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SUSTAINABILITY AS TARGET VALUE – A PARAMETRIC APPROACH

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ABSTRACT

Our time is characterized by climate changes that impose sustainability in every industrial activity, an additional objective to our design and construction processes. The classic Lean Construction approach needs to be further developed to take sufficient care of the sustainability issue. The design of modern buildings is a work process that can be set up and run with tools that secure a more sustainable final product. This study proposes to extend the classic range of objectives pursued by the Lean construction approach, as to include sustainability in the design process, in a systematic and structured way. The case of a building project is analyzed. In the early design stages, advanced structural design tools are used to explore various alternative designs of the bearing structure. The structural design tools are combined with tools used to calculate embodied carbon in the construction. The levels of embodied carbon following each of the many possible, alternative, structural solutions are estimated. These insights are provided to the owner in a very early stage of the design process. Through these design practices owners and investors can add sustainability targets to the classical project targets (cost, quality, time), and include sustainability as a part of the fulfillment of the client's functional needs.

KEYWORDS

Lean construction, Target Value Delivery (TVD), sustainability.

INTRODUCTION

Lean production thinking applied to construction management has evolved since 1940. Today it represents an approach to facilitate and secure value creation for the client as well as the actors involved in a construction project (Abdelhamid et al. 2008). Although the concept of value may be defined in various ways (Lombardo et al. 2017), in construction projects value is often understood as the fulfillment of the client's functional needs, and of the financial objectives of all involved actors (Drevland and Klakegg 2017). This understanding of value entails the set-up of project objectives like low production costs, optimized production flow, waste reduction, alignment of design and production, and pull production planning (Kalsaas, 2020). These objectives remain within the technical realms of engineering and construction and are widely acknowledged as fundamental to achieving high levels of efficiency and quality in the AEC industry. The relatively recent introduction of practices like integrated concurrent engineering, virtual design and construction (Fischer et al. 2017), and last planner system (Ballard et al. 2000), capitalizes on this understating of value and this kind of objectives.

In our times, climate changes impose the objective of sustainability on all of us, in every industrial activity, as a new objective to our design and construction processes. Although

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sustainability is an easy objective to embrace, work practices and tools are yet to be fully developed to secure a sustainable production process and a sustainable final product. This paper questions how sustainability can be an explicit goal of a construction project. And how can the design process support sustainability goals? This research witnesses the search for methods, tools, and practices aimed at introducing elements of sustainability in the construction design process.

LITERATURE REVIEW AND THEORETICAL APPROACH

LEAN APPROACH AND ITS LIMITATIONS

Waste reduction, workflow optimization, design and construction alignment, pull production planning are some of the concepts bound to secure a Lean construction process. A well-implemented Lean construction approach will help designers, and contractors, to focus on cost, quality, and performance objectives. The arguments in favor of including sustainability goals in the definition of project performance are well established in the literature both in terms of principles to be used to guide the design and construction (Bourdeau et al. 1998; Huovila & Koskela, 1998), and on work processes to be adopted at various design stages (Yates and Castro-Lacouture, 2018). Yet good intentions are often curbed by the boundary conditions provided by the project schedule and budget. Consider a large building that shall be designed and built. The number of possible alternative (architectural, structural, energy) solutions that can be studied is in fact quite limited. The designers may not have enough time and resources to analyze enough alternatives to find optimal solutions. Other restrictions may come directly from the very set of project goals adopted by the owner of the project. If sustainability, in any of its facets, is not included among the project goals, it is improbable that the final product be checked in that respect.

Therefore, the normal design approach based on optimizing cost, quality, and time does not necessarily end up in an optimal solution when it comes to sustainability. Two main questions arise:

> How can sustainability be an explicit and ineludible goal of a construction project? And how can the design process of modern buildings be set up to support sustainability goals, such as “the reduction of greenhouse gas emissions”?

These are the research questions of this study, through which we propose an approach to extend the classic range of objectives pursued by the Lean construction approach, as to include sustainability, in a systematic and structured way. A clear definition of sustainability is needed.

SUSTAINABILITY DEFINED

The concept of sustainability is a complex one, and its definition may vary depending on the context in which it is used and may include social, ecological, cultural, and environmental facets. The 17 sustainable development goals of the United Nations (UN) provide a good framework to find a definition suitable to the purposes of this study. Under goal 13 – Climate Change - in particular, several nations explicit their commitment to reducing their greenhouse gas emissions (the EU committed to a 30% reduction, Norway to 55%) (NRK, 2022). The AEC industry may produce an impressive effort to contribute to this reduction. This view can be adapted to focus on the reduction of greenhouse emissions as the AEC industry’s main contribution to the cause of a more sustainable global development.

