Integration of life-cycle assessment in a multimodal building design approach

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Abstract. Decades of rapid and widespread digitization of our living and working environments have not yet brought about a comprehensive qualitative improvement of our built environment in terms of sustainability and functional and aesthetic performance. The designs of the future must be much more consistently concerned with optimizing the multimodal performance of human spaces. This paper presents a design approach to implement and combine life-cycle assessment with different simulation methods such as energy efficiency, daylight analysis, acoustics, noise insulation, structural analysis and fire protection in order to provide the designer with tools to evaluate how architectural decisions affect the building performance and its environmental impacts. This approach was applied by the architecture students of a master course at the Universität der Künste Berlin. They were given the program of a building to be constructed in the Siemensstadt in Berlin and they implemented this methodology to come up with different sustainable designs. This paper also discusses the results of this course and empathizes how the implementation of simulation tools does not constrain the possibilities of the design process, but it enriches it and leads to a more sustainable built environment.

Keywords: Building project, LCA, building performance, parametric design.

1. Introduction
Decades of rapid and widespread digitization of our living and working environments have not yet brought about a comprehensive qualitative improvement of built space in terms of its functional and aesthetic performance. In terms of visual, acoustic and structural properties, current space design practice falls far short of its potential. In the design process, architects and engineers still work largely within the confines of their respective disciplines. The lack of early collaboration often leads to performance deficiencies that become apparent to both designers and users of the human spaces only at the moment of physical realization. Modifications at late stages of the project are responsible on a very large scale for the ever-increasing consumption of energy and resources in construction. The question arises which new forms of work, cooperative as well as political frameworks and digital tools are required to design spaces, buildings and urban quarters that are performative in terms of sound, light, heat and structure and radically reduce energy consumption and material use in the construction sector. The designs of the future must therefore be much more consistently concerned with optimizing the multimodal performance of human spaces. This concerns both indoor and outdoor spaces, their interfaces, and the performance of building envelopes in relation to the architectural context and local
climatic conditions. The design and manufacturing processes in the construction industry are currently on the cusp of a second digital turn, but its objective must be more clearly and precisely focused on the challenges of construction in this century. A decisive question is how quickly and how comprehensively we can establish the topic of life-cycle assessment (LCA) in the early design phases and thus as a component of the multimodal design process.

In this paper, the authors present a methodology to integrate LCA in a multimodal design process and therefore evaluate how architectural decisions affect the building performance and its environmental impacts. Section 2 presents the required simulation methods to achieve this goal and introduces a case-study that was provided to the students of a master course of the Berlin University of the Arts (UdK Berlin) to let them explore different design strategies applying this methodology. Section 3 presents some of the designs the students came up with and evaluates them in terms of carbon emissions and building performance.

2. Methodology

2.1. Simulation methods

Through parametric 3D-modelling it is possible to link a 3D architectural model to a different set of simulation tools. Thus, the designer can have real time feedback about the effect that a certain architectural decision, reflected on the 3D model, has in the outcome of the different simulations and take informed decisions accordingly.

The visual programming interface Grasshopper for the 3D-modelling software Rhinoceros is currently one of the most preferred parametric tools in the AEC industry. A possible approach to combine different performance simulations in Grasshopper is to simultaneously connect the outputs of all of them with a multi objective optimization solver to optimize some numeric parameters of the architectural 3D-model [1]. However, this method has two drawbacks. Firstly, not all design decisions can be represented as a numeric variable. And secondly, this complex workflow can overwhelm designers who are not experts on parametric design. Therefore, the authors suggest the following step-by-step route map shown in figure 1 to integrate LCA in a multimodal design approach.

