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par

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- To my sweetheart, Jennifer,

and our lovely children Chloé, Léon and Elliot. -

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Abstract

The Paris agreement on climate change called for carbon neutrality as of 2050. The built environment is one of the major contributors to the greenhouse effect, representing 39% of global emissions. As a result, this sector is targeted by green standards and regulations to set limits for building carbon emissions.

Life Cycle Assessment (LCA) is widely recognized as an appropriate method to measure these emissions. This is particularly critical at the early design stage where the decisions that most influence the project are made. However, previous studies show that current LCA methods, both time-consuming and requiring a high resolution of detail, are most inadequate, which makes them too rarely used by practitioners today.

This thesis aims to tackle this issue by proposing a novel approach to LCA adapted to the early design context. The first step was the identification of obstacles responsible for the current low use of LCA. This analysis was based on an extensive survey about the practice of 500 architects and engineers in Europe. Secondly, a literature review identified four appropriate techniques to overcome these obstacles: parametric assessment, sensitivity analysis, target cascading and data visualization. Combining them to the LCA led us to the data-driven method for low-carbon building design at early stages we adopted in this thesis, removing the need to set premature assumptions about future design developments.

The method proposes a knowledge-database of design alternatives generated with a parametric approach that applies a combination of user-defined design options, using the Saltelli sampling technique, to a project-specific massing scheme. Later, the carbon emissions of each of these design alternatives are calculated. It is thus possible to explore thousands of alternatives and understand the consequences of architectural choices on the carbon emissions by using data visualization techniques. Moreover, the method proposes Sobol sensitivity indices quantifying the design parameter influence on the carbon emissions, in order to limit the scope of building components that designers should prioritize. Finally, the method specifies carbon budgets, the upper limit of carbon emissions a building component should not exceed, with the possibility to compare this budget with any product available on the market that would not have been included upfront as a design option in the parametric approach.

To assess the usability of the method, a computer-based prototype was thereafter developed to get it tested in the frame of a real design project. By taking advantage of the architectural competition for the Smart Living Lab in Fribourg, Switzerland, this critical testing phase was carried out by asking the practitioners involved to actually use the developed prototype to meet the SIA2040 carbon objectives set for the project.

This thesis proposes a new method for effectively integrating GHG emission targets into the early stages of the design process with the aim to increase both acceptance and use of LCA in the design field, but also to inspire developers towards a new generation of LCA software.

Keywords: Life Cycle Assessment, design support, parametric assessment, sensitivity analysis, target cascading, data visualization, usability

Résumé

L'accord de Paris sur le changement climatique exige une neutralité carbone dès 2050. Par ailleurs, l'environnement bâti est l'un des principaux contributeurs à l'effet de serre, représentant 39 % des émissions mondiales. C'est pourquoi ce secteur est particulièrement visé par la législation et les normes environnementales pour fixer des limites aux émissions de carbone des bâtiments.

L'analyse du cycle de vie (ACV) est largement reconnue comme une méthode de référence pour mesurer ces émissions. Elle est primordiale au début de la conception, où les décisions influencent le plus la performance d'un bâtiment. Cependant, de précédents travaux montrent que les méthodes d'ACV actuelles y sont inadéquates car chronophages et exigeant une haute résolution de détails. Elles sont ainsi trop rarement utilisées dans la pratique aujourd'hui.

En conséquence, cette thèse propose une nouvelle approche de l'ACV, adaptée au contexte amont de la conception. La première étape a consisté à identifier les obstacles responsables de sa faible utilisation. Cette analyse s'est appuyée sur une enquête auprès de 500 architectes et ingénieurs en Europe. Ensuite, une revue de la littérature a identifié quatre techniques appropriées pour surmonter ces obstacles : l'évaluation paramétrique, l'analyse de sensibilité, la mise en cascade des cibles et la visualisation des données. La combinaison de ces techniques à l'ACV nous a conduit à proposer une méthode pilotée par les données pour la conception de bâtiments à faibles émissions de carbone, éliminant ainsi la nécessité de poser des hypothèses prématurées sur les futurs détails de conception.

La méthode propose une base de données de connaissances d'alternatives de conception générée par une approche paramétrique qui applique une combinaison d'options de conception définies par l'usager, à l'aide de la technique d'échantillonnage de Saltelli, à une volumétrie de projet spécifique. Par la suite, les émissions de carbone de chacune de ces options de conception est calculée. Il est ainsi possible d'explorer des milliers d'alternatives et de comprendre les conséquences des choix architecturaux sur ces émissions en utilisant des techniques de visualisation de données. La méthode calcule des indices de sensibilité de Sobol quantifiant l'influence des paramètres de conception sur les émissions carbone, permettant aux concepteurs de prioriser les éléments de construction à prendre en considération. Enfin, elle propose des budgets carbones, soit la limite supérieure des émissions qu'un élément de construction ne doit pas dépasser, avec la possibilité de comparer ce budget avec tout produit disponible sur le marché qui n'aurait pas été inclus initialement dans l'approche paramétrique.

Afin d'évaluer l'utilisabilité de la méthode, un prototype informatique a été mis au point et testé dans le cadre réel d'un projet. Cette phase de test critique a été réalisée en demandant aux praticiens impliqués dans le concours d'architecture pour le Smart Living Lab à Fribourg, en Suisse, d'utiliser le prototype développé pour atteindre les cibles GES de la norme SIA2040.

Cette thèse propose une nouvelle méthode pour intégrer efficacement les objectifs d'émissions de GES dans les premières étapes du processus de conception, pour augmenter à la fois l'acceptation et l'utilisation de l'ACV dans le domaine de la conception, mais aussi pour inspirer les développeurs vers une nouvelle génération de logiciels d'ACV.

