Towards a Pre-Design Method for Low Carbon Architectural Strategies

The case of the smart living building in Fribourg, Switzerland

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ABSTRACT: To face climate change, Switzerland has introduced the 2050 energy strategy by fixing greenhouse gas (GHG) emissions for the built environment. Designers will, as a result, have to use Life-Cycle Assessment (LCA) to increase operating performances while minimizing embodied impacts, but the integration of LCA at an early design stage adds a degree of complexity to the design process. The purpose of this paper is to highlight the potential of a pre-design method that allows to create a database of references able to guide the designer. A reference is characterized by a combination of design parameters, each reaching GHG emission targets. These references are generated with the Morris approach by iteratively changing the various design parameters one by one, and assessed with LCA after being implemented in architectural feasibility studies. The instantaneous global overview of this database highlights an innovative way to understand at an early stage the design consequences of ambitious GHG emission targets. This finding is mainly enabled by data visualization and sensitivity analysis. This method is especially interesting to be implemented for highly innovative projects such as the smart living building, which has been chosen as a case study. This building aims at achieving the 2050 goals of the 2000-watt society vision and is expected to be built by 2020 in Fribourg, Switzerland.
Keywords: low carbon strategies, data visualization, early design stage, design process, sensitivity analysis

INTRODUCTION

The built environment is responsible for 36% of the greenhouse gas (*GHG*) emissions in the European Union (European Commission, 2016). Thus, European policies target buildings as key players for lowering the environmental impacts. In Switzerland, the vision of a “2000 watt per capita society” has been introduced in (Jochem et al., 2004) as a way to tackle the climate change issues. According to (Société à 2000 watts, 2016), today’s *GHG* emissions are evaluated at 7,2 tCO_{2}-eq. per capita per year and they should be reduced to 1 tCO_{2}-eq. per capita before 2150. This means that *GHG* emission targets will be continuously strengthened during the next century. On the other hand, constraints resulting from the economic crisis and the increasing amount of regulation impact the designers’ ability to reach these objectives more and more. How is it possible to achieve such ambitious objectives with limited and decreasing design freedom? It is definitely a methodological issue that designers will have to face. The purpose of the proposed pre-design method is to provide a database of references, specifically generated per project according to their characteristics in term of usage and location. This database could be explored by designers before or during the design process. Each reference would in this context be a combination of design parameters with their corresponding predicted *GHG* emissions, specified for a unique project. Our research hypothesis is that the instantaneous overview and exploration of this reference database by data visualization, enables to better understand at an early stage the architectural consequences of ambitious *GHG* emission targets.

First, this paper looks into the state of the art, in order to review the main obstacles in the design process that limit current tools and methods from including energy performance and climate change complexity into the early design stage. Our proposition will emerge from this analysis: the pre-design method based on sensitivity analysis and data visualization. It has been applied to the smart living building as a case study. Indeed, this building aims at achieving the ambitious 2050 goals of the 2000-watt society vision and is expected to be built by 2020 in Fribourg, Switzerland. Finally, the main findings are discussed in the conclusion.

OBSTACLES TO INTEGRATE *GHG* EMISSION TARGETS AT EARLY DESIGN STAGES

The pre-design method proposed in this paper has its roots in the state of the art review. Based on it, four main obstacles, respectively *O1*, *O2*, *O3* and *O4* are proposed in this paper. The first obstacle *O1* is the lack of low carbon building references which could be used in the design process. According to (Prost, 1992), there are two kinds of references, the ones related to the solutions that refer mostly to aesthetical considerations, and the ones related to the problems that refer mostly to ethical considerations. Architectural design is an iterative process between problems and solutions. Multiplying these iterations allows to better define the design brief, and to find a proper solution. Therefore, many types of references are commonly used as metaphors to transform the design brief into first solutions. If aesthetical references are commonly used by designers, it is far from being the case for ethical aspects related to *GHG* emission targets. From the literature survey, the lack of references can be explained by the two following reasons:

a. The recent awareness of climate change limits the amount of experiences that can be considered as references. For instance, the Intergovernmental Panel on Climate Change was created in 1988 only.
b. The constant progression of climate change objectives for the next century (SIA, 2011), which make the few available building references quickly obsolete.

