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Forth, Kasimir; Schneider-Marin, Patricia; Theißen, Sebastian; Höper, Jannick; Svane, Nanna Dyrup; Borrmann, André

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CONNECTED DESIGN DECISION NETWORKS: MULTIDISCIPLINARY DECISION SUPPORT FOR EARLY BUILDING DESIGN LCA

Kasimir Forth[a,*], Patricia Schneider-Marin[b], Sebastian Theissen[c], Jannick Höper[c], Nanna Dyrup Svane[d], André Borrmann[a]

[a] *Technical University of Munich, School of Engineering and Design, Department of Civil and Environmental Engineering, Arcisstr. 21, 80333 Munich, Germany*

[b] *Norwegian University of Science and Technology, Faculty of Architecture and Design, Department of Architecture and Technology, NO-7491 Trondheim, Norway*

[c] *University of Wuppertal, Faculty of Architecture and Civil Engineering, Institute of Building Information Modeling, Pauluskirchstraße 7, 42285 Wuppertal, Germany*

[d] *Aalborg University, The Faculty of Engineering and Science, Department of the Built Environment, Thomas Manns Vej 23, 9220 Aalborg, Denmark*

[*] corresponding author: `kasimir.forth@tum.de`

Abstract. Life Cycle Assessment (LCA) has become the standard method to evaluate environmental impact throughout the life cycle of buildings. However, detailed data about the future building as well as knowledge about the mutual influence of decisions concerning the various disciplines involved are often missing in early design phases, otherwise known to bear the highest potential for emissions savings. Hence, a meaningful basis for decision making is lacking.

This study suggests a method to digitally represent decisions and their interdependencies in early design phases and visualize their possible consequences for the life cycle of the future building. The method is based on identification of relevant processes and tasks concerning architecture and Heating Ventilation and Air Conditioning (HVAC). Decisions trees of these tasks are used as a point of departure. Connecting the decision trees to a multidimensional, Connected Design Decision Network (CDDN) enables an interdisciplinary design team to pinpoint strategic decision nodes with comparatively more interdependencies with other subsets and high influence on LCA results. We believe that a transparent decision making in early design stages can be valuable to both the design team as well as clients and contractors and bear potential for an increased mutual awareness minimizing late and expensive redesigns.

Keywords: LCA, integrated design process, Multi-Criteria Decision Making (MCDM), early design phase, interdisciplinary decision network.

1. Introduction

Life Cycle Assessment (LCA) has become the standard method to evaluate environmental impact throughout the life cycle of a building, focusing besides operational energy and carbon also on the embodied energy and carbon of building materials. Depending on the type and energy standard of a building, embodied carbon account for up to 80 % over the life cycle, especially for new constructions [1]. The embodied carbon of HVAC systems accounts for about 20–30 % of this share, although the material mass share is usually only around 1–2 % of the total building mass [2]. Thus, it is essential to consider the interdependencies between architecture and HVAC from the LCA perspective when optimizing environmental performance.

The LCA result is highly influenced by decisions made by multiple stakeholders in various disciplines in different stages of the project phase. The content and the point in time of such decisions depend highly on the individual project and the persons connected to the project. A practical example of this interdependent relationship is the choice of insulation material in a construction. In order to maximize the useable area inside the building, it is preferable to use a high performing insulation material that allows for a thinner construction while still fulfilling the energy efficiency requirements. A light construction permits a higher degree of solar access, thereby positively influencing the daylight calculations. However, the high performing insulation material does not carry the same characteristics for fire resistance and sound absorption as standard mineral wool, thereby influencing both the fire strategy as well as the acoustic calculations, not to mention the carbon emissions considered in the LCA calculation [3].

In other words, the increasing complexity of buildings combined with tightening of requirements in building codes calls for a high and continuously updated understanding of building and material physics, technology and economy or a completely optimized interdisciplinary design approach. However, the constant efficiency improvement in the industry apportions limited time for each project, which necessitates the use of rules-of-thumb and simplifications, highly dependent on the individual practitioner [4, 5], especially in the early design phases. A study by Imam et al. from 2017 [6] investigates 108 modellers' ability to rank important parameters for building performance simulations. The analysis showed little correlation between which variables were thought to be important by the modellers and which proved to be objectively important. Furthermore, they found that qualification level and years of experience do not improve the accuracy. This indicates, that even within own discipline, a full overview and understanding of the importance and consequences of design questions, is a difficult task.