Mots clés : Analyse de Cycle de Vie, aide à la conception, évaluation paramétrique, analyse de sensibilité, objectifs en cascade, visualisation des données, utilisabilité

Contents

List of acronyms

AEC	Architecture, Engineering, and Construction
ANN	Artificial Neural Network
BEPS	Building Energy Performance Simulation
BIM	Building Information Modelling
BOQ	Bill Of Quantities
CED	Cumulative Energy Demand
CEDnr	Cumulative Energy Demand
CEN	non-renewable part of the CED
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
COVF	Floor covering
COVW	External wall covering
CPU	Central Processing Unit
DHW	Domestic Hot Water
DVT	Data Visualization Techniques
EU	European Union
FRA	Windows Frame
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GLAZ	Glazing
GUI	Graphical User Interface
GWP	Global Warming Potential
HCI	Human-Computer Interaction
HEAT	Heating system
HORS	Horizontal elements
HVAC	Heating, Ventilation and Air-Conditioning
IDP	Integrated Design Process

IEA	International Energy Agency
INS	Insulation material
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LB	Lifetime of the Building
LCA	Life Cycle Assessment
LCP	Life Cycle Performance
LCPA	Life Cycle Performance Assessment
LIGHT	Lighting power
LM	Lifetime of the component or system
LOD	Level Of Detail
PCP	Parallel Coordinate Plot
POP	Population
PVF	Photovoltaïc panels on the façade
PVR	Photovoltaïc panels on the roof
R&D	Research and Development
RIBA	Royal Institute of British Architects
SAM	Self-Assessment Manikin
SIA	Society of Engineers and Architects
SUS	System Usability Scale
TOE	Ton Oil Equivalent
TRPT	Transportation of building materials
UCD	User-Centered Design
UK	United Kingdom
UN	United Nations
US	United States
UT	User Testing
VERT	Vertical elements
WWR	Window to Wall Ratio

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Chapter 1 Introduction

1.1 Buildings and sustainability

In November 2015, 174 countries signed an agreement to plan a drastic reduction in Greenhouse Gas emissions (*GHG*) at the UN Conference on Climate Change in Paris. The built environment is a major *GHG* emission contributor and becomes a natural target in terms of mitigation potential worldwide. As a result, buildings have to integrate life cycle performance objectives from the earliest stage of their design process.

To introduce this context, we will discuss the role of the building sector when it comes to climate change, starting from a global view then zooming in to reach the Swiss scale. We will have a closer look at Life Cycle Assessment (LCA) methods, i.e. at ways to measure a building's carbon emissions and explore some fundamental aspects about the design process before exposing the motivations behind this research and the resulting thesis structure.

1.1.1 The global climate change context

According to the Intergovernmental Panel on Climate Change (IPCC, 2018), if we want to limit global warming to 1.5°C, the residual carbon budget is no more than 420 Gt CO_2, while the current emissions are around 42 Gt CO_2 per year. At this rate, we will have exhausted our carbon budget in 10 years: with this in mind, one can better understand why environmental activists call for declaring a state of climate emergency. The same IPCC report also states why limiting warming to 1.5°C implies reaching net-zero CO_2 emissions globally around 2050. Hence, the climate change issue is first and foremost a matter of carbon emission assessment.

Yoichi Kaya, a Japanese energy economist, proposed an intriguing way to express the different factors that lead to these CO_2 emissions through what is known as the Kaya identity (Kaya, 1989). This identity stands as follows:

$$CO_2 = POP * \frac{GDP}{POP} * \frac{TOE}{GDP} * \frac{CO_2}{TOE}$$

Equation 1: The Kaya Identity

Where:

CO_2: global CO_2 man-made emissions
POP: global population
GDP: global Gross Domestic Product
TOE: world consumption of primary energy (abbreviation of Ton Oil Equivalent)

This identity explicitly shows that CO_2 emissions are directly related to the global population, whose increase typically results in a growth of the GDP $(\frac{GDP}{POP})$. Energy consumption $(\frac{TOE}{GDP})$ associated with that GDP will lead to new CO_2 $(\frac{CO_2}{TOE})$ emissions. In other words, the identity splits the very definition of CO_2 emissions into its individual drivers.

Since 1965, GDP, TOE, CO2 and POP increased dramatically, as it can be observed in Figure 1. Regarding the main drivers of the Kaya identity, Figure 2 highlights that since 1965, while the carbon content of the energy $(\frac{CO_2}{TOE})$ decreases by 10% (factor 0.9) and energy consumption per GDP $(\frac{TOE}{GDP})$ decreases by 30% (factor 0.7), the GDP per capita $(\frac{GDP}{POP})$ increases by 127% (factor 2.3). As a result, the multiplication of all these factors according to the Kaya identity leads to an increase of the CO_2 emissions per capita by a factor of 1.45. As a result, the energy efficiency of the world industry and the decarbonization of the energy consumption progress too slowly compared to the GDP.

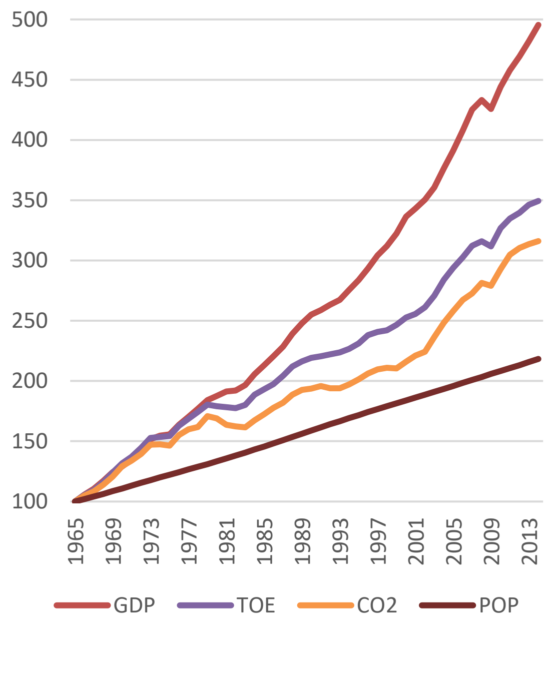

Figure 1: Trends of global Gross Domestic Product (GDP constant 2010 US$), Ton Oil Equivalent consumption (TOE), CO_2 emissions (CO2) and population (POP). Values in 1965 equal 100. Based on (British Petroleum, 2019; The World Bank, 2019)