The starting point is the architectural concept and the consequent column grid. Three independent working lines start from here: a comparative study to choose the slab system, the facade design and the definition of a building structure compatible with the architectural concept, which might involve the design of a transfer floor to allocate a grid change between the upper stories and the lobby. Afterwards, the structural analysis of the building is carried out. If the yielded results are acceptable, the foundation can be designed with the reaction forces from the structural analysis and all relevant building elements should have realistic dimensions, so the global LCA of the building can take place. The results from this LCA determine if the design is satisfactory, if some slight modifications must be made to the building structure – the necessity of a transfer floor may be re-evaluated – or if the original architectural concept has to be reviewed.
2.1.1. Life-cycle assessment. The Grasshopper plugin of the LCA software One Click LCA has already been successfully implemented in architectural design processes [2] and is the suggested LCA tool in this workflow. The LCA should be carried out at least at two different stages both at the begin and at the end of the design process. The first LCA is applied to a representative local 3D-model of the building and focuses on choosing the slab typology according to the carbon footprint and also to basic architectural conditions, such as column spacing, regularity of the floor layout, aesthetic preferences, etc. Several studies have shown that slabs concentrate up to 40-50% of the embodied carbon of a building structure [3], therefore they are the main focus of this preliminary study. Similarly to [4], a decision tree is suggested to generate different design alternatives as shown in figure 2. Since Grasshopper does not support this multi-stage decision-process algorithm with native components, C# scripting becomes necessary to implement a decision tree in this parametric environment. This script should also include basic geometry checks to review the feasibility of the input geometry and some rules of thumb to define element thicknesses so that realistic LCA results are produced.
Figure 2. Decision tree algorithm to generate design alternatives in Grasshopper and compare their carbon footprint using a custom C# script and the Grasshopper integration of One Click LCA.

Once a design alternative has been generated it can be linked to the One Click LCA plugin to calculate its carbon footprint and compare it with other design alternatives.

The second LCA is the last step of the design route map, and its purpose is to calculate the environmental impacts related to the complete and dimensioned model of the building and compare them to generic benchmark projects [5].

2.1.2. Daylighting, natural ventilation and energy efficiency. Facade design focusing on daylighting, natural ventilation and energy efficiency should be carried out in the early stages of the design process due to its influence on the operational carbon of the building. The presented workflow consists of a cross-platform optimization process using the plugins Honeybee and Ladybug [6] for Grasshopper and the software Sefaira [7].

Based on generative design models simulations such as the Whole Building Energy Analysis; the Spatial Daylight Autonomy (sDA), Annual Sunlight Exposure and Useful Daylight Illuminance were conducted and iteratively optimized by modifying e.g., the floor height, the façade geometry, window-to-wall ratio, and the implementation of shading elements. Alongside these investigations, other performance driven aspects were conceptualized and/or analysed such as natural ventilation (NV) potential based on the "Gebäudeenergiegesetz", "ASHRAE Energy Standard 90.1–2019" and the " DIN-EN-17037 Tageslicht in Gebäuden".

In a multimodal driven optimization effort varying environmental design criteria e.g., sDA and NV were combined and improved by using an overarching design feature. For example, the façade design in section 3.1. features the formation of a partial porous brick façade that is parametrically optimized to allow for optimum natural ventilation gains during the office hours. This is archived by modifying the orientation and the gap size of/between the bricks. Towards the upper end of these facade modules an overhang with varying depth is modelled to regulate the sunlight exposure dependent on the cardinal directions.

2.1.3. Acoustics and sound insulation. Structural optimisation aiming to lower the carbon footprint and the resulting mass reduction of the slabs of the building carries the risk of significant deterioration of the sound insulation properties of the slab constructions. For solid slab systems in brick, reinforced concrete or hybrid timber-concrete constructions, the sound insulation is directly linked to the area density of the construction. Therefore, a solid slab system must have a certain mass to meet the sound insulation requirements. The sound insulation of multilayer constructions like wooden hollow box slabs or solid timber slabs is ensured by using laboratory-tested reference constructions.

Since a slab system construction is mainly determined by its structural properties, four different slab systems were analysed regarding the correlation of span width, construction mass and sound insulation. For commercial buildings, the minimum weight for solid slabs has been set at 400 kg/m² without screed (Constructions 3 & 4 in figure 3). The additional weight for multilayer constructions has been set to 90 kg/m² (Constructions 1 & 2 in figure 3).

Based on the architectural design, a matching slab system is selected. The aim is to exploit the multimodal synergies inherent in the constructions and avoid the use of additional mass for structural or acoustical purpose.
Figure 3. Slab system constructions that fulfil structural, acoustic and fire protection requirements.

2.1.4. Structural design and fire protection. The structural analysis of the global model is required after the building loads have been determined from previous design decisions and when the concept of the lateral resisting system of the building and other structurally relevant elements such as transfer floors have been defined. The Parametric FEM Toolbox [8] is the Grasshopper plugin suggested for this analysis. It allows an interoperability between Rhino and Grasshopper with the commercial FEM software RFEM, which includes modules to check all structural elements according to the building codes including fire resistance requirements.

