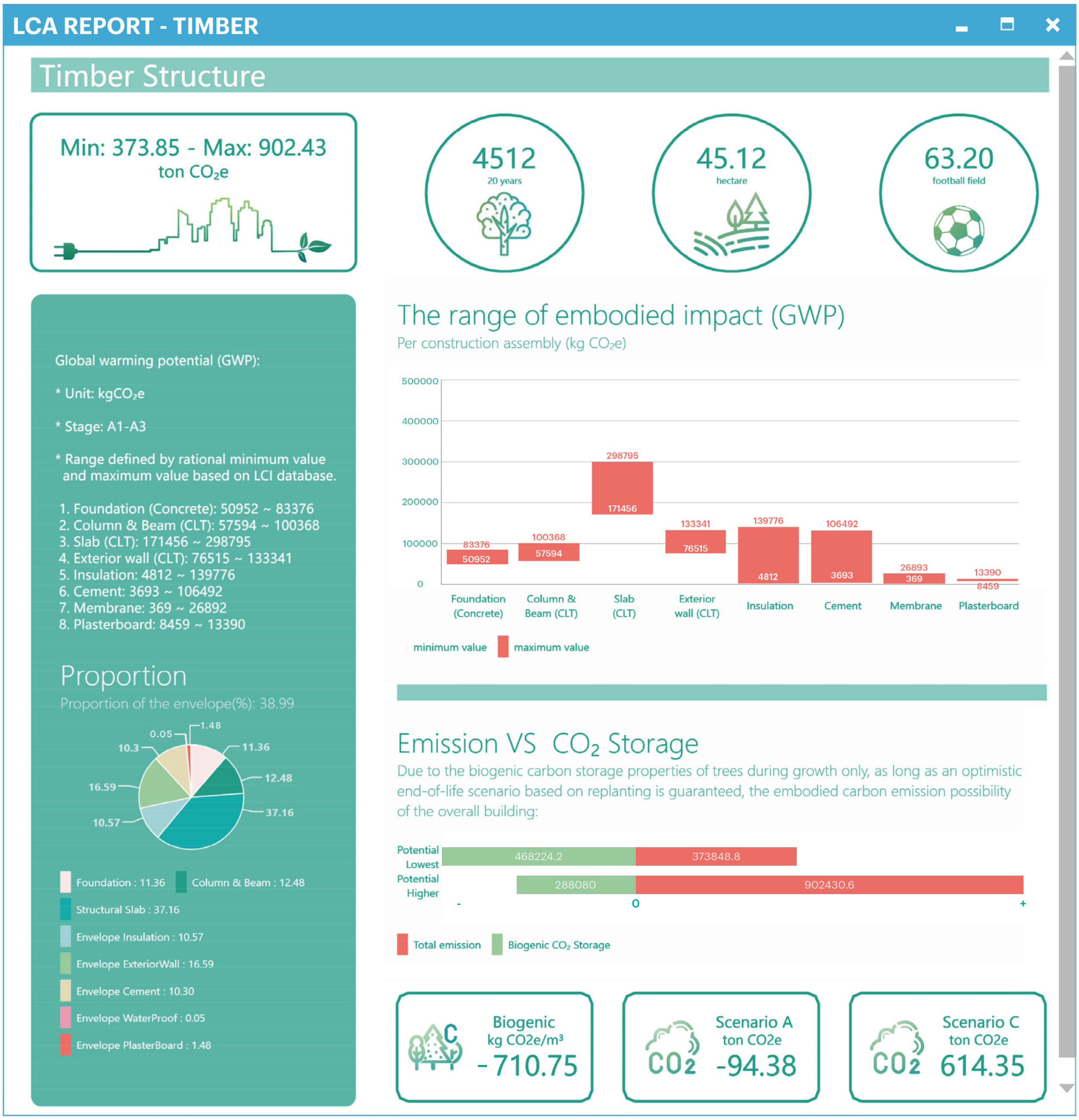


Figure 5.23 Detailed report of Option A with timber structure. Source: Self-developed.

assessment of the option itself.

On the other hand, insulation and cement mortar exhibit a massive variation in results, with the best performing environmental impact value in insulation being only one in twenty-nine of the worst materials. This result highlights the necessity to be extremely careful with the selection of such materials by architects, especially in massing options with a large envelope area.

The additional module of the detail report, which is not available in the general report, is to present the assessment results based on quantifying the advantages of materials with potential recycling possibilities or biogenic carbon storage possibilities to be included in the calculations. Based on the material EPD data that the author managed to collect, with concrete offering the lowest recycling potential of -3.83 CO_2e/m^3 and wood providing the maximum biogenic storage capacity of up to -710.75 CO_2e/m^3(referred to the information claimed in module A1 from the collected EPDs of CLT material), the detailed report respectively provides different scenario predictions.

Benefiting from the high recyclability of steel materials ranging from 74% to 83%, steel structures in the most optimistic scenarios are predicted to have a CO_2 equivalent of only 439.64 tonnes, 34% lower than that of concrete structures. However, if the carbon sequestration of timber is included in the calculations under the assumption that timber is guaranteed to be replanted properly, the wood structural system can even achieve a carbon benefit of 94.38 tons of CO_2e, which is unachievable by any other structural

