Design guidance from a Data-Driven *LCA*-Based Design method and tool prototype

Thomas Jusselme[1,3], Pedro Antunes Fernandes[1], Emmanuel Rey[2], Marilyne Andersen[1,3]
[1]Building 2050 Research Group, Ecole Polytechnique Fédérale de Lausanne (EPFL), Fribourg, Switzerland
[2]Laboratory of Architecture and Sustainable Technologies (LAST), School of Architecture, Civil and Environmental Engineering (ENAC), Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
[3]Laboratory of Integrated Performance In Design (LIPID), School of Architecture, Civil and Environmental Engineering (ENAC), Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

Abstract

As of 2020, every new building in the European Union will have to reach the nearly Zero Energy Building (nZEB) performance. However, building nZEB will not be sufficient to reach carbon neutrality in 2050 as required by the last IPCC report: indeed, even nZEB consume energy due to their *embodied* impacts. Thus, life-cycle assessment will become a mandatory approach to mitigate environmental impact of buildings beyond the nZEB performance. However, the complexity of Life-Cycle Assessments (*LCA*) continues to make it difficult for it to be effectively used at the early design stage.

A promising theoretical framework called *LCA*-based data-driven method had been proposed in prior work by the authors to tackle these issues (Jusselme et al. 2018a). This paper presents the prototype that has been built for the developed method to be tested in a first application. The case study chosen for this application is the future building of the *smart living lab* in Fribourg, which aims to reach the SIA2040 performance threshold. A specific knowledge database of 20’000 design alternatives – with a *LCA* performed for each of them – was thus generated with a parametric approach. First, the method provides sensitivity indices so as to better understand the influence of different design parameters. Second, performance target values are provided at the building component level in order to choose building techniques and materials in accordance to the SIA2040 objectives. Ultimately, the method offers site-specific guidance with an exploratory perspective. By literally exploring a database of design alternatives generated specifically for that site and urban context, the user (designer) gets valuable insights about the choices still available when other decisions are made if the SIA2040 performance ambitions are to be kept. In comparison to current practices, this case study demonstrates the ability of the method to provide a highest amount of design insights beyond the simple assessment process, in a shorter time. Further research needs to be carry out to verify the benefits of the method in the frame of a real design process, thanks to practitioner’s evaluations and feedbacks.

Keywords

Design-support method; Life-Cycle Assessment; Exploration method; Sensitivity Analysis; Global Warming Potential

Introduction

From 2020 onwards, new buildings located in the European Union will be required to reach the Nearly Zero Energy performance level (EU - EPBD 2010). Consequently, operational impacts will continue to trend more and more successfully towards zero, and the evaluation of embodied impacts of buildings will become increasingly important to effectively minimize the environmental footprint of the construction industry. Therefore, Life-Cycle Assessment (*LCA*) is likely to become of major importance in the next years. Furthermore, it is well known that the most important decisions ultimately impacting the performance of a building during its design process are those taking place early on. However, using *LCA* during the early stages is still facing major obstacles (Jusselme et al. 2018a, Zabalza Bribián et al. 2009, Basbagill et al. 2013, Meex et al. 2018). As a recent survey by the authors showed, only 27% of *LCA* practitioners seem to be using dedicated software today (Jusselme et al. 2018b). A first method developed by Hollberg et al. proposed a real-time assessment in order to provide immediate feedback to the designers when drawing a building, which dramatically decreased the time consumption of an *LCA*. Building upon this, the authors developed a theoretical framework to address other issues that made LCA incompatible with early stage design, such as the low resolution of details at that stage, the non-reproducibility of results, etc, which they named *LCA*-Based Data-Driven Design method (Jusselme et al. 2018a). The idea is to offer design guidance by exploring the environmental impacts of a previously generated knowledge base of simulated building projects that is specific to a given site, making *LCA* useful for schematic design also. Its goal is to give designers first insights about the architectural and technical consequences of a life-cycle performance target.

This paper focuses on the implementation of the method into an actual prototype and on its test application on an advanced case study with low-energy and low-carbon targets, namely the smart living lab’s future building in Fribourg, Switzerland.