A THEORETICAL APPROACH TO SUSTAINABLE DESIGN

For a broader review of decision-making methods and how these may affect sustainability goal-setting in construction projects see Penadés-Plà et al. (2016). The approach this study proposes is based on putting sustainability as an explicit objective for the design to be developed, and on giving it the same importance as classic goals like "cost", "time" and quality". This approach largely resonates with the concept of Target Value Design (TVD) which is used to set up project objectives. TVD requires that a fixed goal is set for any given value to be achieved through the design process. Normally a target *cost* is considered relevant and important, along with a target *quality level* and a target for the final *delivery deadline*. The design work is then organized and managed to achieve those targets, following a specific set of rules to check misalignments thought the work process (Zimina et al., 2012). We build this study on previous research connecting sustainability and lean construction (Johnsen and Drevland, 2016) and propose here to set up a sustainability target in addition.

Provided that sustainability is a broad concept, and given the definition this study has chosen, the target to be used to guarantee that sustainability is considered among the project goals can be related to an effort to minimize the greenhouse gas emissions from the building construction project. This target must be quantified, approved by the owners, and implemented in each project phase, from early planning, through the design process and to construction and operations.

The method used to set up this target, and the work process applied in the project is presented in the following sections, limitedly to the early planning and design phases.

METHODOLOGY

This research is executed as an explorative in-depth study of one case. A general contractor company that normally adopts lean construction approaches and has clear ambitions within sustainability; the opportunity to witness a phase where project goals are about to be set; good access to informants and to the corporate database; made this case well suited to our research purposes. Data were collected over six months through non-participant field observations with the design team during the design work; semi-structured in-depth interviews of four key contributors; recording of project plans and project deliverables. To focus our study, our data collection was limited to the design phase of the HQ construction project and focuses on sustainability in the design process rather than on the product.

THE CASE STUDY

Veidekke is a large general contractor in Norway. The company is planning to build its Head Quarters in the Capital city and wants to use this project as an opportunity to contribute to the national effort to cut greenhouse gas emissions. The office building is about 20000 m^2, over five floors, including the cellar. Although the general geometry is defined by the architect, the solutions for the bearing structure, including foundations, are not defined from the start. This study focuses on the assessment of various solutions for the bearing structure, and how this part of the project has been designed to contribute to achieving the sustainability target.

The following alternatives can be considered for the bearing structure:

1. Traditional bearing system in hollow cores slabs (HC) and steel.
2. Traditional bearing system in bubble-deck slabs and steel.
3. Modular building with solid wood decks. Support in the form of glulam beams and columns (hybrid solution)
4. Cast-in-situ concrete solution with post-tensioned slabs.

For each alternative, a large number of variations can in theory be considered, depending on the geometry variables of the construction elements (e.g., walls, beams, slabs), the positions of the elevator shafts, and the solution chosen for the façade, just to mention the most obvious ones. There is therefore a large number of possible solutions to be assessed and, besides the tools that make such an assessment possible, it is necessary to know which criteria the final decision shall be based on.

FINDINGS

TARGET VALUES DESIGN AND CHOOSING BY ADVANTAGES

Target Value Design (TVD) is the approach Veidekke chooses to establish the criteria to be used in the choice of the preferred solution for the bearing structure. In this case, a target *cost* is set, together with a target for the schedule and project completion date before the design starts. A set of target values are set up to assure the qualities of the final product (e.g. room program, functions, materials, etc.). High *flexibility* in the use of the surfaces (floors, walls) during the lifespan of the building is another important target, along with maximal usage of Veidekke's *own resources* (workforce, production technologies). Finally, and most interestingly, a target value is also set up for the maximum allowable volume of greenhouse gas emissions. The building shall be realized with *50% lower emissions* than a comparable building being built in the same period, in the same region, with the most common solutions for design and construction methods. In addition, the new HQ building shall qualify both as Breeam Excellent and as Green Building according to the EU taxonomy (Rademaekers, 2014). Putting these targets influences all the design decisions and forces the designers to adjust their thinking and their choices to achieve these targets.

In the following section the set-up of the design process is described, to explain the approach, the work process, and the tools there were adopted.