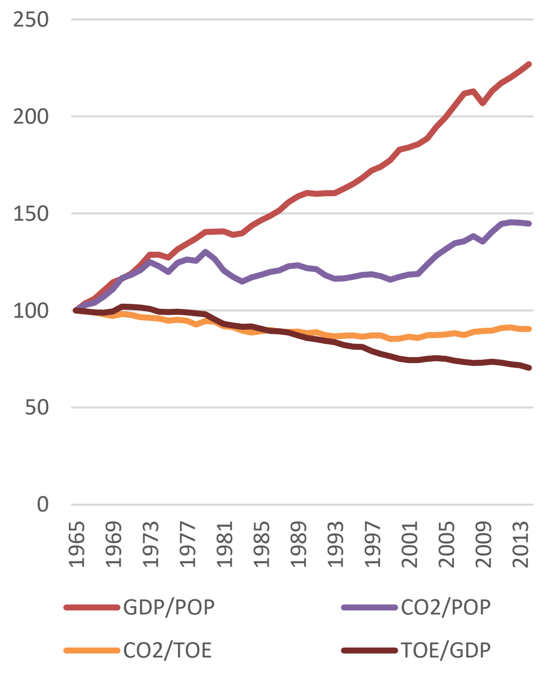

Figure 2: Trends of the Kaya identity drivers. Gross Domestic Product (GDP constant 2010 US$), Ton Oil Equivalent consumption (TOE), CO_2 emissions (CO2) and population (POP). Values in 1965 equal 100. Based on (British Petroleum, 2019; The World Bank, 2019)

Anticipating future trends for these drivers tends to reinforce a pessimistic vision of how climate change might evolve:

- Due to emerging countries, the world GDP is expected to double (+100%) until 2050 (Ward, 2011),
- The global population is likely to increase by +26% before 2050 and reach a median scenario of 9.7 billion compared to the present 7.7 billion (United Nations et al., 2019).

If we assume these previsions remain valid for our society in the next decades, the only available drivers that could lead us to carbon neutrality by the 2050 horizon would be dramatic increases in energy efficiency within the world industry combined with massive decarbonization of energy use.

Zooming in on the building sector, we shall remember that in 2017, it represented 36% of the final energy use and 39% of energy-related carbon dioxide (CO_2) emissions (IEA and UNEP, 2018). Figure 3 gives an overview of the energy consumption of the residential sector (Lucon et al., 2014) in case of a frozen scenario i.e. assuming energy efficiency of buildings does not significantly improve. The combination of an increasing number of households, coupled with the fact that the number of people per household keeps getting smaller, leads to a bigger built surface per person and consequently to higher energy consumption in 2050 (factor 1.8). Similarly, the GDP exponential growth will make energy consumption of commercial buildings double by then (Lucon et al., 2014).

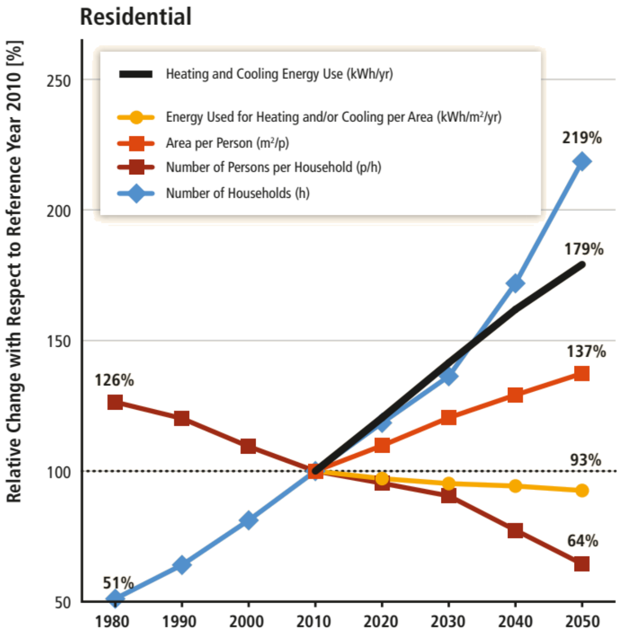

Figure 3: Trends in the different drivers for global heating and cooling thermal energy consumption in residential and commercial buildings. Source: (Lucon et al., 2014).

These different trends emphasize the gap between current forecasts and the carbon neutrality objectives that were set at the 2050 horizon. This situation calls for an urgent and radical shift towards a new way of life, supported by a highly efficient industry that includes the building sector, and powered by very low carbon energy.

1.1.2 The Swiss building context

By extension, it is possible to adapt the Kaya identity to the Swiss building context. Equation 2 highlights the main drivers that lead to CO_2 emissions.

$$CO_2 = POP * \frac{ERA}{POP} * \frac{TOE}{ERA} * \frac{CO_2}{TOE}$$

Equation 2: The Kaya Identity applied to the Swiss building context

Where:

CO_2: Swiss CO_2 emissions

POP: Swiss population

ERA: Swiss building Energy Reference Area

TOE: Swiss consumption of primary energy (abbreviation of Ton Oil Equivalent)

The energy reference area (ERA) is defined in the SIA standard 416/1 as the sum of all floor area of below-ground and above-ground spaces, included within the thermal envelope, that require heating or air conditioning for their use.