Methodology

The methodology described by (Jusselme et al. 2018a) aims to provide a database of design alternatives with thousands of life-cycle performance simulations thanks to parametric assessment. The objective is to extract knowledge from this database thanks complementary

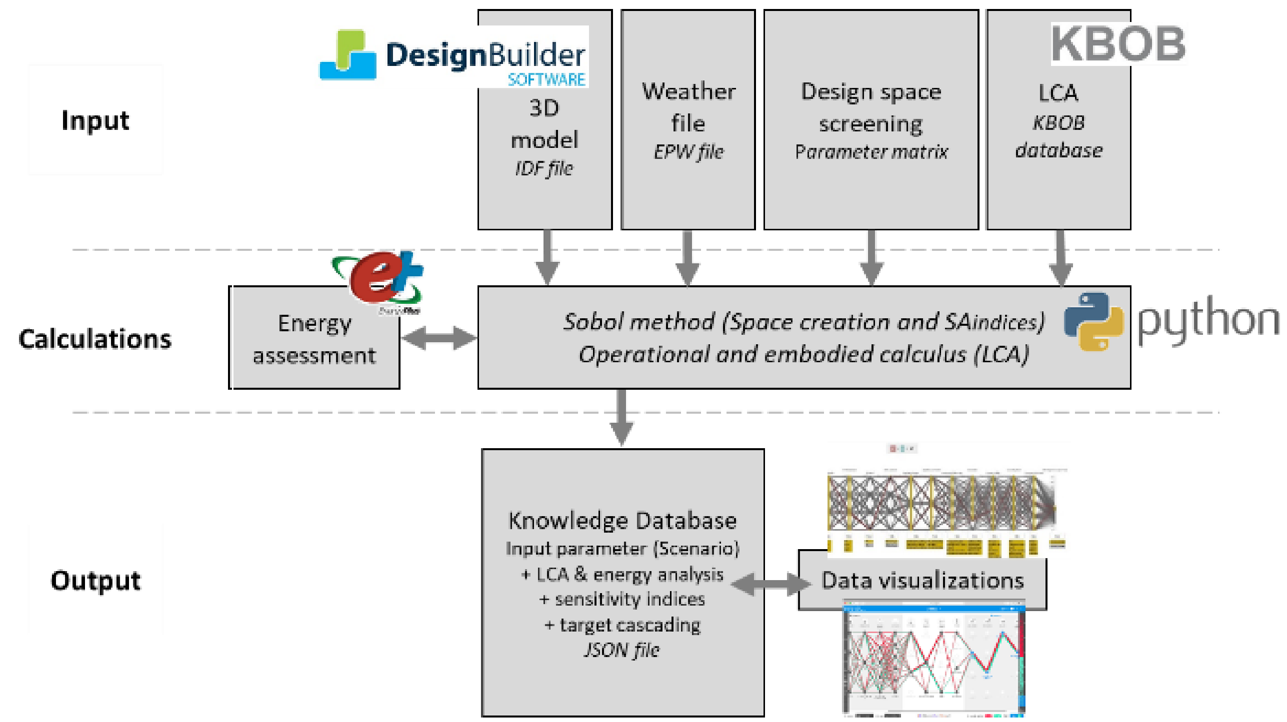

Figure 1: Description of the input, calculations and output that embedded the workflow.

techniques such as target cascading, sensitivity analysis and data visualization. The frame of this article will focus on the implementation of this entire workflow except the data-visualization part, which will be the subject of future research and development.

The present section describes how the five steps of the *LCA*-based data-driven method (Jusselme et al. 2018a) has been implemented into this first prototype. Figure 1 gives an overview of the general workflow, which is hereunder further detailed.

Impacts of the building life-cycle

The methodology aims at supporting the Swiss 2050 energy strategy, which is based on the 2000-Watts society concept (Jochem et al. 2004). It defines environmental targets for buildings in terms of Cumulative Energy Demand (*CED*), non-renewable *CED* (*CEDnr*), and Global Warming Potential (*GWP*). Specific targets for building offices that were set for the 2050 horizon (SIA 2017a, Kellenberger et al. 2012) are provided in Table 1.

Table 1: SIA 2040 targets for Offices

CED	209 kWh/m².y
CEDnr	120 kWh/m².y
GWP	13 kg $CO_{2\text{-}eq}$/m².y

These targets encompass the whole building life-cycle impacts (I_{BLC}) with their operational (I_{OP}) and embodied (I_{EM}) impacts according to the following formula (1):

$$I_{BLC} = I_{OP} + I_{EM} \quad (1)$$

Thus, in this research, the impacts of buildings will be assessed according to the CEN standard (EN 15978 2011), which takes into account the different life-cycle stages of a building: production, construction, use and end of life. According to this norm, I_{OP} embeds the Operational energy use (B6). I_{EM} embeds the following modules: Raw material supply (A1), Transport/Product (A2), Manufacturing (A3), Transport/Construction (A4), Replacement (B4), Demolition (C1), Transport (C2), Waste processing (C3) and Disposal (C4).