The pre-dimensioning of the building elements for the first LCA is usually carried out through simple geometric rules of thumb. If complex irregular structural systems want to be used, a simple parametric structural model becomes necessary in this first stage as well. Fire protection requirements must be considered in the pre-dimensioning of the slab constructions and other building elements, since they have a strong influence in the thicknesses and dimensions of slabs, columns and walls, especially if they are going to be designed in timber.

2.2. An office building in the Siemensstadt as case-study
In the context of an architecture master course of the Berlin University of the Arts (Udk) that took place throughout the summer semester of 2021, the students were provided with the location and architectural program of one of the future office buildings to be designed in the Siemensstadt in Berlin, as part of the recently approved plan to expand this quartier [9]. They used this mid-rise building as case-study to
implement the above-described methodology to explore new design strategies to improve the building performance and help fight the current climate emergency and resource scarcity. The designs of some of the groups are presented in the next section.

3. Results

3.1. Case Study One: A masonry mid-rise building with vaulted slabs

The development of the alternative masonry building system was based on insights gathered through comparative life cycle analyses with two conventional building systems. It was carried out using the One Click LCA workflow for Rhino and Grasshopper as described in section 2.1.1. A continuous comparison with a steel-skeleton supported precast and pretensioned concrete slab system and a timber hybrid system has accompanied the process. While the reinforced concrete construction with 319t CO2e per typical floor performs, as expected, worst, the other two systems are on par. The timber-hybrid system achieves the lowest value with 161t CO2e, followed by the masonry system with 187t CO2e. Both, the reinforced concrete building and the timber-hybrid building concentrate most of their mass and embodied emissions in the horizontal components. In opposition to that, the new proposal presents a more evenly distributed picture. The activation of the façade as part of the load-bearing concept is particularly striking.

In its structural design, a masonry slab system is free of composites and composite materials. Easy accessibility to the different components enables better maintenance and interchangeability, as well as the separation of the building materials by type at the end of their life cycle [10]. Reclaiming bricks has a long tradition, but is currently only carried out by very few small companies due to high labor costs [11]. Figure 4 shows the carbon footprint results and recycling potential of the masonry system.

![Figure 4. Global warming potential of the compared floor typologies in kg CO2e/story and recycling potential of the selected brick-based design.](image)

Allocating structural mass in the façade is also beneficial to the overall energy concept. The design relies on the activation the building materials thermal capacity. For energy concepts without excessive technical systems, the activation of thermal component masses plays a decisive role [12]. Moreover, the internal arrangement of the windows allows the depth of the façade structure to be used as a passive shading element. Despite a high proportion of completely closed façade surfaces, the spaces can be naturally lit almost all year round during core usage times. A decentralized ventilation concept, which is also integrated into the façade, contributes to the maintainability and flexibility of the building's technology. The façade is completed by an outward facing-shell made of recycled bricks, which are parametrically aligned with the main wind directions of the building site, so that they can optimally direct or slow down the air flow on the façade towards the decentralized ventilation facilities (see figure 5a). The energy concept was the result of an extensive modelling process using Ladybug and Honeybee.
in Grasshopper as well as Sefaira. The aim was to use as little mechanical building services as possible, as these are among the elements with the shortest lifespan. Wherever possible, technical tasks should be taken over by passive features of the building structure. The analyses helped optimize the distribution of daylight and the passive shading provided by the building structure. The result is a very energy-efficient office tower with an annual energy consumption of 55kwh/m²/a (see figure 5b). However, the limitations of these software tools must also be acknowledged as they are very much related to conventional approaches of building climatization, thus it is difficult to model conceptual approaches with them.

Figure 5. Facade design concept (a) and results of the operative energy analysis with Sefaira (b).

Due to their lightness and their geometry, vaulted masonry slabs have problems in terms of structural sound insulation. These have to be compensated for by adding additional mass in the form of weighting fillings. In this case, the load-bearing geometry weighs only 216 kg/m². To increase the mass, a heavy filling of recycled materials is applied. The target weight of 550 kg/m² necessary for sound insulation is achieved with the total build-up. Good sound insulation properties are also ensured by an elevated double functional floor (see figure 6).

Figure 6. Sections through the masonry vaulted slabs of the mid-rise building.
The study of masonry resulted in the design of a completely different building system. The primary load-bearing structure is a steel frame, which is horizontally (vaulted slabs) and vertically (façade) fitted with masonry. The use of highly insulating large ceramic blocks allows the construction of a building envelope that meets all energy efficiency standards while taking over the stiffening of the building. Shifting the bracing to the façade makes it possible to omit structural cores.