Besides code requirements, the building designers must satisfy client requirements, often considered as definitive objective requirements. However, many clients do not sufficiently understand the consequence of their prerequisites, which can entail undue difficulties and an unsustainable design process from day one. This calls for a higher transparency and an informed basis upon which clients can set their conditions.

The goal of this study is to propose a meta-model of the conventional design decision process as a facilitator for the multi-criteria decisions needed in early design phases. The method offers an easyreadable indication of potential interdependencies across disciplines when making a design decision. We believe that the technique enables a more transparent decision making, showing possible alternative design paths and their connected consequences for the later design stages.

2. Literature Review / State of the Art

2.1. Multi-Criteria Decision Analysis and Making (MCDA & MCDM)

Multi-Criteria Decision Analysis and Making (MCDA and MCDM) methods exist to a large extent in literature and are used in many different applications/areas. In general, they aim to find the best option/alternative of complex decisions considering multiple criteria [7].

Some of the most commonly used methods are the Weighted sum model (WSM), the analytic hierarchy process (AHP), the ELECTRE method, the TOPSIS method, among others.

Although these methods have different individualities, they all correspond to a multidimensional evaluation procedure and aim to decompose the overall objective into sub-objectives. Thereby, they are suitable for evaluating many criteria or indicators with different states (quantitative, qualitative). Furthermore, they follow a similar process:

(i) identification of the problem;

(ii) deriving the preferences;

(iii) evaluation of alternatives; and

(iv) identification of the best alternatives [7].

The Architecture, Engineering, and Construction (AEC) industry considering sustainable design decisions shows growing interest in MCDM, but still, it is rarely used. As highlighted by Klumbyté et al. [8], within an analysis of 66 articles from 2016–2020 the number of scientific papers using MCDM methods for sustainable construction decision support increased on average around 13 %. However, the total amount of papers is still very low, compared with scientific papers using MCDM in other research areas. Another review by Tan et al. [9] on combining Multi-Criteria Decision Making (MCDM) Methods with Building Information Modelling (BIM) underlines a growing interest and the fact that MCDM in AEC is mostly used in combination with sustainable decision support.

While many of the analyzed studies aim to identify the best option of a material choice, including many criteria, e.g., embodied energy and carbon for an LCA, they are limited studies considering the influence of multiple disciplines. As an example hereof, Sonetti et al. [10] used AHP to identify the best roof design decision out of three design choices considering the following criteria: thermal resistance, construction costs, aesthetics, social usability and environmental impacts.

Moghtadernejad et al. present advantages and limitations of MCDM methods applied to building facades [11]. One of the main findings is that choosing the best MCDM is challenging, complex and thus not suitable for day-to-day planning. In addition, all considered MCDM methods' lack in considering multi-domain performance attributes.

Conversely, this means that interactions between different design disciplines are neglected. Thus, there is no decision support across disciplines meaning that the significance and consequences of design decisions on other disciplines are not considered.

2.2. Interdisciplinary interactions and dependencies

Attempts to limit energy use and related emissions in buildings require multidisciplinary efforts between (at the least) architects, building physicists and HVAC engineers. The common problem of building-related disciplines "fixing" the "problems" created, often unknowingly, by the architect, can be alleviated by early cooperation with the goal that the building's construction and HVAC systems work as one integrated system. Despite the apparent advantages of such an approach, design processes frequently fail in practice, resulting in increased costs and time. With each discipline working with their specific extensive knowledge, there is a lack of understanding of the interactions with other disciplines. If such decisive interactions can be visualized and communicated, designers, consultants and clients profit from a more transparent, smoother process and more integrated results.

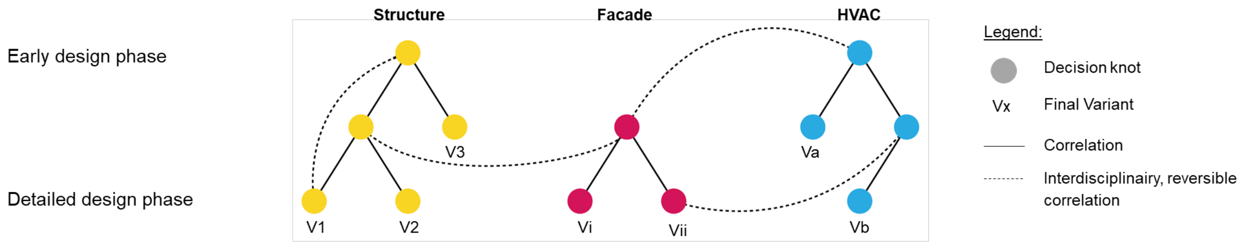

FIGURE 1. Combining discipline-specific decision trees.