Embodied impacts (I_{EM})

In order to calculate the embodied impact I_{EM}, the building is decomposed into *n* so-called components (e.g. insulation material, heating equipment…). Each component *i* is expressed as a mass (kg), a surface (m²) or a quantity (unity) m_i and multiplied by its environmental impact conversion factor CF_i. Then, the building lifetime *LB* and the component lifetime *LMi* are integrated to obtain environmental impact over the whole building lifetime. Finally, the impacts are normalized to the building lifetime (LB) and to the building surface (SB), to be consistent with SIA 2040 targets. I_{EM} is derived from (Jusselme et al. 2016) and the following equation (2):

$$I_{EM} = \frac{\sum_{i=1}^{n} m_i \cdot CF_i \cdot \left[\frac{LB}{LM_i}\right]}{LB \times SB} \quad (2)$$

To determine the specific environmental impact CF_i, we used the KBOB database (KBOB 2014). The latter is dedicated to building components in agreement with the CEN standard (EN 15804 2012). It provides the *CED*, *CEDnr* and *GWP* impacts based on the ecoinvent database (Ecoinvent n.d.). Thus, I_{EM} can be calculated for each of these impacts. The components and the building lifetime are considered in agreement with the SIA 2032 (SIA 2032 2010), e.g. 60 years for the building.

Operational impacts (I_{OP})

The operational impacts are decomposed into *p* different types of energy, e.g. biomass or gas. The energy demand E_k is calculated with an hourly time-step over the entire building lifetime and is multiplied by its specific environmental impact CF_k. As off I_{EM}, the impacts are normalized to the building lifetime (LB) and to the building surface (SB). I_{OP} is derived from (Jusselme et al. 2016) and the following equation (3):

$$I_{OP} = \frac{\sum_{k=1}^{p} E_k \cdot CF_k}{LB \times SB} \quad (3)$$

CF_k is a conversion factor given by the KBOB database. The self-consumed and exported photovoltaic electricity conversion factors are chosen according to the Swiss SIA 380 (SIA 380 2015), and illustrated by Table 2 as follows:

Table 2: Conversion factors (CF) of various types of energy used in the method, according to SIA2024 and SIA380.

	CF CED kWh/kWh$_{fe}$	*CF CEDnr* kWh/kWh$_{fe}$	*CF GWP* kg $CO_{2\text{-}eq}$/kWh
Electricity	3	2.52	0.102
Biomass	1.2	0.16	0.0273
District heating	0.875	0.549	0.108
Self-consumed PV	-3	-2.52	-0.102
Exported PV	-1.4	-0.289	-0.081

The EnergyPlus simulation engine (Crawley et al. 2001) has been chosen to run the hourly-step energy consumption and photovoltaic production assessments. It is widely used and recognized by the scientific community for its robustness, and it allows us to use its simulation engine to run parametric assessments. The SIA 2024 (SIA 2015) gives usage scenarios to set the occupation parameters in the office building. According to this norm, an average occupation scenario is assigned to each surface considering 50% of the space as open space; 10% as individual offices, 10% as meeting rooms, and 30% as corridors, social and technical rooms. Finally, Meteonorm V.7 generates the weather file used by EnergyPlus. It is specific to the building location in a .epw file format.

Parametric assessment

A 3D model of the project was first created in the DesignBuilder software (DesignBuilder 2016). In the methodology, the shape can be as simple as a volume with its different floors. The urban surrounding landscape was included in order to account for its shading effect on the photovoltaic system and the building solar heat gains. The 3D model was then directly exported from Design builder as an IDF file. Thanks to a Python library called Eppy (Santoch 2015), these parametric modifications of the IDF file was performed using a very similar approach to the one described by Glazer (Glazer and Analytics 2016). The parametric modifications of this template changed the building components according to the user specifications (Table 3). It delivered a database of IDF files representing design alternatives with all different design properties (e.g. different Heating systems). Another open source library (Bull 2018) was integrated and extended to allows the geometric modifications in terms of the building envelope (e.g. windows size). Each IDF file was later sent to the Energy Plus Simulation engine and used for the embodied impacts calculation in order to create the knowledge database represented as the output in Figure 1. The embodied impact calculations have been coded with the Python language and integrated to the method following the previous I_{EM} calculation description. To satisfy the high computational load of the performance simulation of 20'000 scenarios, a multiprocessing batch mode was implemented. In the end, it reduces the required calculation time to 8 hours. This duration was largely influenced by simulation constraints of the 3D model such as the number of zones, windows per zone, time steps and technical specifications of the server machine running the simulation. In this case, 12 logical processors Intel Xeon CPU E5 v3@3.5 GHz with 16 GB DIMM memory have been used. Finally, all the results was extracted from the Energy Plus tabular output files in XML format using epXML2CSV.py (Glazer and Analytics 2016), a previous script which has been adapted to support the presented methodology. Thus, the embodied and operational impacts computations was compiled in a .csv file.