THE DESIGN WORK PROCESS

Having received from the owner and the contractor the set of target values, which included a reduction by 50% of the emission of CO2 compared to similar projects in the region, the design team went on preparing the structural analysis that should deliver solutions within the given targets. The design process can be summarized in the following main steps:

Step 1. Architect provides the main geometry of the building (Revit model, LOD200).

Step 2. The main geometry of the building was given by the architects, the second step was to decide on the technology to be used to realize the bearing structure. The first two structural solutions to be analyzed, were the two main variants with steel frames and prefabricated slabs: (alt. 1 post-tension slab and alt.2 use of bubble deck).

Step 3. Given the main geometry and one alternative of the bearing structure, the designers and the contractor identified the geometrical elements, or variables, of the bearing structure that should/could be modified (position and dimensions) in order to explore many variants of the given solution.

The following variables were considered:

Location and dimensions of piles
Position and dimensions on columns
Location and dimensions on load-bearing walls
Location and typology of slabs
Floor heights
Location of bathroom cabinets
Location and size of lift, stair and technical shafts
Placement of tension cables, if any, in the plane and in the cross section

Step 4. The list of variables to be considered flexible was used to set up a parametric model (in Grasshopper software) of the bearing structure. This model allows the simultaneous variation of a given number of the above-mentioned variables, and the creation of as many sub-alternatives of the given structure.

Step 5. Besides the geometrical model (e.g., Revit, LOD200) components (materials, loads) to be used for the structural calculations are *also* included in the parametric model. A full-fledged Finite Element Model (FEM) in SAP 2000 (a structural calculation tool) is contained in Grasshopper and interconnected with the Revit model. In this way, any change in the geometry entails new figures in the finite element analysis. For any given geometry a complete FEM analysis is delivered, and a preliminary structural analysis verification is automatically performed.

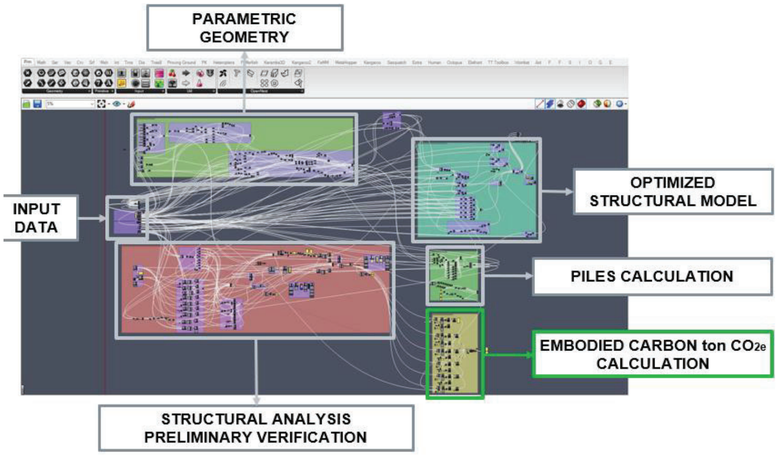


Figure 1: Parametric Model (Grasshopper) including Geometry, FEM and CO2 calculations

Step 6. Software, for the estimation of the emission of CO2 equivalents (in this case OneClick LCA) is plugged into the parametric model. Given a geometric and a structural solution (including the chosen materials) for any given alternative bearing structure an estimate of the greenhouse gas emission is delivered, provided that the Environmental Product Declaration of the elements used in the structure is available.

Step 7. An optimization plug-in for Grasshopper (in this case Opossum), including two of the best-performing, single-objective optimization algorithms is launched and, after some necessary iterations, a solution is optimized to minimize the volume of CO2 emissions.

The process from Step 2 to Step 7 is iterative, as shown in Figure 2.

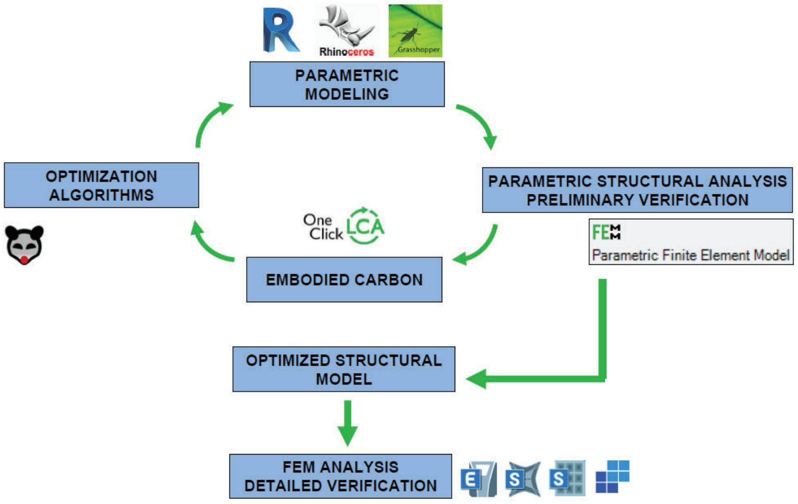


Figure 2: Optimization cycles - parametric approach

Step 8. A final detailed FEM analysis is performed to verify the given structure, and the results are provided along with the relative CO2 emission estimates.