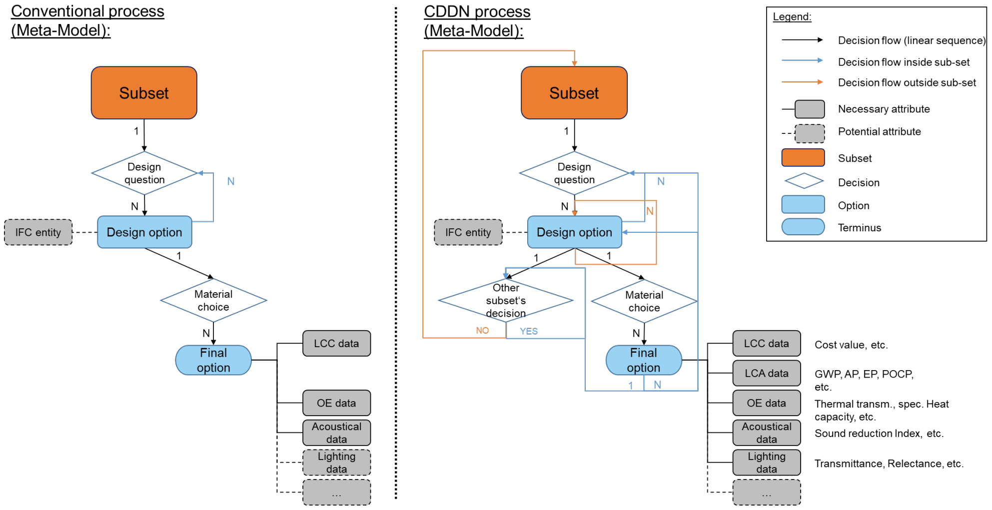

FIGURE 2. Meta-models of conventional and CDDN-processes.

Especially the building's structure and finishes and the building services interact and overlap in many areas allowing for opportunities to improve the building's life cycle performance. For instance, insulation levels influence heating demand, and the possibility of low-temperature supply, fenestration and sun shading type and quantity are essential for lighting and cooling demand, and thermal mass is decisive for comfort and heating and cooling demand, whereas building part activation calls for certain choices of surfaces. Many such examples can be found for each discipline, leading to the process becoming quickly complex. The proposed method to map such interactions aims to ease the coordination process and identify decisions and alternatives important for life cycle performance.

3. CONNECTED DESIGN DECISION NETWORK (CDDN) APPROACH

Existing methodologies of MCDM or MCDA often take one subset of the building into account. Thereby, they do not consider the perspective of several disciplines at the same time and their dependencies between each other as they only examine one specific design question/problem.

Furthermore, MCDM requires very specific input, such as a choice and definition of the criteria to be applied, an alternative for comparison and a clear objective. Therefore, it presupposes that the decision-maker already has know-how about the criteria, e.g., benchmarks for GHG emissions, and understands the consequences of the MCDM results on other disciplines. However, this is very challenging due to the many complex interrelationships between different design domains and disciplines.

In sum, MCDM or MCDA are (automatically) optimizing design parameters according to multiple criteria defined by the decision-maker rather than showing interdisciplinary relationships in advance and providing decision support with analysis results (Figure 1).

Due to the described limitations, we suggest a new method, called Connected Design Decision Network (CDDN). In contrast to the existing methodologies, the CDDN enables decision making across multiple disciplines along all planning phases (from early to detailed). Based on a baseline CDDN of conceptual design decisions, it can be transferred to new projects and easily extended according to project-specific design questions.