The literature review of current tools has pointed out that most of the tools guide designers through an optimization process (Crawley et al., 2008; Maile et al., 2007), assessment after assessment. It allows to improve a project, but not really to understand the sensibility of each design parameter. Sensitivity analysis is devoted to this purpose (Nguyen and Reiter, 2015), and enables to rank parameters according to their impact on the results.

The second obstacle *O2* is the complexity of the design process in a highly constraint field. Project complexity has amplified exponentially since the late 1980s (Cleland et al., 2009). Climate change issues represent a new layer of complexity that has been added recently.

The third obstacle *O3* is the necessity to define a project in a precise manner for an environmental assessment. There is an antagonism between the complexity of environmental issues and their early integration into the design process. It is, indeed, a multivariable, interdisciplinary and intercorrelated problem (Marszal et al., 2011). The more detailed the project, the higher the robustness of its environmental assessment.

As shown in the work of (Attia et al., 2012) and (Riether and Butler, 2008), every method used in early design stages has to face the problem of system resolution. This issue has been solved using two different possibilities. The first one is an over-simplification of the building's energy simulation to easily reach a rough assessment of the project. The second one is a high definition of the building that leads designers to use many hypotheses, regarding parameters not yet defined in the early design phase. In both cases, the robustness of the results is low.

The fourth obstacle *O4* is the complexity of environmental issues that limit an iterative design process. The relationship between the design efficiency and the early integration of the knowledge about design has been introduced by (Fabrycky and Blanchard, 1991). The Integrated Design Process (*IDP*) (Larsson, 2004) has been specifically developed to integrate energy issues at early stage of design. It proposes to involve all the skills and experiences of the design team as early as possible. But the *IDP* is an open inter-disciplinary discussion which most of the time is not compatible with the constraints that impact the building makers. Indeed, most projects start with an architectural competition, without any financial support, and with a very short time to submit a proposition. Moreover, *IDP* is time consuming and it reduces the possibilities to develop an iterative process, which is also crucial for project quality. According to this previous analysis, fast feedback on the project assessment is without any doubt one of the most important feature of a decision making tool (Athienitis et al., 2010; Clarke et al., 2015). In the literature review, mathematical methods are developed to quickly assess the results of a project, avoiding building performance simulation and using techniques such as the multivariate regression (Hygh et al., 2012). Even if the assessment started to be quick, it still did not enable an instantaneous global overview on many variants for a better understanding of the problem.

Thanks to this literature review, four obstacles have been specified to the early integration of *GHG* emission targets into the design process. Each obstacle can be tackled by the corresponding goal (*G*). The pre-design method presented in the second part of this paper will try to come to terms with these goals:

G1: The method should be able to provide low carbon building references thanks to sensitivity analysis,

G2: The number of references should be as large as possible. The higher the amount of references, the easier for designers to find a reference that matches every constraints,

Table 1: Design parameters, components, systems and their respective values used to create the reference database with the Morris method

Components		**Main materials employed**
Backfill		Demolishment of brick structure
Excavation		Mechanical
Foundations		Reinforcing concrete, Bitumen waterproofing, mortar
Floors Roof	*Structure*	Reinforcing concrete or wood
	Insulation	Cellulose fibre, glass wool or polystyrene
	Coverings	Concrete, mortar, plaster, parquet or ceramics.
Walls	*Structure*	Reinforcing concrete, brick, or wood
	Insulation	Cellulose fibre, glass wool, or polystyrene
	Coverings	Polyethylene, plaster or mortar.
Windows		Single, double, triple glazing with wood, aluminium or PVC frames
Doors		Wood glazed door or not