Step 9. Based on the four assessment criteria (construction cost, room flexibility, use of own resources and CO2 emissions cut) a choosing-by-advantage approach (Suhr, 1999) is taken to perform the final assessment (see table 1). Hence, sustainability is included as a determinant factor in the final choice of the most advantageous alternative solution for the bearing structure.

Table 1: Choosing By Advantages table

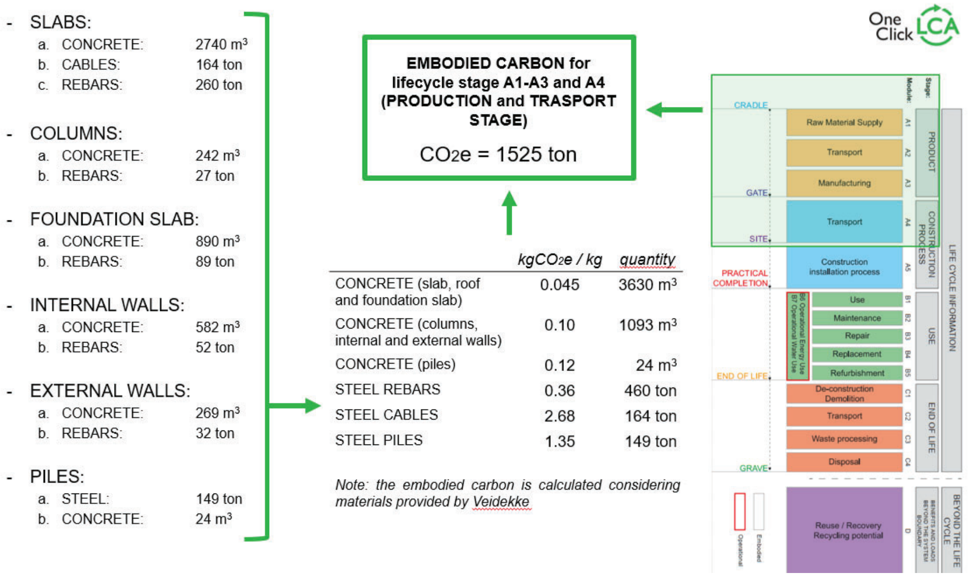
	Post tensioned.	**pts**	**Bubble decks**	**pts**	**Hollow cores**	**pts**	**Wooden structure**	**pts**
Cost	2nd most expensive	4	2nd most expensive	4	Least expensive	6	Most expensive	1
Additional cost	*5%*		*5%*		***0%***		*15%*	
Flexibility	most flexible	6	2nd most flexible	4	2nd most flexible	4	Least flexible	1
Loss in flexibility	***0%***		*-10%*		*-10%*		*-40%*	
Own Resources	Max usage of Own Resources	6	High rate of Own Resources	4	No use of Own Resources	1	Low rate of Own Resources	2
Own res. used	***100%***		*90%*		*0%*		*50%*	
CO2 emissions	31%	4	29%	2	33%	5	34%	6
Variation CO2e	*-3%*		*-5%*		*-1%*		***0%***	
SUM pts		*20*		*14*		*16*		*10*
Advantages in	*2 criteria*		*none*		*1 criterium*		*1 criterium*	

In the table: Points are given from 1 to 6 (best); Relative advantage is given in relation to the best alternative for any given criterium (e.g., CO2e from Wooden structure is best, and post-tensioned structure is 3% higher emissions than that). The criterium "CO2 emissions" provides a percentage reduction in embodied carbon from the reference building.

From the choosing-by-advantages approach, the two most advantageous solutions appear to be the one based on hollow cores and steel, and the one based on bubble decks and steel.

The parametric analysis of a large number of these two bearing structure alternatives resulted in several estimates of the tons of CO2 equivalent produced by each solution. The values of the most optimal solutions for each alternative are reported in the following.