3.1. CDDN META-MODEL

The meta-model of the CDDN extends the conventional design decision process (Figure 2). In the conventional process, each subset of the building, e.g., structure, building envelop, heating system, decides several design options in a linear sequence and mainly within the same discipline. Design questions with several design options are chosen successively, leading to one decision tree for each subset. The materials are selected in the final step for each option, mainly considering costs and functional values fulfilling legal restrictions, such as acoustics or operational energy. In contrast to this conventional process, the proposed CDDN process is not limited to decisions within the same discipline or subset, but design options can influence another discipline's decisions concerning design questions or just specific options. This leads to a combination and network of several decision trees of the conventional process. Meaning that the choice of material is not an endpoint, but in fact a decision that influences other design decisions at other and earlier stages of the process.

On a very simplified level, decision trees for construction projects increase in their granularity of decisions starting from an early design phase and leading to a detailed design phase. Usually, each discipline follows its logic and correlations in these decision trees according to its domain knowledge and norms, as decision trees follow a linear decision-making process. Nevertheless, some decisions can be reversible, which is not represented in a conventional tree structure. Reversible in this case means that the decisions can be reconsidered at a later stage without decisively influencing or changing the design path at the current stage.

In an integrated design process, these design decisions are discussed orally between different domain experts, as each decision might influence the decision of other disciplines. These interdisciplinary correlations can include decisions of different design phases and lead to decision conflicts that can only be resolved by a multi-disciplinary synthesis finding the best compromise. We do not believe that decision trees and oral exchange represent a decision-oriented process well enough. Therefore, this study defined a further development based on meta-models and followed by an application example.

To formalize this theoretical approach, we firstly developed a meta-model for decision trees of conventional processes. In a second step, we extended the conventional process and developed it further to an integrated approach of a CDDN process. Generally, each decision tree is a discipline-specific subset and follows different design questions. Each of those questions can lead to one or multiple design options that can link in a Building Information Modelling (BIM) Process to an Industry Foundation Classes (IFC) entity. This design option can be a material, construction technology or logistics and can lead to other design questions and, as a final stage, a material choice and the selections of final options. Those options have physical properties and induce costs.

The CDDN process does not stop at these final material options but also integrates other subset's decisions. These can occur after a design option but also after a final material selection. In comparison to the conventional process, more semantical information shall be included in the decision-making process, such as data for life cycle assessment.

3.2. Case study

In this chapter, a possible application example of the proposed CDDN approach is described on an early conceptual design level. The use case is a new construction of a non-residential building, for which building structure, building envelope and heating systems are chosen as subsets. In the first stage, we defined a decision tree for each subset. Hereafter, we implemented the dependencies between different decisions of subsets (shown with orange highlighted arrows on Figure 3). No subset is prioritized, i.e., the decision network can start from every subset and lead to all other ones.

In the proposed application example, two different design decision levels for the structural subset are given: the structural system (load bearing wall vs. skeleton system) and the related structural material (concrete vs wood vs masonry/steel).

For the building envelope, the two levels considered are

(1.) the window-to-wall ratio (high vs low) and the façade system (glazed curtain wall vs solid facade) and

(2.) the decision concerning the main exterior wall material (wood vs steel/masonry vs aluminium/concrete).

A dependency between the different subsets, building envelope and structural system, is shown: The decision for a solid façade system calls for a structural design with load-bearing exterior walls whereas a skeleton system favours a curtain wall. In terms of the heating system, four different decision levels are defined. Starting with the design question about the available energy sources, further the heat generation, heat distribution medium, and the installation of heat transfer must be chosen.

The presented dependency shows the influence of the curtain wall choice on the heat transfer: If a fully glazed curtain wall façade is chosen, heat transfer should not be in front of the windows, i.e., it either needs to be integrated into ceilings or floors or convection heaters. Activated ceilings or floors set constraints to the floor construction and material, for example certain surface materials cannot be used (e.g., thick carpet on floors or light dropped ceilings). Such decisions might occur much later in the process but are anticipated by an early design choice. Additionally, if the window-to-wall ratio is high, special attention to cooling demand is required. In terms of material choices, a skeleton with curtain wall system is typically built either with a concrete, wood or steel structure with the corresponding curtain wall materials or as a hybrid system. Each of these materials has a different thermal capacity which, in turn, can influence the choice and size of the heating and cooling systems.