Option B

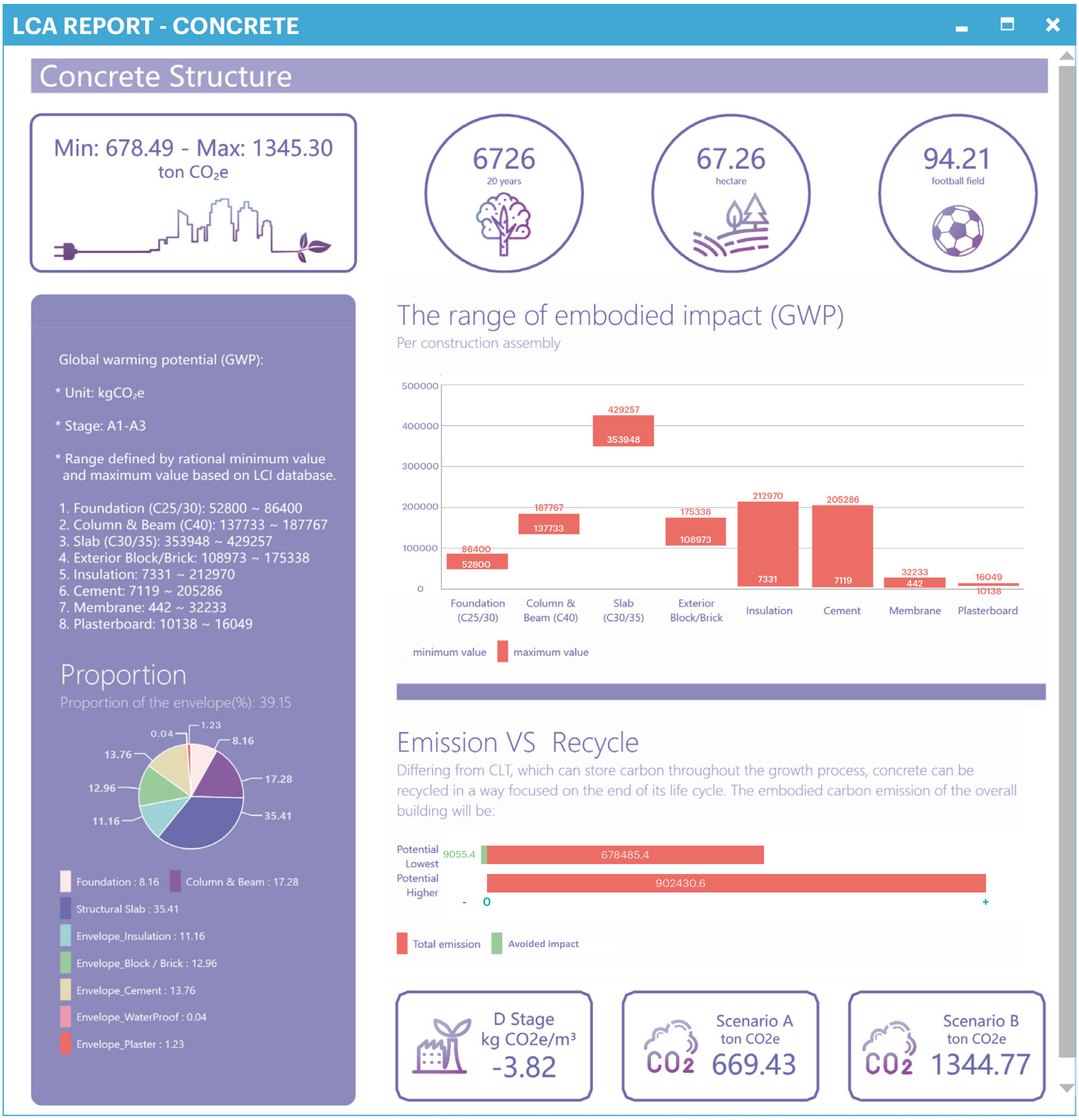


Figure 5.24 Detailed report of Option B with concrete structure. Source: Self-developed.

Option B

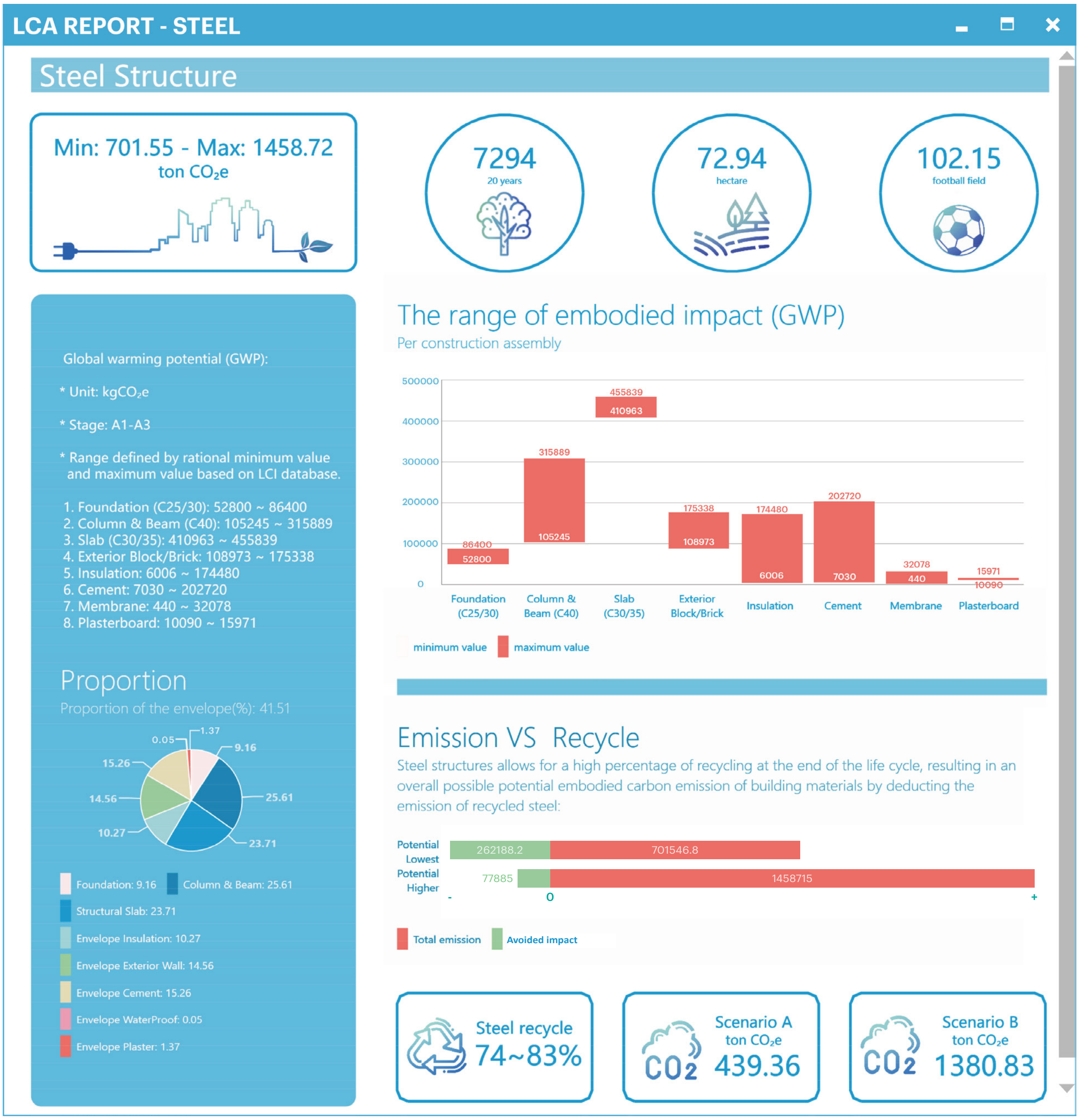


Figure 5.25 Detailed report of Option B with steel structure. Source: Self-developed.