Parameters	**Values**			
Shape	1	2	3	-
*WWR** south	50%	75%	100%	-
WWR east and west	25%	50%	75%	100%
WWR north	20%	40%	60%	80%
Windows type	Double glazing	Triple glazing	-	-
Frame quality	Metal	PVC-XL	Wood + PUR	
Frame quantity	5%	10%	15%	20%
Rooftop PV	25%	50%	75%	100%
Natural ventilation ratio	0% SIA	30% SIA	60% SIA	100% SIA
Lighting timing	SIA schedule	80% SIA	65% SIA	50% SIA
Lighted surface	25% surface	50% surface	75% surface	100% surface
Appliances	SIA 380/4	80% SIA 380/4	60% SIA 380/4	40% SIA 380/4
Heating system (kg CO_2 /MJ)	0.005	0.01	0.02	0.05

**Window to wall ratio (WWR)*

G3: For a high usability and understanding, these references should be as detailed as possible. This goal is also perfectly coherent for their robust environmental assessment,

G4: The reference database should be generated before starting the design stage in order to facilitate the number of iterations during the design process with instantaneous feedback.

METHOD DESCRIPTION

The proposed method is a combination of sensitivity analysis, *LCA* and data visualization techniques.

First, design parameters which influence the building's *GHG* emissions, are identified thanks to a literature review. According to (Heiselberg et al., 2009) and (John, 2012), components and systems having an influence on the building's embodied impacts and operating impacts are noticed. Thanks to (Minergie, n.d.; SIA 308/4, 2006; SIA 382/1, 2014), each components and systems have been qualified or quantified in a range of values specified in Table 1.

Based on this, a sensitivity analysis performed with the Morris approach (Morris, 1991), is used to create a set of design parameter combinations by randomly changing them one at a time. The minimal significant number of scenarios '*N*' generated by the Morris approach is a function of the number of trajectories '*r*' and the number of design parameters '*k*'. Here, '*r*' is considered to be six. It can be calculated by the following equation:

$$N = r \times (k+1)$$

Secondly, these combinations are attributed to architectural feasibility studies (Sinclair, 2013). Indeed, every building project should perform such studies at the design brief stage, to make sure that the selected location will be able to host the occupant requirements in terms of volume capacity and urban rules. In this frame, the drawn volumes are then used as ground material on which each parameter combination is applied. This allows the method to be set up at the brief design stage, before starting the design process.

Thirdly, the *GHG* emission impacts of scenarios are assessed with the help of the KBOB-list (KBOB, 2014), provided by the "Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren". This institution published *LCA* for the building industry in the so-called KBOB-list, based on the Ecoinvent database (Ecoinvent, n.d.), one of the world's most consistent life cycle inventory database. The building's lifetime is considered to be 60 years. The impacts are calculated from the decomposition of the scenarios in building's components and systems. The following equation is used for this calculation:

$$I_f = \sum_{i=1}^{n} \mathrm{m}_i \cdot \mathrm{k}_{f,i} \cdot \left(\left\lfloor \frac{LB}{LM_i} \right\rfloor + 1 \right) + \sum_{k=1}^{p} \mathrm{C}_t \cdot \mathrm{k}_{f,t}$$

I_f [kg CO_2-eq] is the environmental impact *f* of building; *n* [unity] is the number of components and systems into which the building is decomposed; *p* [unity] is the number of different types of energy demand; m_i $[kg,\ unity]$ is the mass or quantity of components or systems *i*; $\mathrm{k}_{f,i}$ $[\frac{\mathrm{kg\ CO2-eq}}{kg,\ unity}]$ is the environmental impact *f* associated with the life cycle of one unit mass or quantity *i*; $\left\lfloor \frac{LB}{LM_i} \right\rfloor$ is the largest integer not greater than $\frac{LB}{LM_i}$; LB $[years]$ is the lifetime of the building; LM_i $[years]$ is the lifetime of the component or system *i*; C_t $[MJ]$ is the consumption of the energy in the operating phase of the building. $\mathrm{k}_{f,t}$ $[\frac{\mathrm{kg\ CO2-eq}}{MJ}]$ is the environmental impact *f* for the unit energy *t* (European Committee for Standardization (CEN), 2012; Hoxha, 2015). Energy consumed for heating, ventilation, domestic hot water, lighting and appliances is simulated in a dynamic way using the software Lesosai (E4tech, 2016).