The first solution: Bearing Structure with post-tensioned slabs offered a CO2 equiv. the emission level of CO2e = 1525 ton (Embodied Carbon for lifecycle from cradle to site, stages A1 A3 and A4) see Fig. 3



- SLABS:
  - a. CONCRETE: 2740 m³
  - b. CABLES: 164 ton
  - c. REBARS: 260 ton
- COLUMNS:
  - a. CONCRETE: 242 m³
  - b. REBARS: 27 ton
- FOUNDATION SLAB:
  - a. CONCRETE: 890 m³
  - b. REBARS: 89 ton
- INTERNAL WALLS:
  - a. CONCRETE: 582 m³
  - b. REBARS: 52 ton
- EXTERNAL WALLS:
  - a. CONCRETE: 269 m³
  - b. REBARS: 32 ton
- PILES:
  - a. STEEL: 149 ton
  - b. CONCRETE: 24 m³

EMBODIED CARBON for lifecycle stage A1-A3 and A4 (PRODUCTION and TRASPORT STAGE)

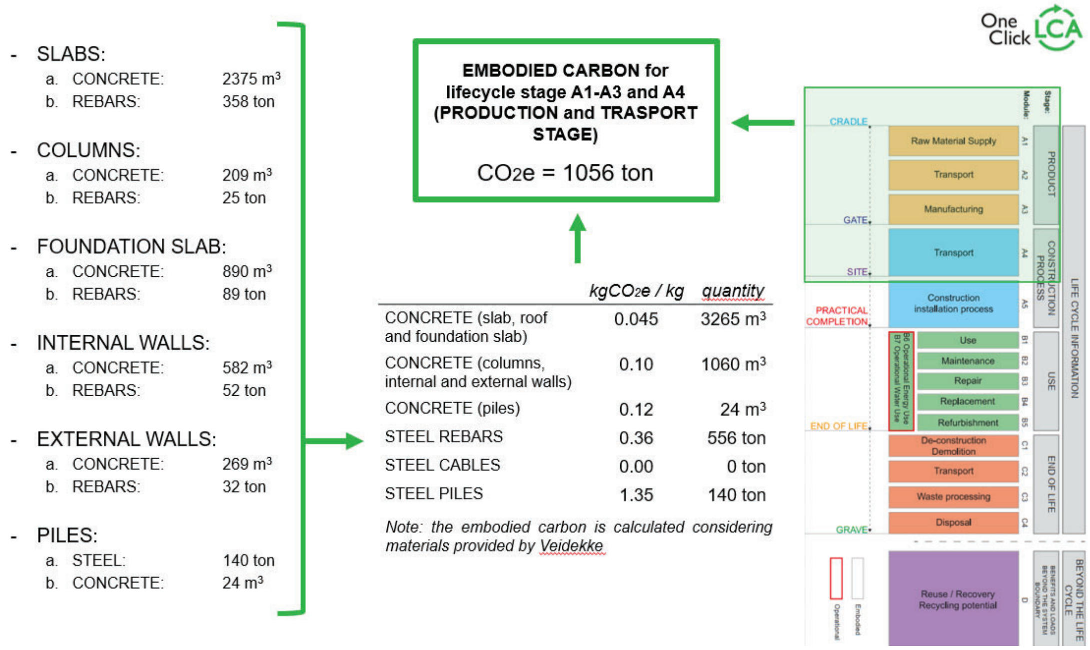
CO2e = 1525 ton

	kgCO2e / kg	*quantity*
CONCRETE (slab, roof and foundation slab)	0.045	3630 m³
CONCRETE (columns, internal and external walls)	0.10	1093 m³
CONCRETE (piles)	0.12	24 m³
STEEL REBARS	0.36	460 ton
STEEL CABLES	2.68	164 ton
STEEL PILES	1.35	149 ton

Note: the embodied carbon is calculated considering materials provided by Veidekke

Figure 3: Alternative 1 - Post-Tensioned Slab – Embodied Carbon

The second solution: Bearing Structure with bubble deck slabs offered a CO2 equiv. the emission level of CO2e = 1056 ton (Embodied Carbon for lifecycle from cradle to site, stages A1 A3 and A4) see Fig. 4



- SLABS:
  - a. CONCRETE: 2375 m³
  - b. REBARS: 358 ton
- COLUMNS:
  - a. CONCRETE: 209 m³
  - b. REBARS: 25 ton
- FOUNDATION SLAB:
  - a. CONCRETE: 890 m³
  - b. REBARS: 89 ton
- INTERNAL WALLS:
  - a. CONCRETE: 582 m³
  - b. REBARS: 52 ton
- EXTERNAL WALLS:
  - a. CONCRETE: 269 m³
  - b. REBARS: 32 ton
- PILES:
  - a. STEEL: 140 ton
  - b. CONCRETE: 24 m³