Option B

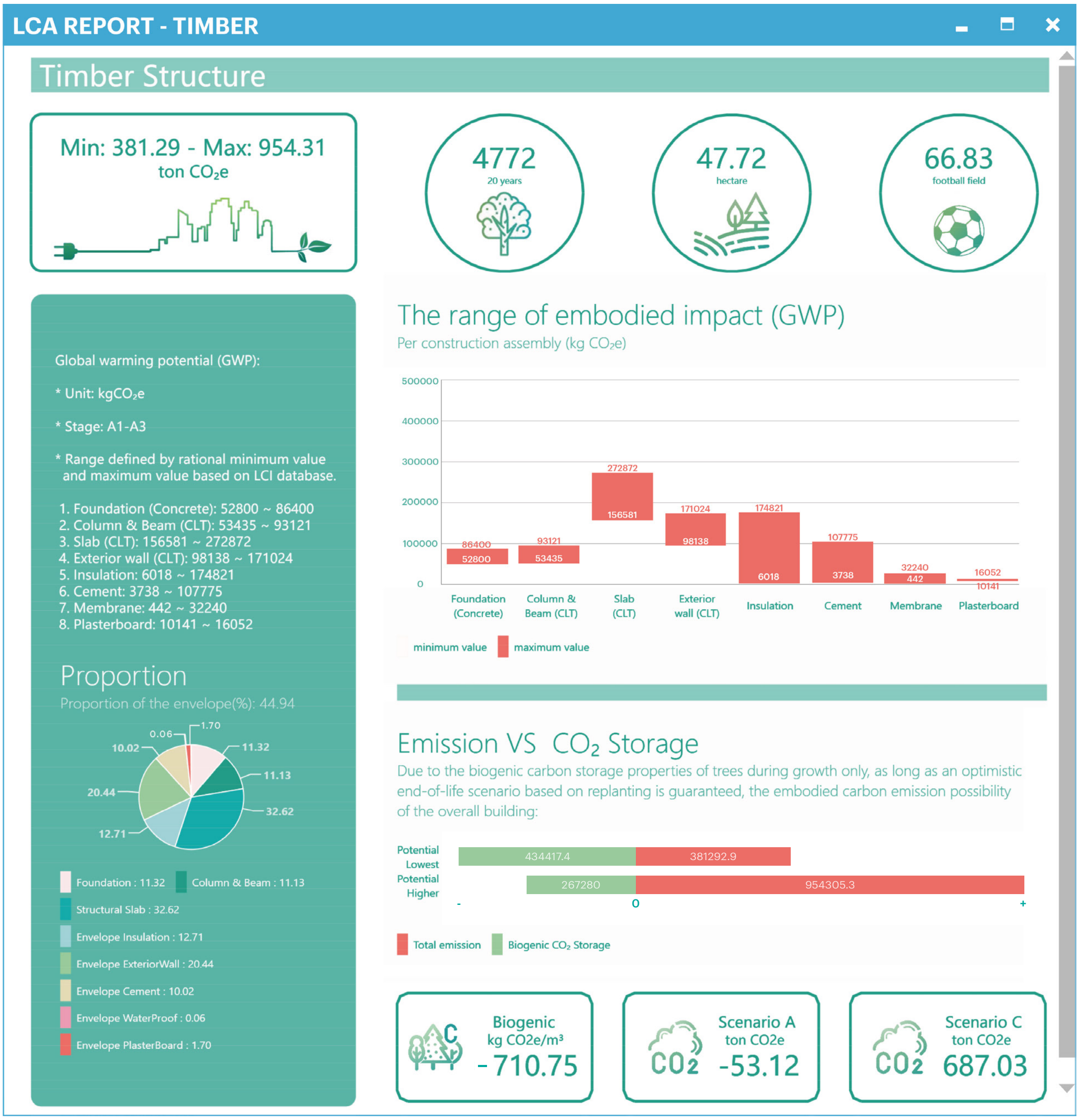


Figure 5.26 Detailed report of Option A with timber structure. Source: Self-developed.

 system.

Similar conclusions and regularity can be observed in the detailed report of Option C. However, the results of Option B show slight discrepancies, primarily reflected in the results regarding the proportion of environmental impacts of each material. By comparing the percentage of embodied emissions from the whole envelope in the three volumetric options, it can be seen that Option A and C are both approximately 35%, whereas Option B is estimated to be around 41%, suggesting that the environmental impacts of the materials that make up the envelope will have a proportionately stronger contribution to the final overall LCA results. This is futher substantiated by the overall reported results of Option B.

By continuing to compare the detailed reports of the reference case, the author found that although the LCA results of the control option in the general report are statistically superior to those of Option A,B and C, the timber-structure results of the control option do not significantly outperform the other three proposals after calculating the value of biogenic storage. In the most optimistic scenario estimation, the reference option can only achieve a carbon benefit of 42.95 tons CO_2e, which is approaching 20% less than Option B's 53.12 tons CO_2e.

Together with the data performance of the hotspot analysis, the author argues that the reason behind this figure may be precisely attributed to the carbon sequestration capacity of timber. The volumes of CLT panels in the envelope and beams/columns of

Option C

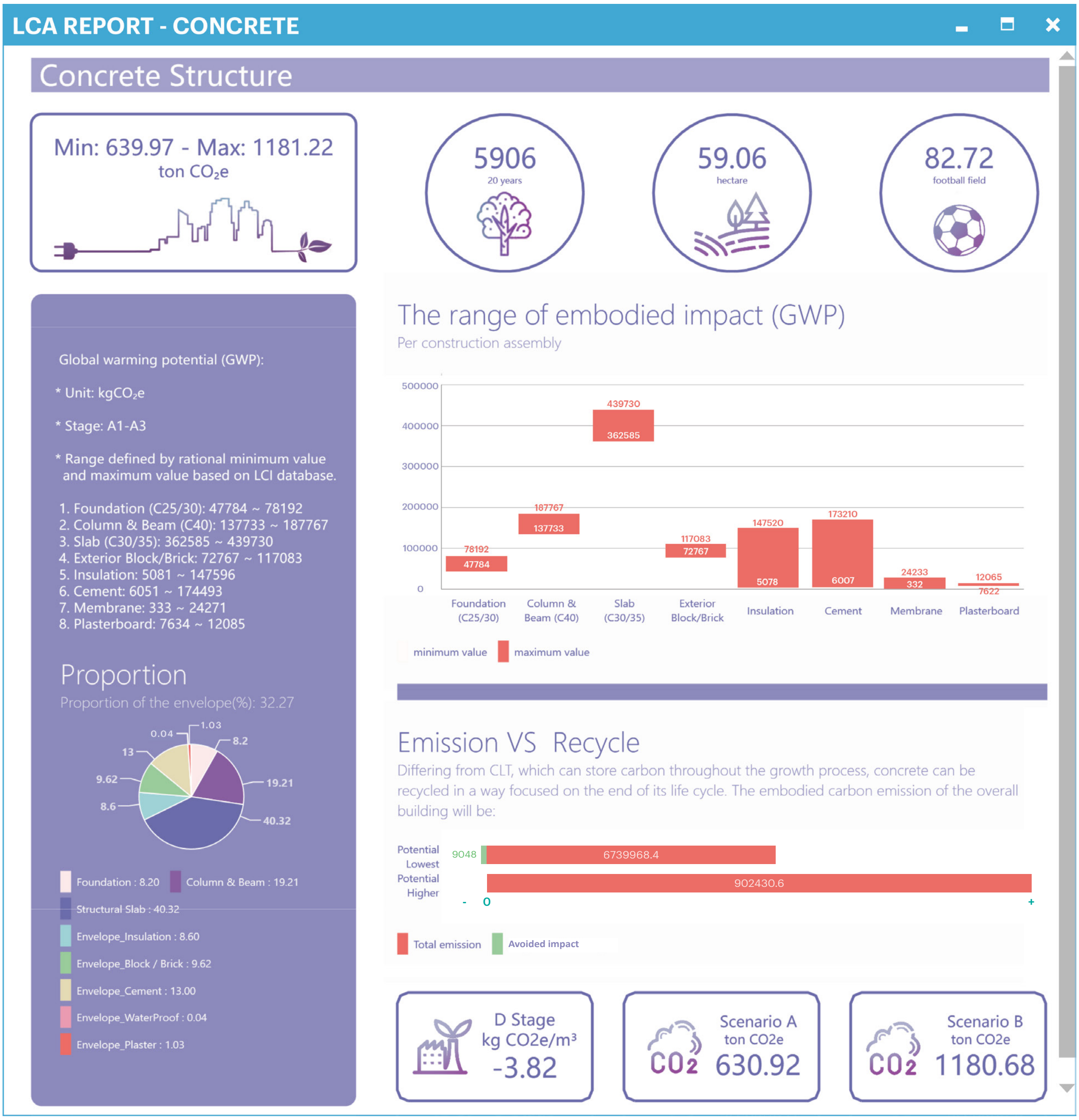


Figure 5.27 Detailed report of Option C with concrete structure. Source: Self-developed.