Here, one can understand that CO_2 emissions are influenced by the Swiss population, whose increase typically results in a growth of ERA ($\frac{ERA}{POP}$). This ERA influence energy consumption ($\frac{TOE}{ERA}$) that will finally emit some CO_2 ($\frac{CO_2}{TOE}$).

Since 1990, ERA and POP increased significantly, respectively by +23% and +41%. TOE is fluctuating but increased by only 4%, unlike CO2 which decreased by (-)10% as can be observed in Figure 4. Regarding the main drivers of the Kaya identity, Figure 5 highlights that since 1990, the carbon content of energy ($\frac{CO_2}{TOE}$) decreased by 14% (factor 0.86) while energy consumption per ERA ($\frac{TOE}{ERA}$) decreased by 26% (factor 0.74), but also that the ERA per capita ($\frac{ERA}{POP}$) increased by 14% (factor 1.14). As a result, the multiplication of all these factors according to the Kaya identity leads to an overall decrease in CO_2 emissions per capita, by a factor of 0.73 (-28%). Which means that in Switzerland, advances regarding energy efficiency within the building industry together with a decarbonization of the energy used end up progressing faster than built surfaces' expansion. However, we are still a long way from reaching the Swiss 2050 objectives through, as described in the following section.

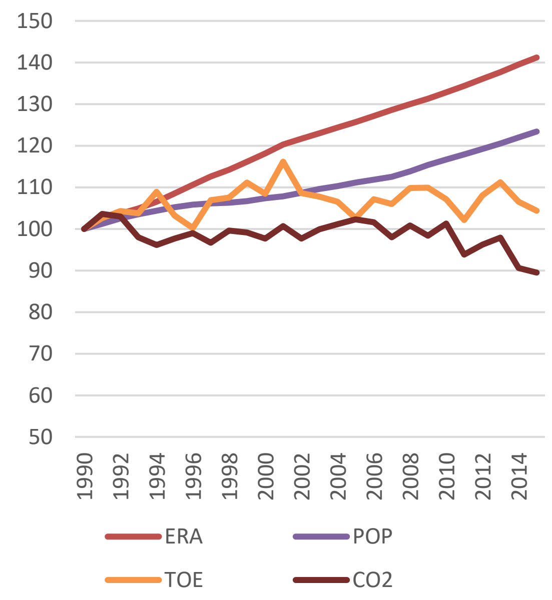

Figure 4: Trends of Swiss building Energy Reference Area (ERA), population (POP), Ton Oil Equivalent consumption (TOE) and CO_2 emissions (CO2). Values in 1990 equal 100. Based on (British Petroleum, 2019; OFEV, 2017)

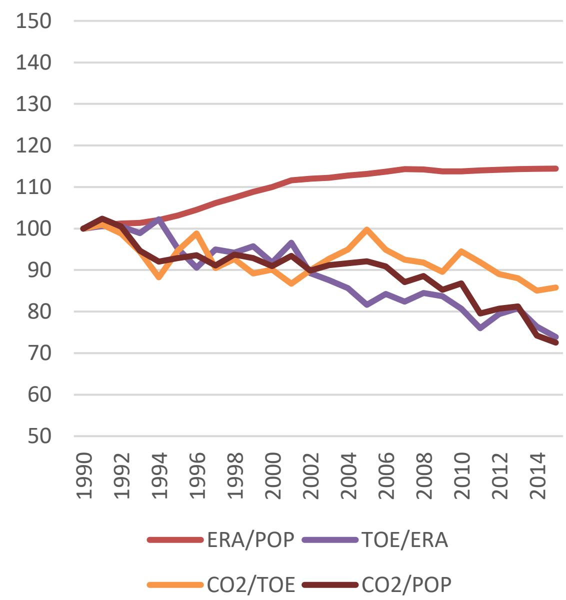

Figure 5: Trends of the Kaya identity drivers for the Swiss building context. Energy Reference Area (ERA), Ton Oil Equivalent consumption (TOE), CO_2 emissions (CO2) and population (POP). Values in 1990 equal 100. Based on (British Petroleum, 2019; OFEV, 2017)

1.1.3 The Swiss 2050 energy strategy

On May 25th, 2011, after the Fukushima disaster, the Federal Council decided to phase-out nuclear power by 2034. Since then, the Confederation has implemented a new strategy looking out to 2050, that includes a "*New energy policy*" and more specifically the energy act adopted by the federal council on September 4th, 2013. This policy sets the following objectives: "[…] *energy-related CO_2 emissions in Switzerland will range between 1 to 1.5 ton per inhabitant in 2050"* (Conseil Fédéral, 2012). This threshold is actually based on the 2000-Watts society vision, first developed at ETH Zurich (Jochem et al., 2004). It is founded on sustainable use of energy resources and aspires to equitable use of the world's raw materials. According to this vision, each citizen should have his/her environmental impact reduced to 2000 Watts of Cumulative Energy Demand (CED), 500 Watts of non-renewable CED (CEDnr) and 1 t CO_2-eq for the Global Warming Potential (GWP) at the 2100 horizon. The 2000-Watts society vision actually also sets mid-term objectives for 2050, as shown in Figure 6.