The combinations of design parameters and their relative GHG emissions enable to create the reference database. The first three defined goals based on the literature review are now reached: references to climate change are proposed, in high quantity and as detailed as possible. However, due to its complexity and richness, the database is hard to understand and not really usable. To reach the last goal - which is the instantaneous feedback with a quick understanding of the database - visualization techniques are used. Visualization is a scientific domain, historically related to Human-Computer Interaction (HCI) and Computer Graphics.

Parallel coordinates (Fig. 1) (Inselberg and Dimsdale, 1991) are one of the popular techniques to explore and understand multi-dimensional numerical datasets. Each data point in the dataset is represented as a polyline plotted according to *n* parallel lines corresponding to the *n* dimension of the data. The parallel lines are generally presented vertically and equally spaced. The polylines are drawn along the horizontal axe with vertices crossing the vertical parallel lines at the position that correspond to the relative value of this data point for the considered dimension. One of the strong points of this technique is that the axes can be arranged in different ways, in order to group, for instance, similar dimensions to present data first according to the most discriminant dimensions or to identify correlations between pairs of dimensions. It can be used in combination with other visualization techniques using link and brush mechanisms, and in conjunction with mining techniques for instance to highlight clusters of data.

RESULTS

This method has been applied to the smart living building currently under design. It will be built by 2020 in Fribourg, Switzerland. This building aims at achieving the 2050 goals of the 2000-watt society vision, an ambitious and complex target hard to integrate in the early design stage. According to (Jusselme et al., 2015), this means that this building should not exceed 70 kg CO_2-eq per capita and per year. Thus, the usability of the pre-design method has been applied in the frame of the smart living building design complexity.

According to the Morris approach, 90 references have been created (6 trajectories and 14 parameters), and their related operating impacts assessed. To each reference, three different sets of materials have been applied, their related embodied impacts assessed, and identified in Table 1. For this first prototype, 270 references with full *LCA* have been therefore generated as a database.

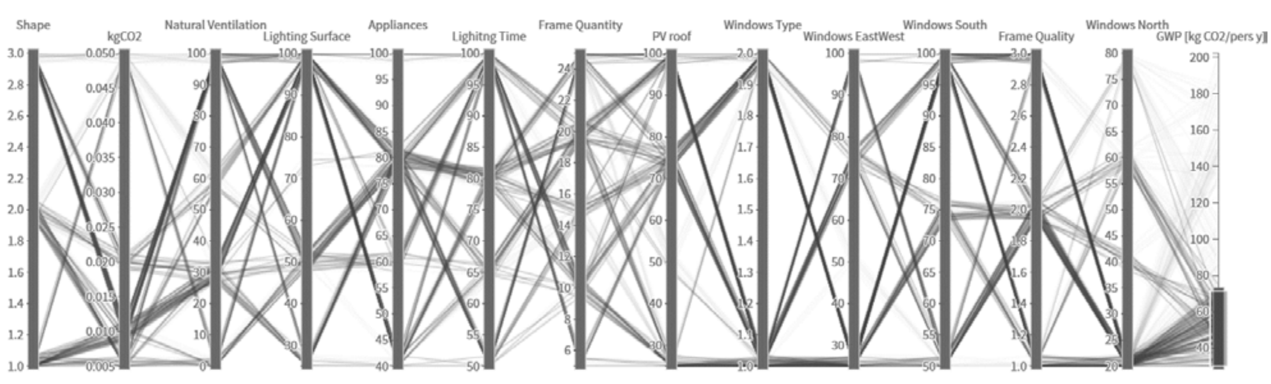

Figure 1: Parallel coordinates visualisation technique applied on the smart living building references. On the rightmost dimension, a range of target value (GWP) is selected, highlighting in dark grey only those references that match the 2000W society objectives.

Fig. 1 presents this full database illustrated with the parallel coordinates visualisation technique. The interactive interface allows to hide parameters in order to highlight the one that the designers want to focus on. In this Figure 1, only the design parameters that influence operating impacts have been kept. The *GWP* vertical parallel line is the *LCA* result of a reference, characterized by a polyline. The threshold has been interactively set to 70 kg CO_2-eq per capita and per year: references below are highlighted dark grey polyline and the ones above are filtered out.