Option C

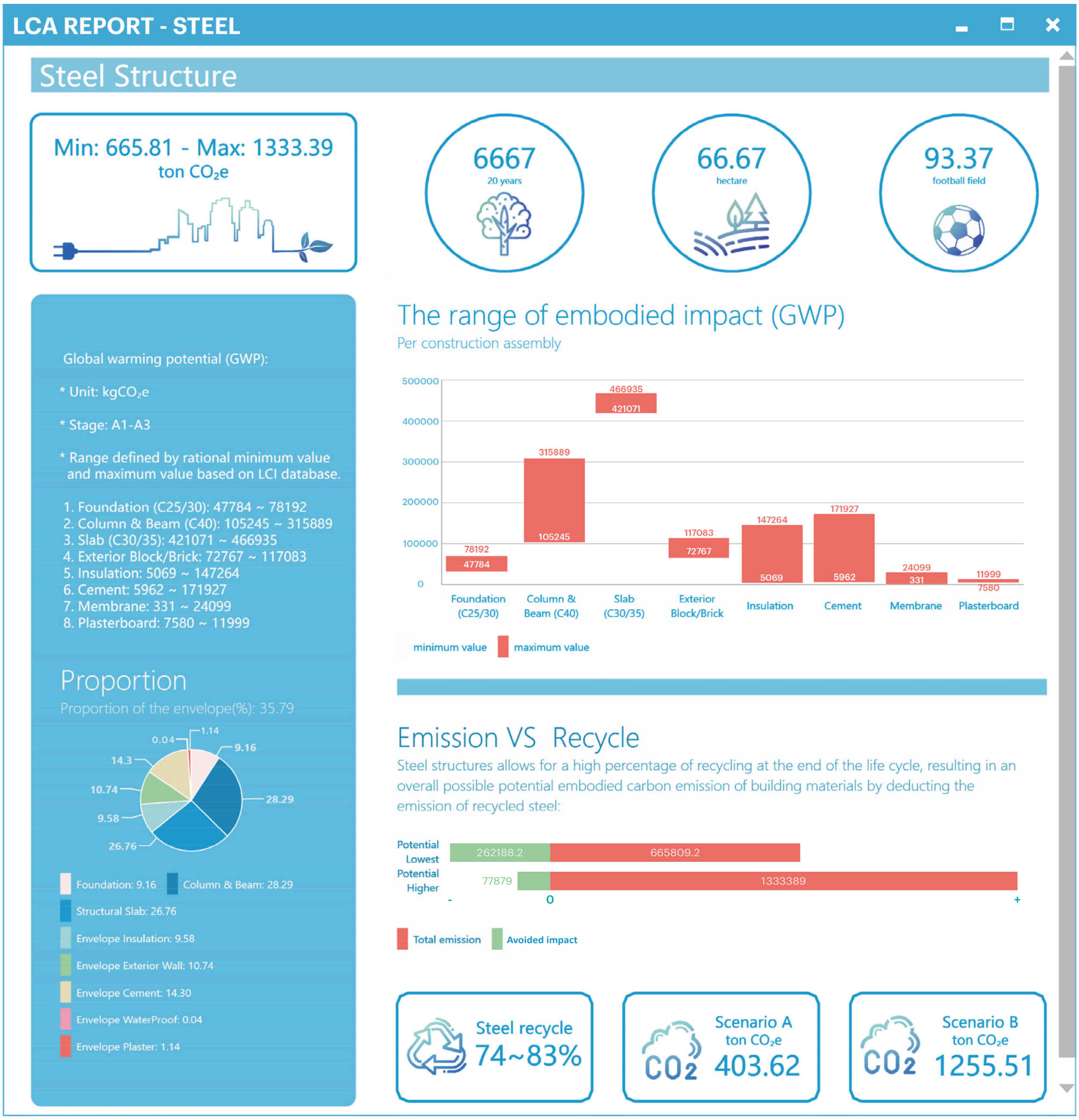


Figure 5.28 Detailed report of Option C with steel structure. Source: Self-developed.

Option C

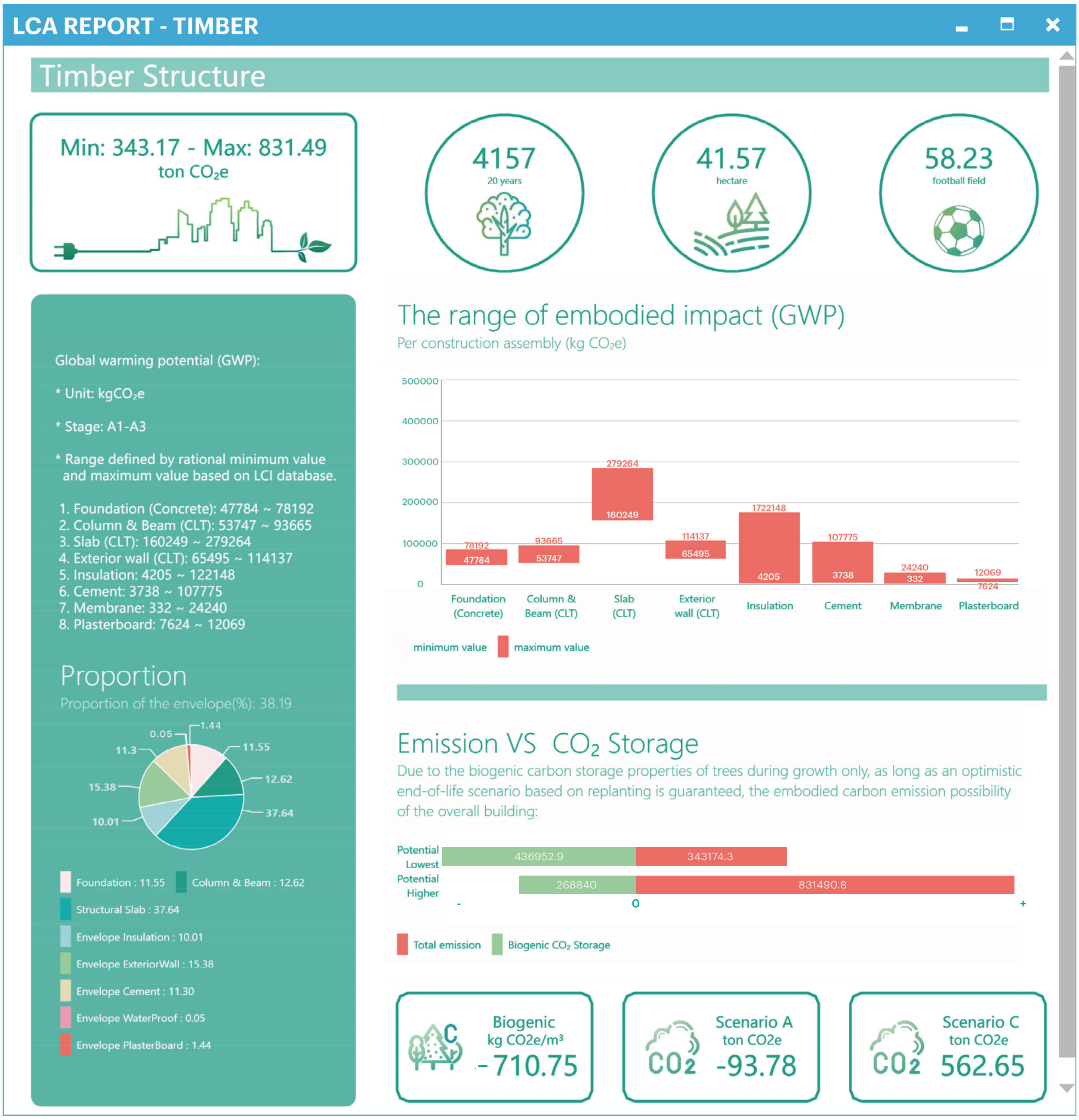


Figure 5.29 Detailed report of Option C with timber structure. Source: Self-developed.

the control option are to some extent smaller than the other three options, whereas the higher volume of timber utilized delivers incremental carbon benefits to the overall project.