Sensitivity analysis

The Sobol method (Sobol 1993) later improved by Saltelli (Saltelli 2002) was selected to perform the sensitivity analysis. This allowed to determine the Sensitivity Indices (*SI*) of the parameters used to generate the design alternative database. This variance-based method is able to deliver quantitative results, to handle the interactions between the parameters, and to use discrete values (Duprez et al. 2019, Jusselme et al. 2018a). This method actually requests a high computational effort as the database population needs to be include at least 1000 times the number of parameters that are changed. However, this high number of alternatives is in fact of major interest to the future users of the method, as it increases the number of design alternatives usable during the exploration process. The Sobol method delivers both first-order indices and total-order indices but considering the high number of parameters, our approach only focuses on total order indices. The computation of these SI has been made possible by the integration of the SALib library (Herman and Usher 2017) to the parametric assessment previously described.

Target cascading

According to Hoxha et al. target cascading is both a top down and bottom up approach that allows to break down an overall building performance target into sub-targets at the building component level (Hoxha et al. 2016). In our methodology, the building performance targets T_B are those defined by the SIA 2040 in Table 1. The sub-targets T_i at the component level are then determined within the design alternative population that fits with this SIA 2040 threshold. Selecting only this population ensures that the target cascading process will provide target values with a distribution in agreement with the building target. Then, the average weight $\overline{T_i}$ of the component impacts is calculated and rebalanced upwards to the SIA building target T_B. Doing so, the sum of each component targets equals the building overall objective. The target cascading process can be expressed with the following equation (4):

$$T_i = \overline{T_i} \cdot \frac{T_B}{\sum_{i=1}^{n} \overline{T_i}} \quad (4)$$

It is also possible to set target values to specific subpopulations of the database, e.g. specific target values for the population of design alternatives that use a concrete structure and a biomass heating-boiler.

Table 3: List of parameters used by the method and their related descriptions

Parameters	Descriptions			
Window to wall ratio *(WWR)*	25%	40%	55%	70%
Glazing (GLAZ)	Double glazing (U=1.3)	Triple glazing (U=0.6)		
Windows Frame (FRA)	Wood/ Alu	Alu	PVC	Wood
Building U value (W/m²K)	0.1	0.2	0.3	
PV Roof (PVR)	0%	30%	60%	90%
PV Façade S/E/W (PVF)	0%	10%	20%	30%
Heating system (HEAT)	Heat Pump	Biomass boiler	District Heating	
Lighting power (LIGHT)	85% SIA	SIA	120% SIA	
Horizontal elements* (HORS)	Reinforced concrete B300**	Laminated Wood B303**	Wood Framed Bi101**	Trapezoid plate B301**
Vertical elements* (VERT)	Fired clay block W02**	Reinforced concrete W04**	Laminated Wood W47**	Wood Framed Wi01**
Insulation material (INS)	Glass wool	PSE	PU	Rock wool
	Cellulose fibre	Wood wool		
Floor covering (COVF)	Cast coating	Ceramic tile	Linoleum	Parquet
	PVC	Carpet		
Wall covering (COVW)	Cement panels	Cement plaster	Wood siding	Zinc
	Steel	Organic coating		
Transport (TRPT)	100 km	200 km	500 km	1000 km

**The environmental impacts of these elements have been increased by 20% to balance their low description in the method (Padey 2013). **The detail composition of these elements are available on bauteilkatalog.ch thanks to these references.*

Building components database

The *LCA*-based data-driven method uses the Saltelli low-discrepancy screening technique to combine building components (Saltelli et al. 2010). It generates the database of design alternatives that represents the design space later explored by the user. Thus, one of the inputs of the method illustrated in Figure 1 is a database of building components and their related environmental impacts conversion factors and lifetime. The "catalogue of building elements" (Kurt 2002) has been used to define these components. Further details about the quantity and quality of materials are available within this catalogue or in its online version at the following link: "www.bauteilkatalog.ch". Table 3 describes all the 14 parameters that have been used to generate the design alternative database.