EMBODIED CARBON for lifecycle stage A1-A3 and A4 (PRODUCTION and TRASPORT STAGE)

CO2e = 1056 ton

	kgCO2e / kg	*quantity*
CONCRETE (slab, roof and foundation slab)	0.045	3265 m³
CONCRETE (columns, internal and external walls)	0.10	1060 m³
CONCRETE (piles)	0.12	24 m³
STEEL REBARS	0.36	556 ton
STEEL CABLES	0.00	0 ton
STEEL PILES	1.35	140 ton

Note: the embodied carbon is calculated considering materials provided by Veidekke

Figure 4: Alternative 2 – Bubble Decks – Embodied Carbon

The cases studied show that one solution, with bubble decks, has a significantly lower greenhouse emission level.

DISCUSSION

The findings show that the approach used in this project provides a powerful tool to elicit insights from the structural engineers in a phase that traditionally is the exclusive realm of project developers and architects.

During the planning phase sustainability target values are set up along with the classic project management cost, time, and quality targets. Already in the very early project phases, a parametric design approach can be used to determine which parts of the bearing structure can be considered as flexible and which parts shall remain fixed, as determined by the architects. The parametric model implements the variable parameters and runs the FEM analyses of the alternatives to yield optimized solutions that match the target values given at the outset. The parametric model is then used to run analyses of a large number of alternative structural solutions. Already at this early stage of the project development, parametric modeling is used to get insights into CO2 emissions levels. For each solution, quantity estimates of the greenhouse gas emission are provided for each alternative solution of the bearing structure. There is no theoretical limitation to the number of variants that can be studied.

Although the technology of parametric modeling enables these analyses at a very early stage in the design process, the core of the methodology rests within the set-up of the Target Values that steer the optimization process. Sustainability is therefore a choice made *a priori*, i.e. at the outset of the decision-making process. It is the owner of the sustainability goal, who takes the responsibility to set the sustainability targets. The investors may own the sustainability goal, as well as the general contractors. The latter will have to implement the targets in the construction process. In the case studied the structural engineer included embodied carbon calculations in their structural analyses. The designers, such as architects, engineers, and sustainability consultants need to contribute to the sustainability targets, by applying the right competencies to the design process. Although innovative and in line with the generic call to help in fighting climate change, the choice of giving sustainability such an important place in the design process does not appear as a simply idealistic one. The project uses choosing by advantages methodology to assure that while sustainability is taken systematically into account in a rigorous decision-making process, the other assessment criteria are given equal attention.
The final choice includes sustainability considerations and reflects a larger spectre of assessment criteria.

CONCLUSIONS

The Veidekke HQ project shows that Target Value Design opens the door to including sustainability in the design process from the first phases of the project life cycle. This is in line with the principle of Lean construction, and yet this approach requires innovative technologies and rigorous decision-making methodology when sustainability is included among the goals of the project.

Advanced parametric modeling of the bearing structure makes it possible to analyze a large number of alternative structural solutions, in early design stages, and at a pace that makes it valuable to invest in such insight, for both investors and architects.

Getting this kind of insight requires therefore both the technical capability of running parametric structural models integrated with greenhouse emissions software, and the political willingness to break with traditional planning practices and let structural engineers “intrude” in the early project phases. The added value of this modeling approach is given by the high number of alternative solutions that can be studied at a very early stage of the design process. Provided that the project sets up a target value for the CO2 emissions, the design optimization process can be modeled accordingly.

The adoption of choosing by advantages decision-making system makes it possible to balance sustainability goals with other more classic objectives.

A systematic application of this method, structured and implemented as described, could change the design practices in the AEC industry and merge the fundamental principles of Lean construction with the ineludible needs for the sustainable development of our cities and infrastructure.

The limitations of this study are mainly related to the structural analyses of only two kinds of structures. Other limitations are those implicit in the kind of software that was used to calculate the structures and the CO2 emissions (e.g. precision of the optimization algorithms; the precision of the embodied carbon data of the materials and components adopted in the construction).

The results of this study could therefore spur further research efforts. The proposed approach could be repeated to study different kinds of bearing structures (e.g. including materials such as CLT or aluminum). The software used to calculate CO2 emissions could be further developed so as to include estimates of the impact on the project phases that were not included in this study.

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