This result highlights that in the case of options where large quantities of materials with carbon benefits such as timber are adopted, architects can get more carbon storage, thus leading to a better environmental impact. However, the author argue that this result could be influenced if more impact indicators has been employed which could be improved in the future study.

Subsidiary test

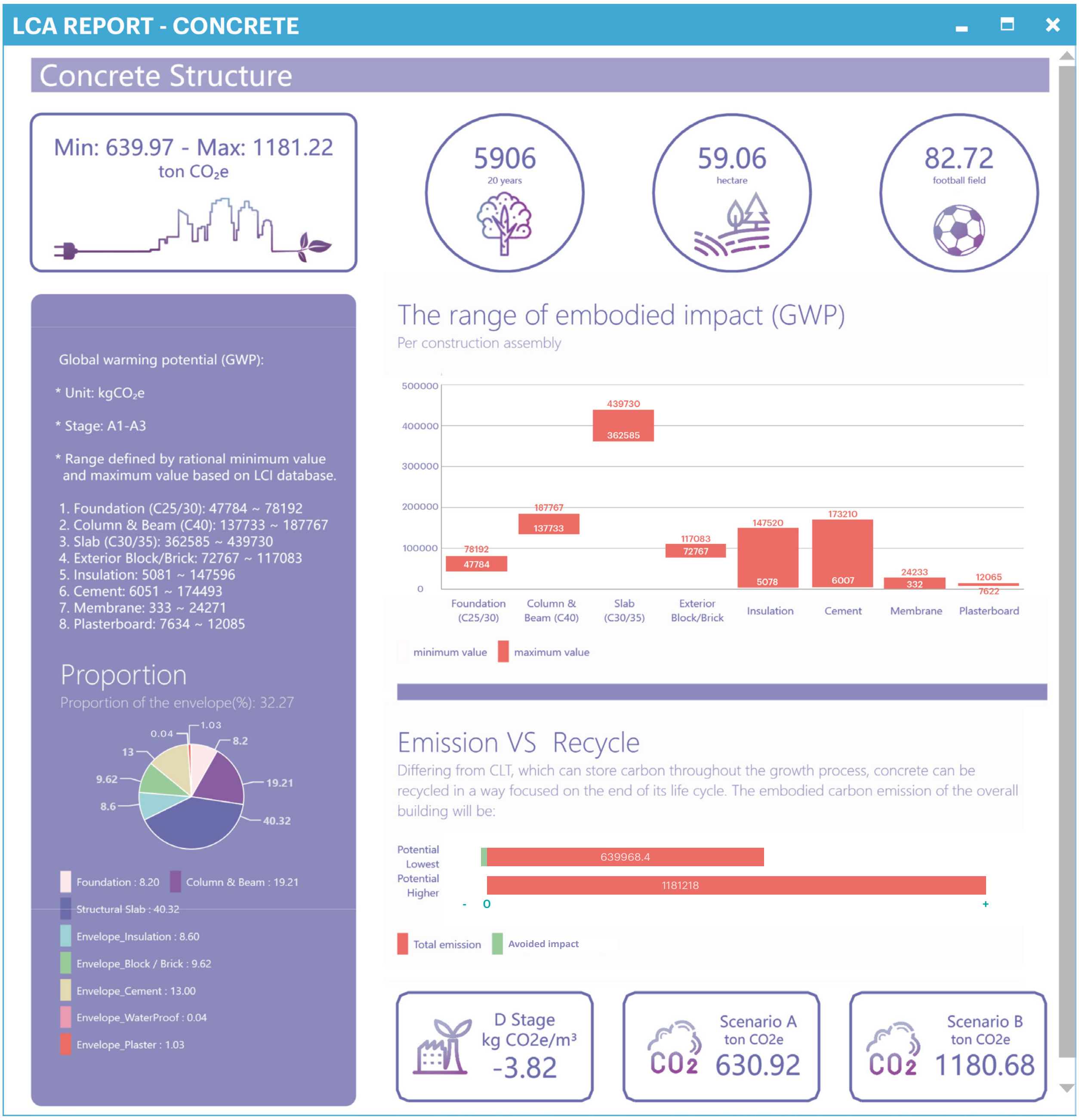


Figure 5.30 Detailed report of subsidiary test with concrete structure. Source: Self-developed.

Subsidiary test

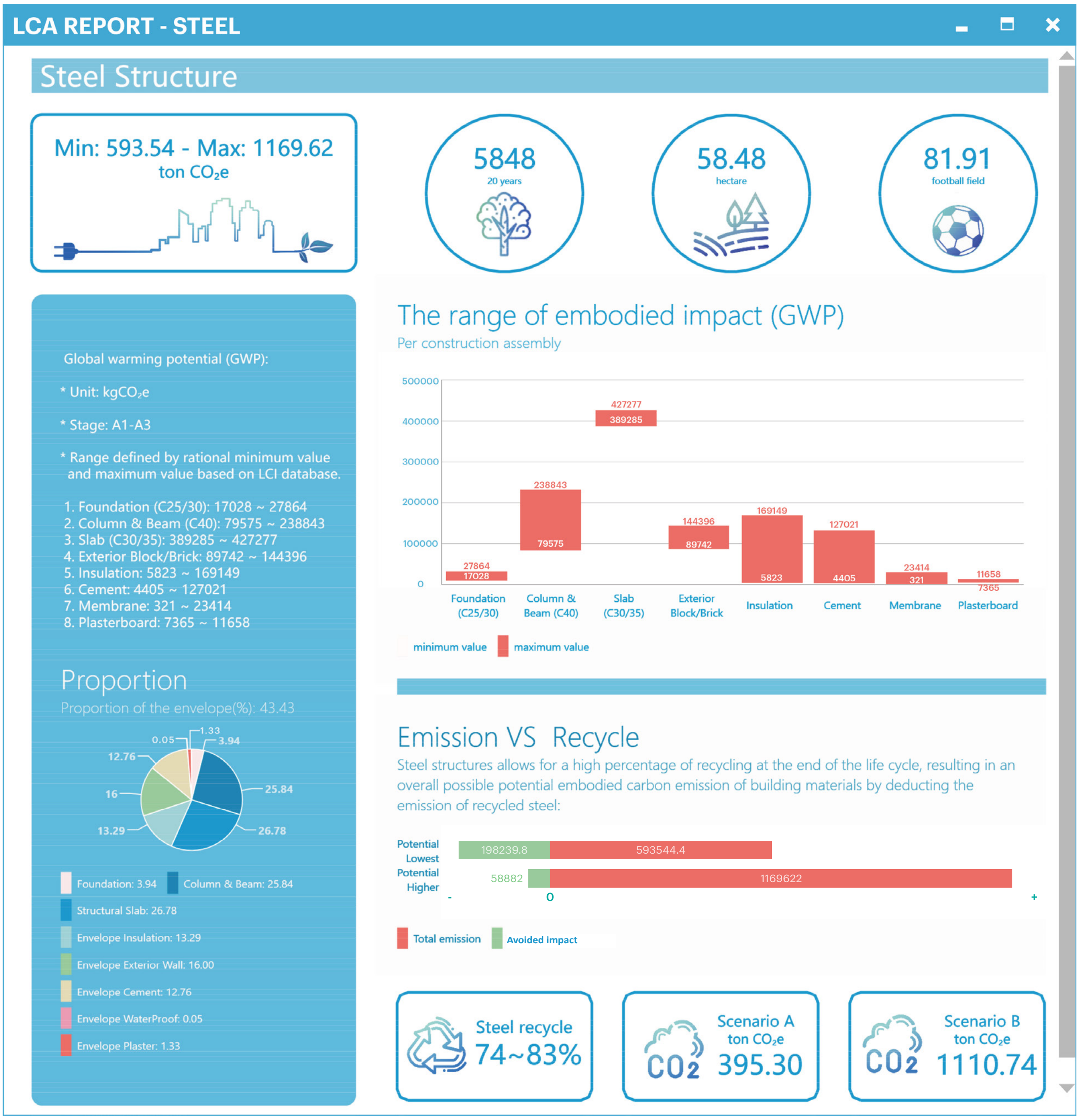


Figure 5.31 Detailed report of subsidiary test with steel structure. Source: Self-developed.