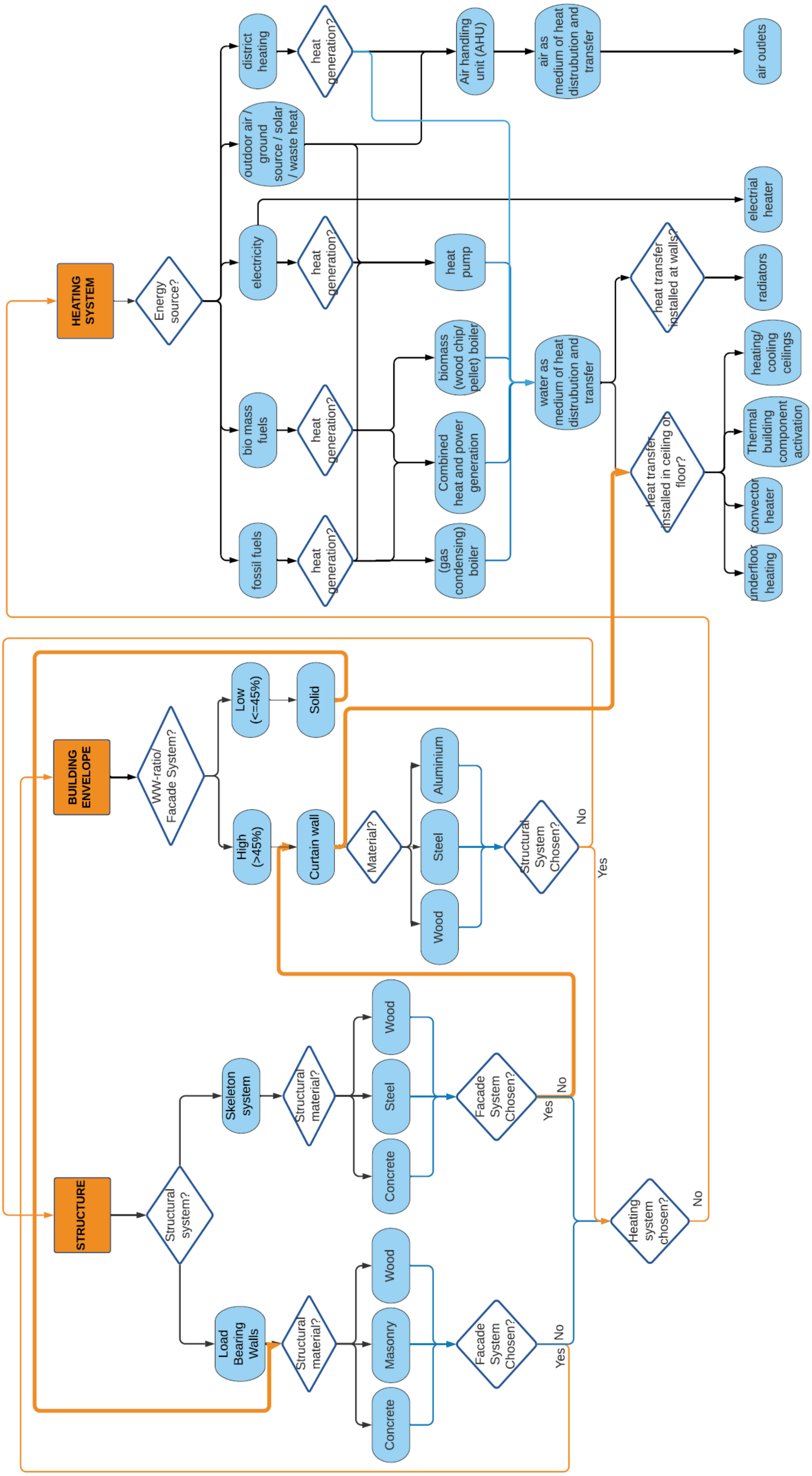

Figure 3. A case study of a CDDN in an early design phase for conceptual decision making.

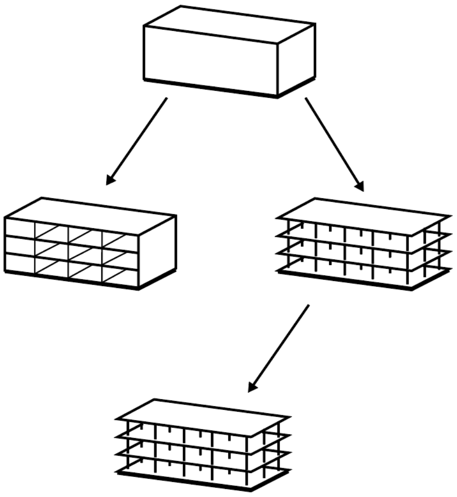

Figure 4. Case study refinement.