It is interesting to notice that all the values on the other vertical parallel lines are still usable. Thus, the design freedom is already relatively large with these first 270 references.

Figure 2 is another example that illustrates the case of a designer interacting with the parallel coordinates and wanting to know the consequences of choosing a heating system with a related emission of 50g CO_2-eq per MJ of heating needs (a gas boiler, for instance), while still reaching the GWP target of the 2000W society. The resulting visualization shows this is still possible, by limiting natural ventilation to 30% of the areas, and the frame surface to 10% of the windows. It is really interesting to understand immediately the consequences of this choice on other parameters that will enable designers to take decisions quickly on this issue, according to other constraints like economical or aesthetic considerations. Moreover, it does not only assess the performance of the project, but it could also potentially guide designers towards a better understanding of the mechanisms impacting the performance.

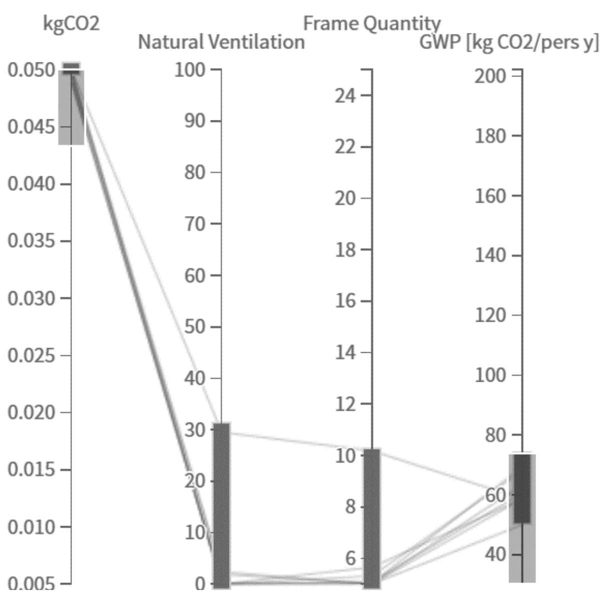

Figure 2: Insight gained with data visualization.

Using current tools and methods, the process to optimize a first architectural proposition with *LCA* would have been highly time-consuming during the iterative process, and then would have limited these iterations. The result would be an optimized proposition regarding a single target, but with a high probability to miss other building constraints an architect has to face.
Here, this pre-design method allows to modify a large range of parameters, and the consequences of these modifications are made immediately explicit to the users. The high level of understanding of *GHG* emission targets at an early design stage provided by the pre-design method still has to be proved by end user test. The first uses of this method allow, however, to understand its high potential.

CONCLUSIONS

This paper highlights the potential of a pre-design method to guide designers through archetypal low carbon architectural strategies. The core concept of the proposed approach is the data visualization of references related to *GHG* emission targets, which are generated specifically for an architectural project. A reference is a combination of design parameters set up by sensibility analysis. Each one having a *GHG* emission *LCA*. These references are created with the Morris approach by changing the parameter one by one, and assessed with *LCA* after being implemented in architectural feasibility studies. The instantaneous global overview of this database, allowed by data visualization, highlights the potential of an innovative and powerful way to integrate the complexity of climate change within the early design stage. The smart living building case study gives first interesting conclusions regarding the potential of guidance of the reference database.

The proposed method applied within the frame of this case study tackles three of the four goals (*G*) identified. First, this paper demonstrates that it is possible to create references related to climate change (*G1*). These references have been characterized for their usability, but also for their environmental assessment (*G3*). An instantaneous overview of the database allows a quick feedback to facilitate the iterative design thanks to data visualization techniques such as parallel coordinates (*G4*). With additional interaction capabilities, designers can explore and gain insights about the limits of their design space, and the direct consequences of their architectural choices on the most important design parameters, but this has still to be proven with an end user survey in further developments.

Regarding *G2*, the way the database is created increases somehow the number of references. So far, it is limited by the tools used to assess the *GWP* performance which were manually run. Further developments will allow an automatic *GWP* assessment, lead to a higher number of references, and then increase the usability of the method by providing more insight to designers regarding the climate change issue.

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