Subsidiary test

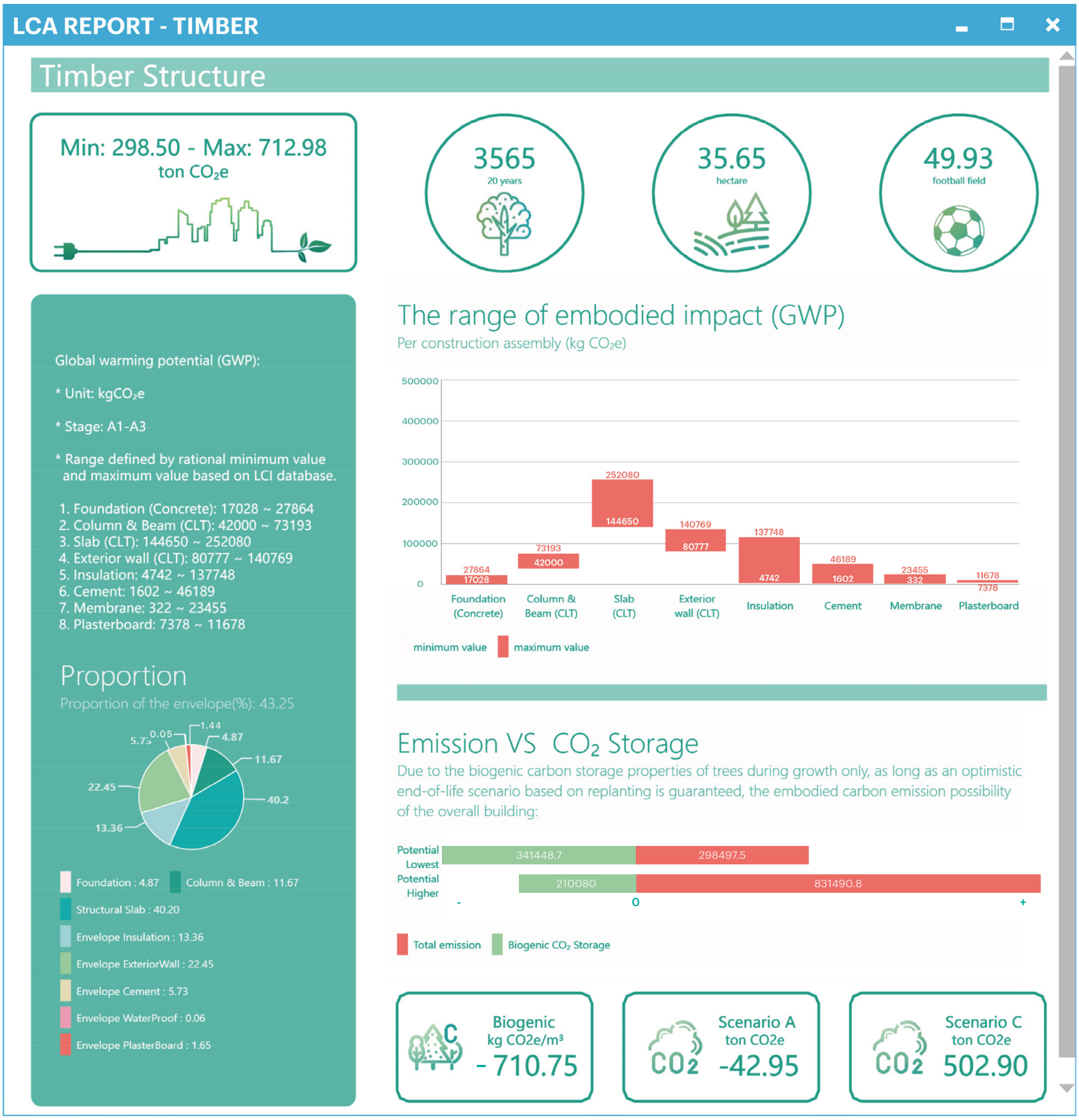


Figure 5.32 Detailed report of subsidiary test with timber structure. Source: Self-developed.

5 | Conclusions and future developments

As of today, although there is no completely unified approach or widely adopted tool on the market, the integrated application of BIM-LCA is gaining more and more attention from researchers. On one hand, they advocate for the development of more national standards or industry-standard protocols for LCA assessment processes and methods for buildings and materials. On the other hand, they are working to enhance the interactivity of BIM-LCA, improve the efficiency of LCA application, and expand the scope of LCA impact. It is evident that integrating LCA into the architectural design process can significantly contribute to improving the sustainability performance of building projects.

This study conducted a systematic review of the literature and analyzed relevant research in the field of BIM-LCA integration over the past decade. The results indicate that there is significant potential in leveraging BIM advantages for early-stage building LCA studies. For example, tools like visual programming have improved the readability of LCA results, and the data exchange capabilities of BIM software enhance the efficiency of LCA calculations.

Furthermore, over the past five years, there has been a growing focus on LCA research in the early stages of architectural design. Researchers have proposed methods to simplify data calculations, reducing the knowledge barrier for LCA research. This study aims to further expand the scope of LCA in the early design process by exploring how it can support architectural decisions and provide an LCA perspective for comparing different massing options at the conceptual stage.

By developing an entire workflow and relative computational tools, this study aims to clarify the timing of intervention in the architectural decision-making process from the LCA perspective. Based on the scripts developed by the author, the tool automates the modeling of building elements that are needed for the extraction of material quantity for LCA calculations, promoting thLOD level from 100 to 200.

The advantage of this workflow is that it preserves the efficiency and flexibility that architects have in the early exploration of architectural forms using Rhino software. Simultaneously, it seamlessly synchronizes model data with Revit, allowing for LCA calculations to be performed in both software environments without increasing labor costs.

The visual LCA dashboard in this study comprises two parts: the overall report and the detailed report. Unlike conventional LCA tools that provide precise and specific numerical values, the LCA calculation in this research offers a range of potential outcomes based on various materials for three different structural systems. With the support of LCA data, architects can optimize massing options as early as possible, starting from the material perspective. The designers can then combine sustainable strategies to further reduce the environmental impact of the building.

Through the case study which is a real residential project in Milan, Italy, the author first discovered that architects should incorporate sustainable strategies that may have a positive impact on the environment as much as possible, bringing more benefit. Taking the control option with the compact and centralized volume as an example, in spite of the LCA results it is indeed more environmentally friendly in terms of embodied carbon emissions per square meter before considering the carbon benefit of the green roof system, relatively complex architectural forms can still compensate for this gap through appropriate sustainable strategies.

When comparing different massing options, architects need to pay extra attention to the reasons behind the LCA results, such as whether the value is directly associated with some specific materials used for certain building components. For instance, structural slabs consistently contribute the most to embodied emissions among all building components, suggesting architects should be cautious in their material selection.

Furthermore, by observing the range of results for different materials, it becomes evident that even within the same material category, different products can exhibit significant differences in environmental performance. Designers should exercise caution when selecting building materials to avoid adverse impacts on the final results.