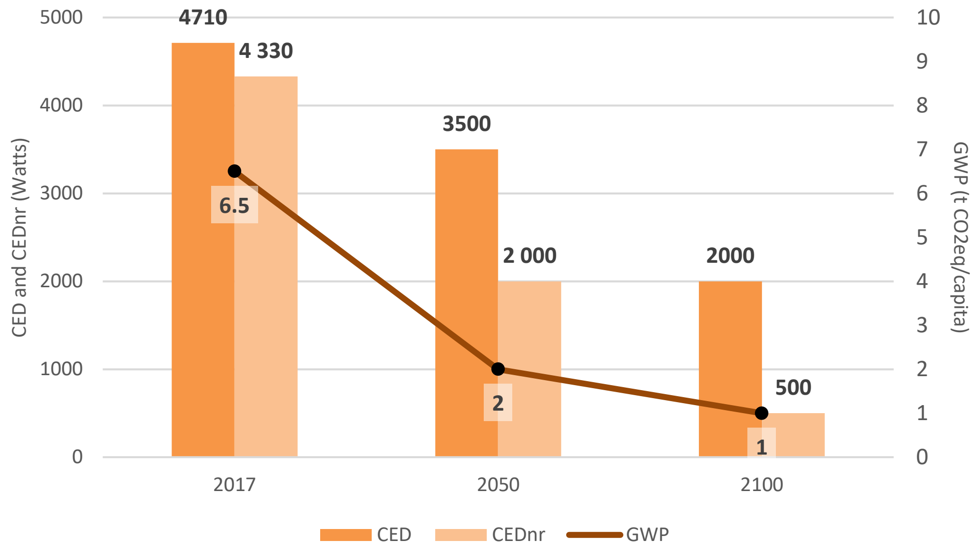

Figure 6: The 2000-Watts society objectives, and the current situation. Cumulative Energy Demand (CED), non-renewable CED (CEDnr) and Global Warming Potential (GWP). Based on (SuisseEnergie, 2018)

The 2050 objective of 2 tons CO_2-eq per capita is very challenging. According to the word bank open data, 82 countries among 175 are currently below this threshold, but only two of them (Liechtenstein and Uruguay) reach a Human Development Index (HDI) above 0.8 (see the green zone of Figure 7).

Between CED, CEDnr and GWP, GWP seems the most difficult to achieve, according to Notter, Meyer and Althaus (Notter et al., 2013). In that study, different analyses were carried out to characterize the environmental and energy impact of a sample of 3'369 Swiss inhabitants in a « bottom-up » approach. They concluded that 10% of the sample are already living below the 2000W threshold. In contrast, no one's carbon emissions are below the 1t CO_2-eq threshold yet.

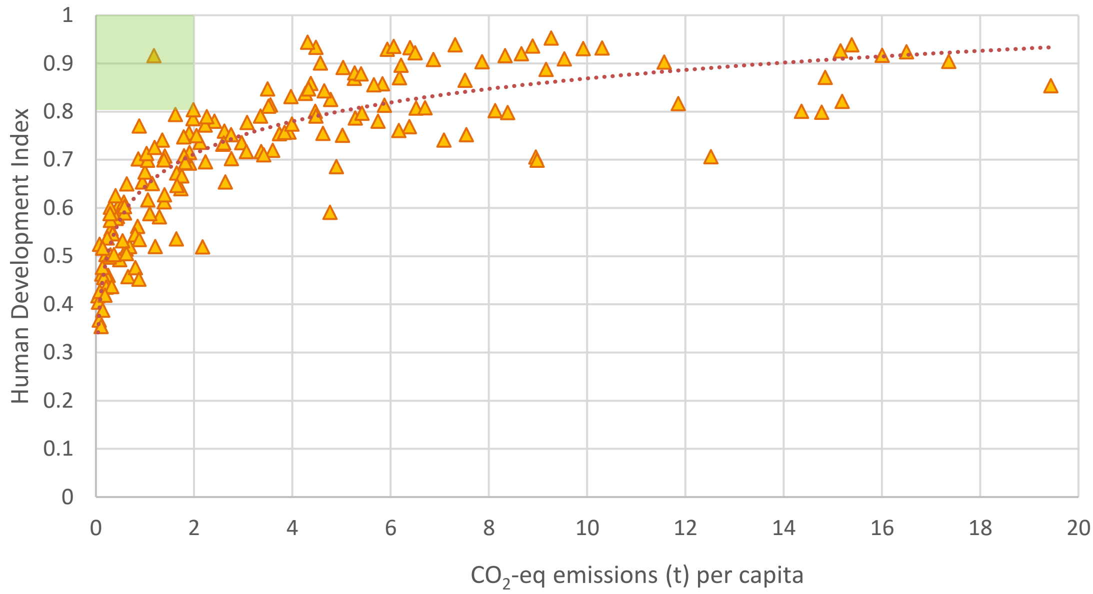

Figure 7: Evolution of CO_2-eq emissions per capita (2014) in relation to the human development index (2017) according to 175 countries. The dashed represents the logarithmic trend line. Based on (The World Bank, 2019)

1.1.4 The SIA 2040 norm

Supporting this 2050 energy strategy, different norms have been developed. Among them, the Swiss society of engineers and architects (SIA - société des ingénieurs et achitectes) proposes target values for the building life cycle in a norm, referenced as SIA 2040 (SIA, 2017a). This norm splits the 2000W objectives into different energy usages, separating dwellings from offices, schools, restaurants etc.

Table 1: SIA 2040 objectives for office buildings. Source: (SIA, 2017a)

	CEDnr (kWh/m².y)		**GHG (kg CO_2-eq/m².y)**	
	New buildings	Refurbishment	New buildings	Refurbishment
Construction target	40	20	9	6
Operation target	80	100	4	6
Mobility target	40	40	7	7
Overall Target	160		20	19
Sub-Target (construction + operation)	120		13	12

Table 1 lists the SIA targets for new office buildings, with an overall objective of 20 kg CO_2-eq/m².y, and a sub-target of 13 kg CO_2-eq/m².y for construction and operation. The mobility is calculated thanks to the SIA 2039 (Hänger and Schneider, 2011), which estimates the GHG emissions of the building users. According to the building location, it estimates everyday mobility based on the travel distance per capita and a split between the different transportation modes. One can note that operation targets for refurbishment are larger than the one for new buildings, while the construction target balance these differences such as the overall target are almost the same between new buildings and refurbishment. In other words, the norm considers that new constructions have higher construction impacts that could be balanced by higher operating performance. Finally, the impact of construction is expressed through the grey energy and carbon emissions according to the SIA 2032 (SIA 2032, 2010). According to the SIA 2040, "Construction target" embrace larger boundaries that construction itself, and includes also any replacement investments and the disposal of a building.