Besides these parameters, other components (Table 4) are simulated to describe an entire building for each design alternative. These elements are kept unchanged as they are considered in our case out of the interest of designers at early design stages, thereby reducing the design space to be simulated, and the computational effort. However, as it is case specific and according to the designer's interest, these components can be switched as parameters in Table 3 if different materials or techniques have to be explored and used in the parametric approach according to step 2 of the method (Jusselme et al. 2018a).

Table 4: Building components kept constant in the design alternative database and their related descriptions

Components	Descriptions
Electrical equipment	KBOB 34.002
Sanitary equipment	KBOB 33.001
Ventilation	Dual flow with 80% Heat recovery, KBOB 32.006
Foundations*	SIA 2032, C 1
Excavation*	SIA 2032, B 6.2
Underground parking*	10 places of 25m² each, SIA 2032, KBOB
Doors*	KBOB 12.004, 0,05m² of doors per building m²
Internal walls*	M1 M030, bauteilkatalog.ch
Elevators*	150m² of vertical elements
Furniture	According to (Hoxha and Jusselme 2017)

**The environmental impacts of these elements have been increased by 20% to balance their low description in the method (Padey 2013).*

Case study

The previous section described the workflow and various aspects behind the proposed method. The developed workflow has been applied to the *smart living lab*'s future building, whose construction is planned to be completed in 2022 in Fribourg, Switzerland. It is currently under the brief phase according to the RIBA plan of work (Sinclair 2013) and its ambition is to satisfy the 2000-Watts society performance targets at the horizon 2050. The concept design will start in 2019. In this context, the *LCA*-based data-driven method is used to provide additional support to the architects and engineers involved in its design through an innovative, collaborative-competitive process (SIMAP 2018). The objective of the case study is to provide to the *smart living lab*'s design teams a knowledge database based on a first site-specific building volume. To that end, a building shape provided by previous urban studies was realized by Urbaplan (Figure 2), an urban design office. This first design was used to produce the IDF file template as per the method previously described. Its gross floor area is 5300 m² and its volume 19450 m^3. The surrounding buildings were also integrated into the IDF file in order to consider their shading effects. The goal is to offer the possibility to the future designers to extract from the resulting knowledge-database some design insights and performance trends, as well as design strategies or promising parameter combinations that will help to understand the consequences of the environmental performance requirement on the technical and architectural solutions they can use. A better overview of the design space available is indeed necessary to integrate life-cycle constraints early in the design process, which is specifically the purpose of this method. As the design follows an iterative process, designers would be able later to refine the knowledge-database according to their specific design proposition, and to use an IDF file template according to the building volume they propose.

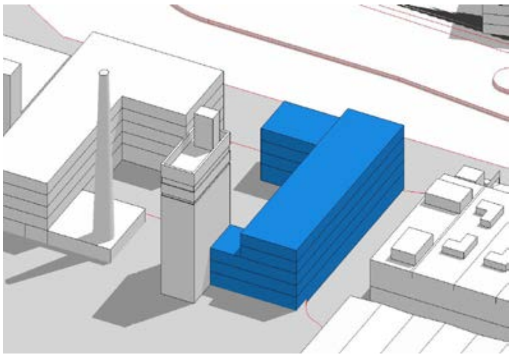

Figure 2: The building shape (in blue) used to generate the generic IDF file.

Results

A database of 20,992 design alternatives was generated, and each one's related *LCA* calculated.

Data exploration

The results will mainly be discussed in terms of *GWP*, as it is known to be the main challenge to handle within the 2000-Watts objectives (SIA 2017b). Indeed, thanks to Figure 3, we can observe that all the design alternatives generated have a satisfactory *CED* impact i.e. that remains below the threshold of a 2000W society. It is also the case for the *CEDnr* indicator. However, regarding the *GWP* impact, only 27% of the whole design alternative database has an impact below the SIA threshold, that is to say, one fourth only of the design space that has been assessed. This confirms that the GWP objective is the main challenge to face. Also, this graphic shows that there is no correlation between the *GWP* and *CED* impacts (r^2=0.01), contrarily to *GWP* and *CEDnr* where a higher correlation has been found (r^2=0.2).

Regarding the final energy distribution (Figure 4), the Photovoltaic production has the highest dispersion from 0 to 44 kWh/m².y, which is expected from the high differences in the solar collector surfaces between the various design alternatives. Also, the maximum gap between design alternatives for heating consumption is 20 kWh/m².y, which highlights the change of thermal properties of the model itself. Domestic Hot Water (DHW), Appliances and Ventilation never vary, as they are kept constant within the database.