Some limitations and possibilities for improvement still exist in this study. First of all, the broadness of the data in the LCI database should be strengthened in subsequent studies, as the availability of more and more comprehensive material data would help architects to make better judgments and evaluations over time. The author argues that there is a need to foster the provision of certified material EPDs by building material manufacturers through more incentives to enable architects to access more up-to-date material information. It is worthwhile to be further enhanced in subsequent studies in terms of standardizing structural material weights and defining material definitions.

Early-stage BIM-LCA studies fill a gap in the application of LCA from the architect's perspective. However, it would be of great significance in the future to have a continuous LCA study, namely a coherent full-cycle assessment that not only calculates the early embodied emissions but also simulates the energy consumption during the operational phases of the building within only one tool, to support the decision making in the early design stage.

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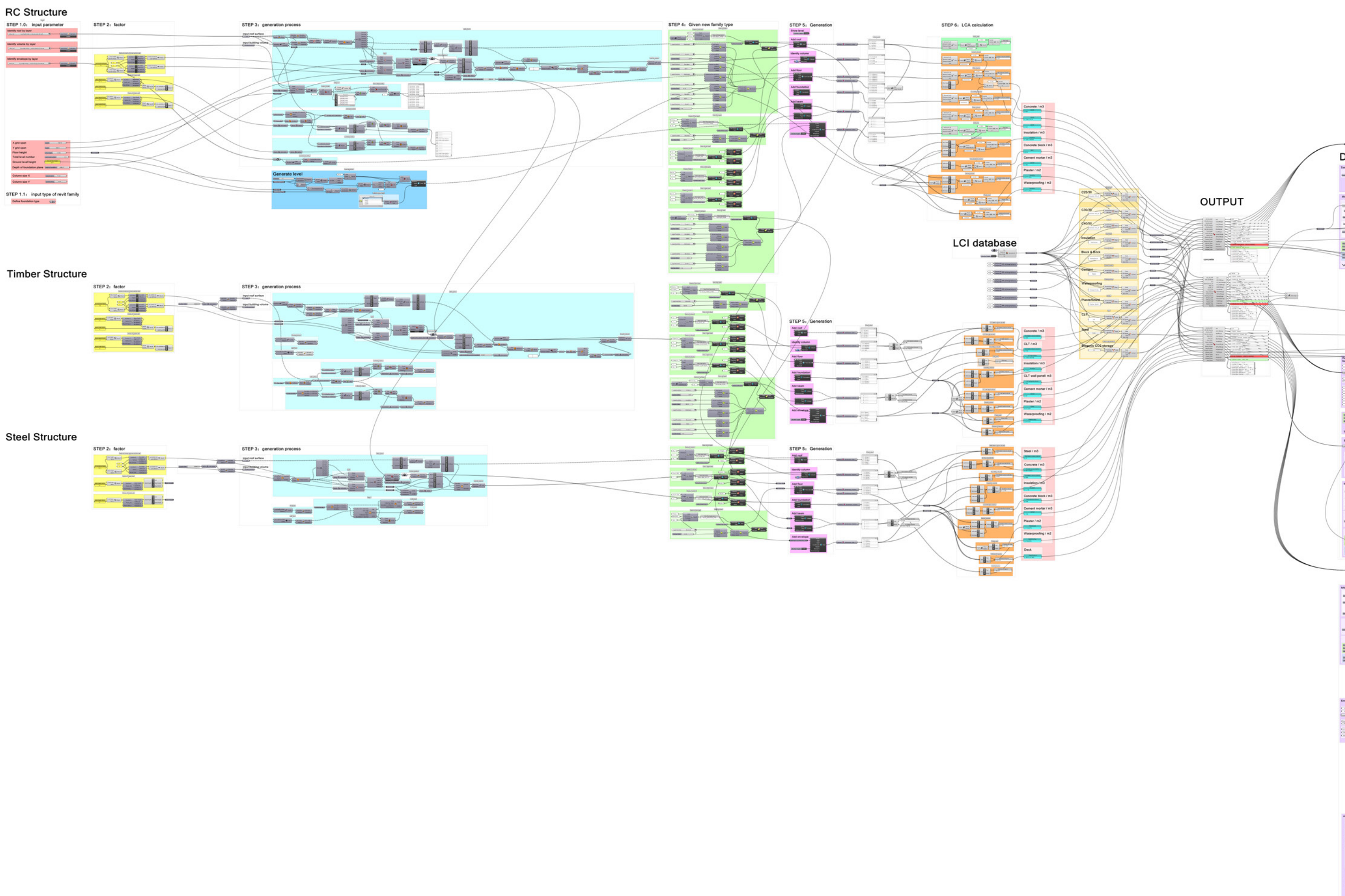
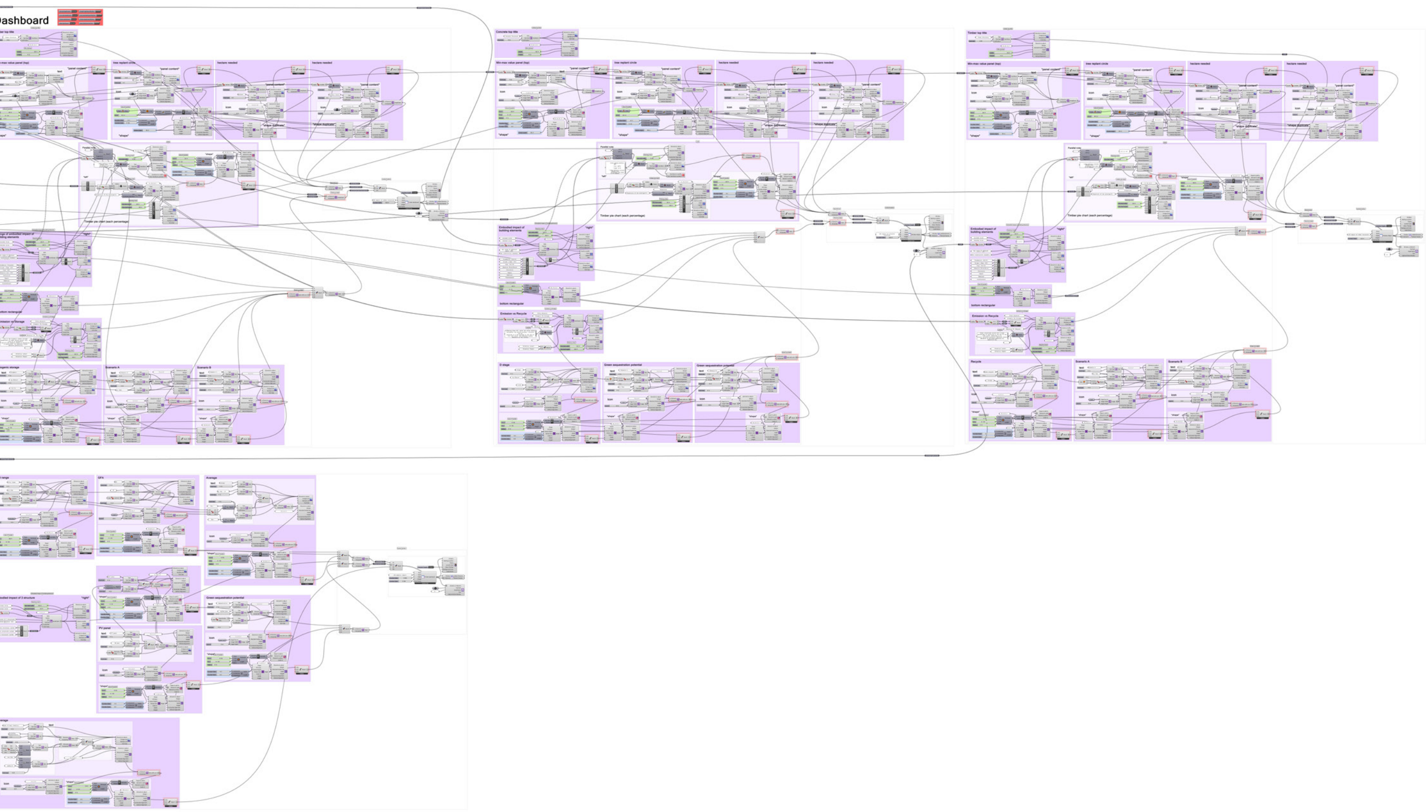
Appendix