3.3. Prototypical decision making

For validating the suggested framework using a case study, the previously shown application (Section 3.2) is considered. A volumetric shape of an office building is the input of the case study, as shown in Figure 4. As a starting design decision, the structural system is to be selected.

The LCA benchmark range for the structural system is derived from a LCA benchmark study [12], based on 50 real-world whole building LCA results. This decision is shown as a prototype, since the full benchmark calculation is still under development. Although the LCA results for load-bearing walls seem more promising (Figure 5), the skeleton system was decided as the structural system, due to a dependency on the flexibility in the room layout. As the CDDN is not a single-criteria optimisation method, but rather giving transparent information about multi-criteria design decision, the lowest LCA has not to be necessarily chosen. Afterwards, wood was chosen as the main material. As no façade system is yet chosen, the CDDN application anticipates the façade system decision, directly leading to curtain walls and the related material decision. At the same step, for the heating systems, the design team is made aware that several systems should be excluded because the heat transfer should be installed in the ceiling or floor due to the previously made decision concerning a curtain wall system.

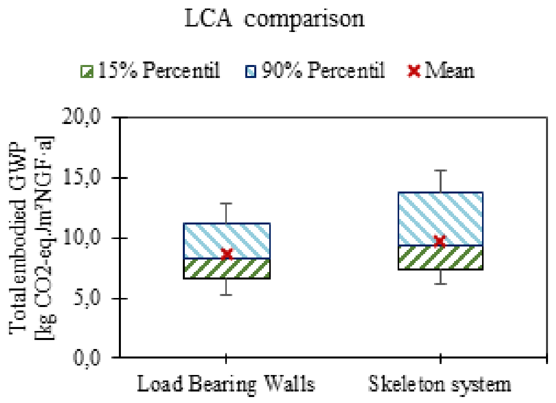

Figure 5. Boxplot showing LCA result for different structural systems based on 50 real-world buildings.

4. Discussion

The purpose of the CDDN is to formalize and visualize design decisions of different subsets and their dependencies. Starting from a predefined general system's level deciding conceptual design options, every project will develop and enrich their CDDN with individual design details. As it is impossible to forecast every possible design path, CDDN's are specific for each particular project. Therefore, CDDN in their conceptual form can be transferred to other projects, while the CDDN for a particular project follows the individual design process. CDDN identifies critical decisions with a high number of dependencies and a wide range of the results of multiple criteria, and, hence, highlights and communicates strategical decisions.

Nevertheless, by formalizing design decisions with the help of CDDN transparently, decisions leading to sub-optimal solutions or even faulty decisions can be more easily identified in later stages or after finishing the design. As a result, a systematic learning effect occurs, and the CDDN can be further developed to avoid similar mistakes in upcoming projects.

In the next step, we plan to calculate the LCA results for various design paths of the mentioned use case to achieve final values for LCA. The calculations for each decision path reveal decisive decisions nodes where interdisciplinary discussion is most beneficial for reduced environmental impacts.

5. Conclusion & Outlook

A connected design decision network (CDDN) enables the interdisciplinary team to formalize design decisions and identify strategic decisions due to interdependencies with other disciplines or results. The CDDN is based on subset specific decision trees, and considers a hierarchical dependency and can classify reversibility. As a result, a more transparent decision making is possible from early design stages showing the performance of alternative design paths and their connected consequences for detailed design stages.

In a next step, prototypical implementation in a tool shall verify the proposed theoretical method and visualise and manage the high number of dependencies and connections. A subset of existing networks will be modified and project-specifically extended in this tool due to upcoming design decisions. Furthermore, we plan a link to the BIM model to enable a fully integrated, model-based design process. We envision that design decision networks are apparent in the BIM model and that a tracking of past decisions enables experience gathering and further development. The CDDN must be available for every stakeholder and implemented notifications warn others if changes affect their discipline. This methodology also enables future development, e.g., applying machine learning to the tracked decisions to predict where and when in time decisions are made. Potentially, this can also improve the quality of risk management and reduce the number of redesigns in future construction projects.

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