In order to prove that the insulating masonry blocks in the façade can actually provide the bracing over the entire height of the high-rise building, the entire system was modelled in the RFEM structural analysis software. During the initial analysis, the concern arose that stresses could develop in the bracing masonry at the edge points. However, analysis of the entire system shows that there are no stresses that can not be absorbed by the steel columns. There could be minimal cracking at some edge points in the masonry, which is not problematic as no corrosion can occur here.

Figure 7. Analysis of stresses in the bracing masonry with the Dlubal RFEM software.

3.2. Case Study Two: The Anemone Tower
The Anemone Tower project is a result of a significant number of design decisions, integrated as one “organism”. First of all, awareness of the housing crisis in Berlin prompted us to include an accommodation program in the assigned office building. In addition, shared spaces, which can be used as an extension of the office space, as well as by residents outside of work hours, are arrayed throughout the building (see figures 8a and 8b).

Figure 8. Axonometric view for a floor (a) and axonometric view showing occupancy distribution for shared spaces in daytime (b).
This mixed typology resulted in a benefit for energy performance due to occupancy optimization together with strategic placement of the spaces in the building volume. By comparing four occupancy models in Sefaira, it turned out that energy efficiency had improved by 22% in comparison to a model of an office building with occupancy hours from 8 a.m. to 6 p.m. and with conventional level heights. By densifying the occupancy with split-level architecture and allowing the usage of multifunctional spaces both by office workers and residents, around 579.899 kWh were saved every year.

The decision for an elliptic volume was dictated through comparisons with a default prismatic volume. The elliptic plan improved performance as it creates less underlit areas on the northern side, higher compactness and better aerodynamic, which is highly important for any high-rise.

The central chimney is designed as a part of a natural ventilation system for air outflow while also combining a light-well function which offers additional space for social encounter.

A key point in the design of the façade was finding the optimal angles for providing shading and photovoltaic (PV) panel performance. With the help of Ladybug Grasshopper’s annual radiation analysis, it was possible to generate the optimum length for each unique PV panel position, based on energy production as well as shading to offer a more comfortable in-door environment for the building occupants. The performance of the building-integrated photovoltaic system considered a total area of 2076 m2, a yearly radiation of 1540 MWh/a and a module and inverter efficiencies of 20% and 90%. The total potential resulted in 277 MWh/a, this being equal to the common energy consumption of 80 German households (see figures 9a and 9b).

![Radiation Analysis](image)

**Figure 9.** Radiation analysis for photovoltaic façade panels in Grasshopper (a) and detail for a regular façade panel showing (b).

The whole soundproofing concept is thought as an add-on-system to the main construction, consisting of stud walls and suspended ceilings, that can be deinstalled in case the function of the room changes. That way, all spaces within the building remain flexible. Further simulations were performed by defining the building components properties based on standards such as Gebäudeenergiegesetz (GEG) and ASHRAE Energy Standard 90.1 –2019. The main envelope components to be modified with optimized levels were the opaque component of the façade with a U-value of 0.25 W/m2K, the skylight glazing with a U-value of 2.7 W/m2K and the curtain wall with a U-value of 1.4 W/m2K.

As for the bearing structure material, timber was always preferred during the design process. Several different grid systems, including a radial and mixed grid, were tested in the architectural concept. Three structural layouts were analyzed on one typical floor with the help of the Grasshopper plugin of One Click LCA (see figure 10). As a result, a system of CLT columns and beams in combinations with concrete anchors and slabs with less CO2 emission potential was chosen. Its advantages also include the prefabrication of beams and columns and the ability for large spanning (9.5x5.5 m).
4. Conclusion

The suggested workflow implies a paradigm shift in architectural design in which architects will have a continuous dialogue with consultant experts to implement simulation results in the early stages of architectural design. Nevertheless, the designs the UdK students came up with are a proof of concept that with this methodology it is possible to achieve aesthetically pleasant designs by pursuing functional and sustainable results. The suggested multimodal approach does not constrain the spectrum of possible solutions for a certain building, but it opens up new design possibilities.

The implementation of simulation tools in a university course implies a considerable effort from both students and teaching staff. Further steps in the suggested methodology that were left out of the scope of this course would be the accurate modelling of the building constructions in order to carry out a reliable LCA of the whole building and compare it to benchmark projects and the implementation of a cradle-to-cradle analysis, even though some students already studied on their own initiative the recycling potential of the employed building materials, as can be seen on figure 4.

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