Sensitivity analysis results

The sample size and the corresponding 21'000 *LCA* is by far higher than the 14'000 requested by the Sobol method when 14 parameters are analyzed with N = 1000. The confidence intervals of the simulations are thus clearly considered to be acceptable, as 95 % of them are lower than 10 % of the Sensitivity Indices (*SI*) values for the most sensitive parameters (Archer et al. 1997).

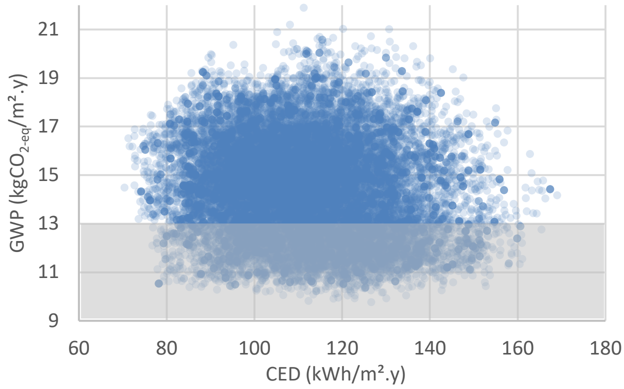

Figure 3: Environmental performance dispersion of the 20'992 design alternatives of the database according to their CED and GWP impacts (I_{BLC}). The grey zone highlights the 2000-Watts design space.

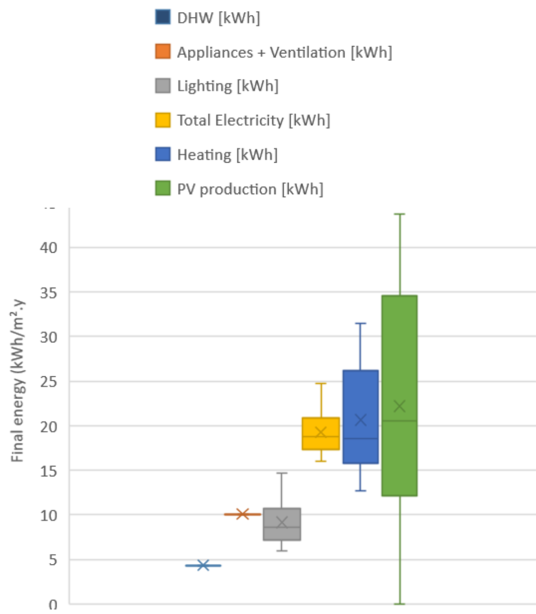

Figure 4: Distribution of the final energy according to different operational consumptions and to the photovoltaic production.

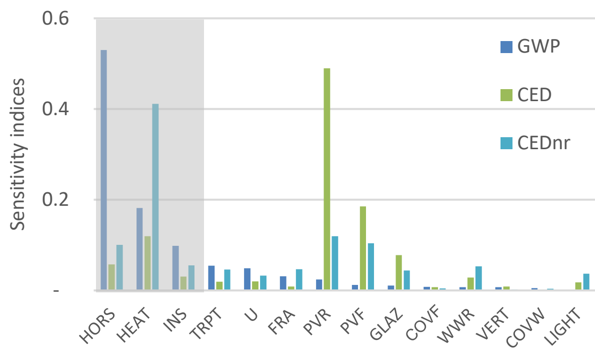

Figure 5: Total order Sobol sensitivity indices (SI) for the GWP, CED and CEDnr impacts of the 14 parameters of the design alternative database. The grey zone represents the parameters embedding 80% of the GWP variance.

There are high differences, however, in the ranking of the *SI* according to the impact that is considered. It is worth noticing that each parameter having the highest *SI* is different according to the environmental impact which is considered (i.e. CED, CEDnr or GWP). Regarding the *GWP* (Figure 5), the horizontal structure has the highest *SI* with 0.53. Indeed, slab, floors and roof represent a high quantity of materials with large surfaces, and there are significant performance differences between these components: the *GWP* impact of the “wood frame” structure (44.4 $CO_{2\text{-eq}}$/m².y) is e.g. four times lower than the one of the “trapezoid plate” (186.6 $CO_{2\text{-eq}}$/m².y).