Then, by bringing these three norms together (SIA 2040, 2039, 2032), a quite clear framework is made available to anyone interested to conduct a life cycle assessment with a scope that embraces construction, operation, and mobility. As the specifics of an LCA are fundamental in how CO_2-eq emissions are actually accounted for, the next section will dive into more details about this method and its origins.

1.2 About Life Cycle Assessment

1.2.1 History of LCA

During the 1960s, various companies in the industrial sector started to worry about solid waste reduction for beverage containers. The first known Life Cycle Performance Assessment[1] (*LCPA*) was performed by Harry E. Teasly, Jr. in 1969 for The Coca-Cola Company (Hunt and Franklin, 1996) under the term "Resource and Environmental Profile Analysis" (REPA). The term REPA was thus used from 1970 to 1990, to be replaced afterwards with the denomination Life Cycle Assessment (*LCA)*. Thanks to the "Brundtland report" (Brundtland et al., 1987) and to the Intergovernmental Panel on Climate Change (1988), sustainability issues became a worldwide concern, which highlighted the construction industry as one of the main contributors in negatively impacting the environment. Since awareness was raised to this issue, more and more *LCA* were performed from the 1990s onwards and ultimately became a proper engineering and research field. With the ISO 14040-43 (1997-2000) norm, Life Cycle Assessment methods became standardized, allowing the method to be disseminated more broadly.

Nowadays, Life Cycle Performance (*LCP*) targets typically integrate most of the green building certification systems (e.g. LEED, BREEAM, HQE) and are about to be mandatory or well supported by governments in selected countries like France, Belgium, Finland, Netherlands, Norway, Sweden… to follow up on a decision of the European Union in 2010 to target a near Zero Energy Building standard for all its new buildings (EU - EPBD, 2010). With such an energy performance level, thinking in terms of life cycle becomes almost unavoidable as most of a building's energy impact will be shifted from its use phase to other phases of its life cycle, i.e. building material production phase, construction phase and end of life phase. Encouraged by these new political orientations, the research community has put in more and more effort to develop methodologies and tools able to increase the robustness and usability *of LCPA*. Developments of note include applicability to building refurbishments (Nicolae and George-Vlad, 2015), to prefabricated buildings (Bonamente and Cotana, 2015), extension to urban scale assessments (Drouilles et al., 2018) or to existing building stocks (Zhang and Wang, 2015), and new certification systems (Roh et al., 2016), to name a few.

1.2.2 LCA methods and tools

The norm ISO 14040-43 (1997-2000) standardized the methodology of life cycle assessments, allowing the method to be disseminated more broadly with a given sequence of four major steps: defining the goal and scope, creating the life cycle inventory, assessing the impact and interpreting the results (ISO, 2006). In addition to this norm, the European Commission released the Product Environmental Emissions (PEF) method, aiming at providing a common framework for evaluating the environmental performance of products (Manfredi et al., 2012).

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[1] In this thesis, we will use the "Life Cycle Performance Assessment" terms to refer to any of the techniques or methods that aimed at measuring the life cycle impacts of a building, to make the distinction with the "Life Cycle Assessment", which is a specific method described by the ISO 14040 norm.

Specifically for the construction sector, EN 15804 proposes a structure for Environmental Product Declarations (EPDs), making the information about building product transparent and comparable (EN 15804, 2012). The norm EN 15978 focuses on the calculation method to assess the environmental performance of a building, based on life cycle assessment (CEN/TC 350, 2011). In Switzerland, the SIA 2032 norm recommends the use of the KBOB life cycle inventory database (SIA, 2010), in full compliance with EN 15804 on the level of inventory analysis, but with a different set of environmental indicators.

However, environmental assessment tools for buildings are not always based on the LCA method and various alternatives have been developed to assess a building's life cycle performance. According to Haapio and Viitaniemi and based on the IEA Annex 31 project "Energy-related environmental impact of buildings" (Haapio and Viitaniemi, 2008), assessment tools can be classified into five categories:

a) Energy Modelling software (e.g. energy plus (EnergyPlus, 2019), Trnsys (TRNSYS, 2019), etc.);
b) Environmental *LCA* Tools for Buildings (e.g. Elodie (CSTB, 2019), eTooL (eTool, 2019), etc.);
c) Environmental Assessment Frameworks and Rating Systems (e.g. BREEAM, LEED, etc.);
d) Environmental Guidelines or Checklists;
e) Environmental Product Declarations, Catalogues, Certifications and Labels.

Among them, one can distinguish "active" tools, which include software that requests the user to calculate and evaluate different scenarios (a and b), and that delivers a quantitative assessment, from "passive" tools (c, d and e): the latter are tools that do not interact with the user but support design decisions with straightforward and qualitative recommendations.

It is commonly accepted that *LCA* tools (b) are the most comprehensive and holistic to support design decision making (Saunders et al., 2013; Sibiude et al., 2014).

Building research helps to improve *LCA* methods year after year, but many challenges still need to be addressed. Based on current literature (Anand and Amor, 2017; Attia et al., 2012c; Bonnet et al., 2014; Malmqvist et al., 2011; Marsh, 2016), the following limitations, relevant with the scope of this research, can be highlighted as prevalent issues to address in the LCA domain:

- Building life cycle assessments are time-consuming;
- They need a high resolution of detail, unavailable at early design stages;
- Boundaries and scopes are specific; results are non-reproducible;
- The service life of a building is not reliable;
- Due to the high number of components, the data collection leads to high uncertainties.