1. Sample of C# for calculating LCA

```
//sort value & find min,max & create tuple range
//======================================================================
C25_30_GWP.Sort();
double minC25 = C25_30_GWP[0] * C25_30_Volume;
double maxC25 = C25_30_GWP[C25_30_GWP.Count - 1] * C25_30_Volume;
C25_30Range = Tuple.Create(minC25, maxC25);
//----------------------------------------------
C30_35_GWP.Sort();
double minC30 = C30_35_GWP[0] * C30_35_Volume;
double maxC30 = C30_35_GWP[C30_35_GWP.Count - 1] * C30_35_Volume;
C30_35Range = Tuple.Create(minC30, maxC30);
//----------------------------------------------
C40_50_GWP.Sort();
double minC40 = C40_50_GWP[0] * C40_50_Volume;
double maxC40 = C40_50_GWP[C40_50_GWP.Count - 1] * C40_50_Volume;
C40_50Range = Tuple.Create(minC40, maxC40);
//----------------------------------------------
Insul_GWP.Sort();
double minInsul = Insul_GWP[0] * Insul_Volume;
double maxInsul = Insul_GWP[Insul_GWP.Count - 1] * Insul_Volume;
InsulRange = Tuple.Create(minInsul, maxInsul);
//----------------------------------------------
Block_GWP.Sort();
double minBlock = Block_GWP[0] * Block_Volume;
double maxBlock = Block_GWP[Block_GWP.Count - 1] * Block_Volume;
BlockRange = Tuple.Create(minBlock, maxBlock);
//----------------------------------------------
Cement_GWP.Sort();
double minCement = Cement_GWP[0] * Cement_Volume;
double maxCement = Cement_GWP[Cement_GWP.Count - 1] * Cement_Volume;
CementRange = Tuple.Create(minCement, maxCement);
//----------------------------------------------
WProof_GWP.Sort();
double minWProof = WProof_GWP[0] * WProof_Area;
double maxWProof = WProof_GWP[WProof_GWP.Count - 1] * WProof_Area;
WProofRange = Tuple.Create(minWProof, maxWProof);
//----------------------------------------------
Plaster_GWP.Sort();
double minPlt = Plaster_GWP[0] * PlasterB_Area;
double maxPlt = Plaster_GWP[Plaster_GWP.Count - 1] * PlasterB_Area;
PlasterRange = Tuple.Create(minPlt, maxPlt);
//----------------------------------------------
//get total range based on minimum range
double minTotal = minC25 + minC30 + minC40 + minInsul + minBlock + minCement + minWProof + minPlt;
double maxTotal = maxC25 + maxC30 + maxC40 + maxInsul + maxBlock + maxCement + maxWProof + maxPlt;
TotalRange = Tuple.Create(minTotal, maxTotal);
//=============================================================
//create a list for proportion
List<Tuple<string, string>> percent = new List<Tuple<string, string>>();
double C25Md = CalculateMedian(C25_30_GWP) * C25_30_Volume;
double C30Md = CalculateMedian(C30_35_GWP) * C30_35_Volume;
double C40Md = CalculateMedian(C40_50_GWP) * C40_50_Volume;
double InsulMd = CalculateMedian(Insul_GWP) * Insul_Volume;
double BlockMd = CalculateMedian(Block_GWP) * Block_Volume;
double CementMd = CalculateMedian(Cement_GWP) * Cement_Volume;
double WProofMd = CalculateMedian(WProof_GWP) * WProof_Area;
double PlasterMd = CalculateMedian(Plaster_GWP) * PlasterB_Area;
double MdTotal = C25Md + C30Md + C40Md + InsulMd + BlockMd + CementMd + WProofMd + PlasterMd;
double C25Prop = (C25Md / MdTotal) * 100;
double C30Prop = (C30Md / MdTotal) * 100;
double C40Prop = (C40Md / MdTotal) * 100;
double InsulProp = (InsulMd / MdTotal) * 100;
double BlockProp = (BlockMd / MdTotal) * 100;
double CementProp = (CementMd / MdTotal) * 100;
double WProofProp = (WProofMd / MdTotal) * 100;
double PlasterProp = 100 - C25Prop - C30Prop - C40Prop - InsulProp -BlockProp - CementProp - WProofProp;
//calculate proportion with department
string formattedC25Prop = FormatNumber(C25Prop);
string formattedBCProp = FormatNumber(C40Prop);
string formattedSlabProp = FormatNumber(C30Prop);
string formattedInsulProp = FormatNumber(InsulProp);
string formattedBlockProp = FormatNumber(BlockProp);
string formattedCementProp = FormatNumber(CementProp);
string formattedWProofProp = FormatNumber(WProofProp);
string formattedPlasterProp = FormatNumber(PlasterProp);
percent.Add(Tuple.Create("Foundation : ", formattedC25Prop));
percent.Add(Tuple.Create("Column & Beam : ", formattedBCProp));
percent.Add(Tuple.Create("Structural Slab : ", formattedSlabProp));
//--------------------------------------
percent.Add(Tuple.Create("Envelope_Insulation : ", formattedInsulProp + " "));
percent.Add(Tuple.Create("Envelope_Block / Brick : ", formattedBlockProp));
percent.Add(Tuple.Create("Envelope_Cement : ", formattedCementProp));
percent.Add(Tuple.Create("Envelope_WaterProof : ", formattedWProofProp));
percent.Add(Tuple.Create("Envelope_Plaster : ", formattedPlasterProp));
//--------------------------------------
double EnvelopeTol = BlockProp + InsulProp + CementProp + WProofProp + PlasterProp;
string formattedEnvelopeTol = FormatNumber(EnvelopeTol);
double recycleConcrete1 = (C25_30_Volume + C30_35_Volume + C40_50_Volume) * 3.82;
double recycleConcrete2 = (C25_30_Volume + C30_35_Volume + C40_50_Volume) * 0.225;
Proportion = percent;
ProportionSum = formattedEnvelopeTol;
Recycle = Tuple.Create(recycleConcrete1, recycleConcrete2);
//Print runtimes
Print("Run#" + Iteration);
}
// <Custom additional code>
public double CalculateMedian(List<double> inputList)
{
  inputList.Sort();
  int count = inputList.Count;
  int middleIndex = count / 2;
  double median;
  // If the count is even
  if (count % 2 == 0)
  {
    double median1 = inputList[middleIndex - 1];
    double median2 = inputList[middleIndex];
    median = (median1 + median2) / 2.0;
  }
  // If the count is odd
  else
  {
    median = inputList[middleIndex];
  }
  return median;
}
//=============================================================
public string FormatNumber(double number)
{
  if (number.ToString("0.00") == "0.00")
  {
    return "0";
  }
  else
  {
    return number.ToString("#0.00");
  }
}
// </Custom additional code>
```

2. Entire script developed by the author





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I hope to never regret the decision to step out of my comfort zone today.

I aspire to continue embracing a love for learning throughout my life, enthusiastically exploring new topics.

Best wishes.