Also, it is interesting to notice that PV panels on the roof or on the façade have a low *SI*, due to high embodied carbon emissions, and a low carbon content of the Swiss grid, which makes their *GWP* mitigation potential not very attractive. On the other hand, PV panels have high *SI* regarding the *CED* impact thanks to their short payback time. Finally, regarding the *GWP* impact, one can observe that 21% of the components (HORS, HEAT, INS) represent 81% of total *SI* which follows the Pareto law where 80% of the effects come from 20% of the causes.

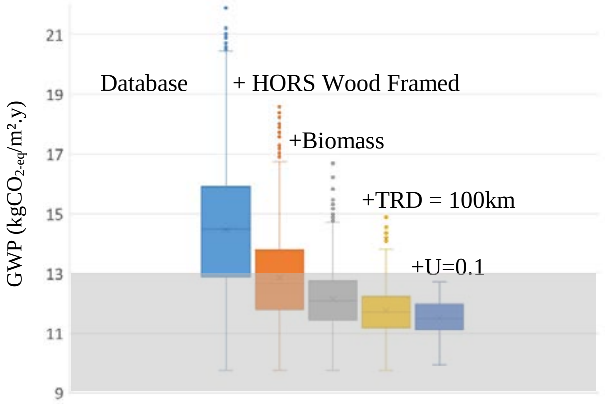

Figure 6: Distribution of the GWP impacts of the full database (left), and other subpopulations with cumulative constraints. The grey zone represents GWP impacts below the SIA2040 objective.

Thus, from a design process perspective, this finding might be very valuable as it permits to focus on the parameters having the highest *SI*, and therefore reducing the complexity induced by the building elements which are all considered in the *LCA*. This is demonstrated by dispersion when filtering the database successively by design choices in the *SI* order. For example, after four design choices only, all the remaining 124 design alternatives having a wood framed structure for the horizontal elements, a biomass boiler, a material transport from manufacturing plant to construction site of 100km, and a thermal envelope with a U value of 0.1 W/m²K, are below the *GWP* objective of the SIA2040. Also, filtering the database with only the two first design constraints delivers a subpopulation where more than 75% of the remaining design alternatives reach the SIA target.

Target cascading results

One of the key techniques of the *LCA*-based data-driven method is the target cascading. Is it complementary to the sensitivity indices as it highlights the relative environmental weight of the building elements. Indeed, a design parameter could have a low *SI*, but a high impact. Figure 7 highlights the results of this target cascading process for 18 elements and systems, divided in embodied impacts and operational *GWP* impacts.

One can notice that PV has high embodied impacts, which are not fully counterbalanced in average by the PV electricity production. Hence, in some design alternatives, the carbon content of the PV electricity production might be higher than the one from the Swiss grid. Horizontal elements have the highes t impact target, with a maximum value that can reach 6 $kgCO_{2\text{-eq}}$/m².y, that is to say almost half of the SIA target. According to the target cascading approach, it is possible to split the carbon emission responsibilities between building elements, and thus between designers that would have the responsibility of their details. As an example, thanks to Figure 7, windows might have in average an impact below 1.44 kgCO2-eq/m².y to be compliant with the SIA2040, which gives a useful threshold for the design team to benchmark windows, even if they were not included within the parametric approach. Thus, the method allows any windows to be compared with the targets of this project. Moreover, targets could be more specifically set according to a design strategy. As an example, if the target cascading process is performed on the sub-population of references having reinforced concrete for the horizontal elements and 25% of the façade with windows, the window target decreases to 1.1 kgCO2-eq/m².y.