Research efforts aiming at solving the time-consuming and resolution of detail issues often lead to simplifying the *LCA* method (Bonnet et al., 2014; Kellenberger and Althaus, 2009; Lasvaux, 2010; Malmqvist et al., 2011; Moncaster and Symons, 2013). However, these solutions also decrease the design guidance, and typically do not place enough emphasis on design alternatives: as the early design process tends to rely on a particularly iterative path, it usually involves numerous pairwise comparisons between design alternatives. The ability to explore such alternatives from the standpoint of *GHG* emissions early on thus seems crucial to implement *GHG* emission targets effectively in a design process. In its early stages, comparisons and benchmarking through alternatives were indeed shown to be more promising than absolute value evaluations (Attia et al., 2012a; Flager and Haymaker, 2009; Miyamoto et al., 2015; Østergard et al., 2017; Ritter et al., 2015).

1.3 About the design process

1.3.1 Integrated design

The theoretical Integrated Design Process (IDP) was developed to integrate performance targets into a building's conceptual and design development. This process is by nature iterative and – in an ideal scenario – brings together all the relevant actors from the construction industry to work collaboratively from the beginning of a project. It was indeed recognized that integrating knowledge into the design process as early as possible allowed for greater efficiency (MacLeamy, 2004), as illustrated in Figure 8.

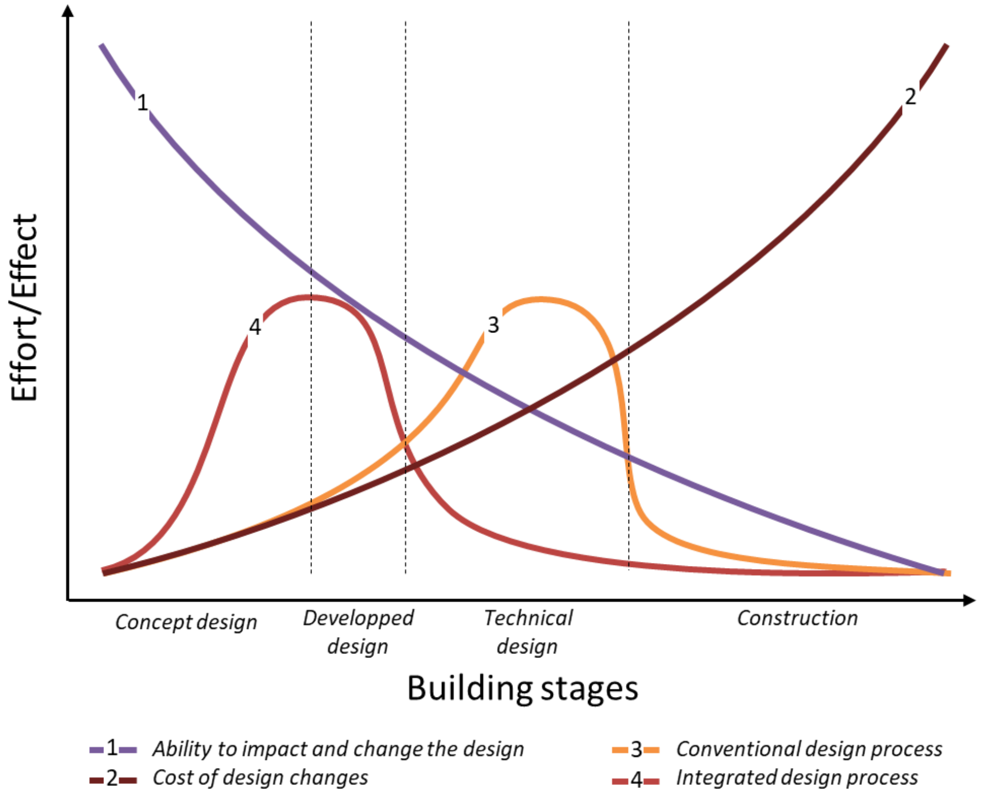


Figure 8: Shifting efforts earlier for an integrated design process. Adapted from (MacLeamy, 2004; Sinclair, 2013)

In this figure, one can note that early design allows the highest ability to impact and change the design, while the cost of these changes remains very low. As a result, switching from a conventional design process – one that maximizes the efforts during the technical design – to an integrated design - with highest efforts in the conceptual and developed design stages – seems to be most beneficial to both reduce effort (thus cost) and increase (positive) effect.

According to Larsson (Larsson, 2004), the theoretical framework of the IDP includes some key components:

- an interdisciplinary approach among design stakeholders right from the beginning of the design process,
- a clear understanding and definition between client and designers of the different performance metrics the building will have to reach,
- at least one specialist in the field of Building Energy Performance Simulation (BEPS),
- an iterative design that includes various design alternatives and resorts to the use of energy simulations to provide quantitative information about their performance.

In other words, the key issue of the IDP lies in using BEPS as a decision-making tool for architects and engineers to convert performance outcomes (based on relevant metrics) into design solutions at early design stages. Therefore, broadening this conclusion to LCA simulation tools calls for a better understanding of the phases typically taking place in an architectural design process, to better integrate GHG mitigation objectives. Also, the potential application of this IDP will be later evaluated thanks to section 2.6.

1.3.2 The role of references within the design process

The design process is a research field itself, and this section does not pretend to cover an exhaustive state of the art of this area. However, it is of major importance to better understand the mechanisms that lead designers to transform a problem – i.e. the building specifications -, into a solution – i.e. the building design-. Among researchers that offered important contributions to theorizing the architectural design process, one can find Conan, Farel and Prost starting from the 1990s (Conan, 1990; Farel, 1991; Prost, 1992). Their work has also been used as references in more recent research contributions to better define a systemic model of the design process (Claeys, 2013; Gallas, 2013), or the role of architectural references within the design process (Kacher, 2005). In his book "*Conception architecturale: une investigation méthodologique*", Robert Prost notably points out that architecture should be considered as a process that produces knowledge and not just objects, and elegantly frames it into (a) problem formulation versus (b) solution formulation processes.