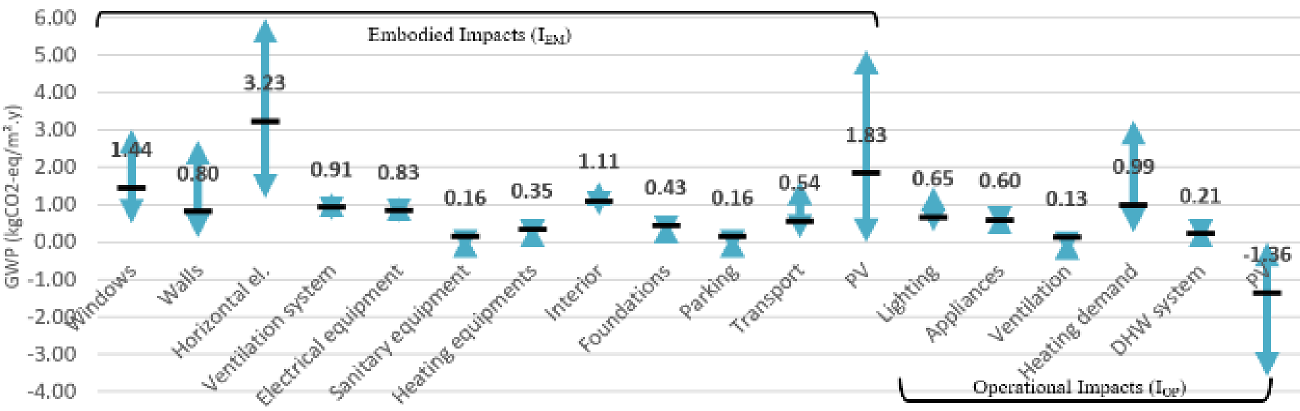

Figure 7: Minimum, Maximum (blue arrows) and target values (black numbers and dots) for the different building components

Discussion

The knowledge-database delivered by this first prototype reveals many insights that might be relevant for the designers. However, the following limits have been noticed and should be carefully taken into consideration for later developments.

First, the .csv file delivered by the prototype allows the user to customize its own data visualizations to fit with the design issues at hand. However, software platforms as Excel remain very limited when it comes to handling millions of data. Most of the graphics in this paper have been carefully chosen to be compatible with ability of Excel to support the millions of data embedded in the knowledge-database. Future development of the method could target an automation of the graphical output to be ready to use, limiting the time needed to extract and process data, and choose the proper graphical representation. Previous research carried by the authors about suitable data visualization techniques (Jusselme et al. 2017) might be very helpful to integrate a multidimensional data-exploration. Doing so, future users would be able to interact dynamically with a graphical user interface.

Second, it is hard to evaluate if the database size is large enough to fit with the designer's exploration wishes. So far, the database size was guided by the sensitivity analysis method. However, constraining the database leads very quickly to have much less alternatives to explore. As an example, filtering the database with four design constraints narrow down the available design alternatives from 20'000 to one hundred. Thus, the remaining design space is very small, while 10 parameters are still unspecified. Two solutions might tackle this issue. As previously proposed by the authors (Jusselme et al. 2018a) in the description of the method, an iterative process could lead the user towards a second database generation with a lower number of parameters, and then deeper exploration possibilities. Indeed, a first database would in that case allow to fix some parameters according to the design wishes, and remove some parameters from the parametric approach if, as a result of the first analysis, they happen to have low sensitivity indices or target values. A different approach would be to train metamodels on the knowledge-database in order quickly assess new design alternatives according to the user exploration wishes, as proposed by Duprez et al. (Duprez et al. 2019).

Third, in the chosen case study, the prototype has been used in early design phase, where several site-specific constraints were not known yet, e.g. the geotechnical context. This might have an impact on the building components' sizing (such as the structure), and change its environmental impact. In order to generalize the method, this reveals that it is important to integrate unknown constraints that might have a high environmental impact according to the literature, into the parametric approach.

Fourth, this case study confirms that the sensitivity analysis is relevant, but not sufficient. Indeed, a parameter might on the one hand have a low *SI* if the building components chosen in the parametric approach have the same impacts, and on the other hand, this parameter might have a high environmental impact. It is the case here for instance for the windows. Frame and glazing have low *SI*, but high target values. Thus, these two techniques are complementary and should be applied at the same time.

Conclusion

This paper presents a first prototype that enabled to implement the *LCA*-based data-driven design method. It demonstrates that thanks to the knowledge-database, it is possible to explore the consequences of an environmental performance threshold on the architectural and technical design strategies, at the very beginning of the design process. The method gives a high diversity of insights: the sensitivity indices of the design parameters; target values of the building components, thousands of design alternatives and their related environmental performance. It allows to provide information about life-cycle performance far beyond current practices, with a high consistency with the low resolution of details of the early design stage. Moreover, after further development including cloud computing, the computation time might dramatically decrease to an hour. Also, and a dedicated graphical user interface integrating data-visualization techniques might increase significantly the user-friendliness of the knowledge-database.

However, if this case study demonstrates the ability of the method to provide knowledge about the life-cycle performance, the methodology still has to demonstrate its usefulness and impact to a real design process thanks to practitioner's feedback. This is in fact already planned as the next step to achieve in the development of this work.

Acknowledgement

The research presented in this paper has been funded by the State of Fribourg (message du Conseil d'Etat au Grand Conseil 2014-DEE-22). The authors would like to warmly thank their colleagues within the Building2050 research group for their support and specifically Emilie Nault for her close collaboration. We also thank Urbaplan for providing the building shape used for the case study.

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