In what he calls (a) "problem formulation" processes, building specifications are described by "utilities" in the form of functions and spaces, in a descriptive and prescriptive way for future designers. The author points out the increasing complexity of the programs, supported by the increasing comfort requirements and the relationship to the technological progress of our society. The weight of these technical components anchors the architectural discipline on multiple rationalities and introduces a notion of performance. Among several methodological issues, one refers to the degree of novelty of a statement. Indeed, this notion of novelty prevents any empirical reference and therefore the reproduction of programmatic reasoning and places designers in a situation of innovation. Another methodological issue is the degree of operationality of a statement. On this point, the limitation of the architectural project to quantitative specifications is reductive and cannot replace a dynamic dialogue between problem formulation and solution formulation for a transformation "from words to things".

On the other hand, in what he calls "solution formulation" processes, the author points out that the transition from problem statement to solutions is largely obscure and can be assimilated to a black box, as shown in Figure 9. However, it can be assumed that this shift is not linear and is based on references that give substance to the solution. These references are of two kinds, based on the problem and its context or on the architecture as a problem. There is then a reflexive dynamic between these two types of references to make the transition from problem to solution. It should be noted that the author has a methodological approach that allows him to place the reference as a tool used by the designers but does not claim to explain how it guides the solution formulation process.

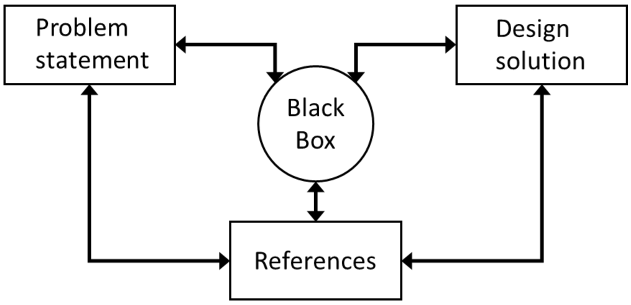


Figure 9: The iterative design process between problem statement, design solutions and references according to Robert Prost. Source: (Prost, 1992)

The author identifies architecture-specific references as a "system of thought". These references are made up of works, starting with one's own if one seeks continuity in one's approach or those of other authors. The references, therefore, constitute "fragments juxtaposed by mental collage" which at the same time make it possible to situate the work being created within the architectural discipline and at the same time to distinguish oneself from it in order to legitimize the work and its author.

In synthesis, according to Prost, references are at the core of the design process but start to be limited when it comes to an innovative statement, which is the case for the scope of our research as the climate change is a recent issue. He also argues there will always be a qualitative part into the statement, inducing a dynamic dialogue between problem formulation and solution formulation, i.e an iterative design.

1.4 Research motivations and thesis structure

1.4.1 Research motivations

The previous sections of this introduction highlight four key points when it comes to integrating life cycle performance objectives into the design process. First, as discussed in section 1.1, the carbon budget at the building level is a result of a top-down approach, from international agreements on climate change to the building scale. Key contributors to climate change (e.g. population, building surface) force other drivers to become extremely effective (e.g. energy efficiency, decarbonization of energy consumption). Second, life cycle performance is assessed thanks to the LCA methodology, which is time-consuming and needs a high resolution of detail (cf. section 1.2). Third, according to an idealistic integrated design process, the life cycle performance objectives should be introduced as early as possible into a building project, where the effort to effect ratio is the highest (cf. section 1.3). Finally, thanks to previous studies that theorized the design process, we learn that it is an iterative process between problem statements and design solutions. These iterations might be facilitated thanks to references to the architectural corpus or to the building context (cf. section 1.3).

Looking at these four key points lead us to consider that *LCA* at the early design stage is of crucial importance. However, there is a mismatch between the low resolution of details of the early design stage, and the large data collection required to perform an LCA. Thus, we are particularly interested in a double issue behind this mismatch. On the one hand, designers who want to be supported by LCA at early design have to detail a project that does not exist yet, which forces them to set **design hypotheses**. On the other hand, the description of this **hypothetical project is time-consuming** and leads to **high uncertainties** in LCA calculation.

Previous research tackled the time-consuming issue by simplifying the method with predefined inputs, which unfortunately leads to a decrease in the design guidance of the LCA, as part of the results do not reflect the state of the project. Thus, **a first research motivation lies in the resolution of the time-consuming issue without decreasing the design guidance potential**.

We also believe that this guidance potential might be enhanced thanks to a better understanding of the fundamentals of the design process that places references at the centre of iterations (Figure 9) between problem statement and design solutions. Therefore, references could be used to facilitate the transformation of life cycle performance objectives into architectural and technical solutions. References to low-carbon buildings being still very few, **our second research motivation lies in the generation of new and specific references** (later considered as design alternatives), that would support the iterative design process.

1.4.2 Research topics

Our main research objective can be summarized as the ability to answer a single question: "How can the usability of Life Cycle Assessment at the early design stage be improved, in terms of both time-efficiency and design support?" To this end, a new methodology will have to be developed, specifically addressing three adjacent topics:

1. The issues engineers and architects have to face when it comes to assessing the life cycle performance in the early design phase.
2. The techniques that seem most promising to address these issues, given the iterative nature of the design process and its reliance on references.
3. The limited-time available and the low-resolution details at early design stages to support a decision-making process with LCA calculations.

1.4.3 Thesis structure

In this thesis, the structure adopted to answer the previous questions is made of the six following chapters.

Chapter 2 aims at identifying LCA practices at the early stage. To that end, user-centered techniques are used to identify the main obstacles engineers and architects are facing. These obstacles will have to be later overcome by the LCA-based method to be developed.

Thanks to **chapter 3**, the research gap is clarified, and the most promising techniques that would be interesting to integrate into the future LCA-based method are identified. Hence, the theoretical need for a new approach is framed.

In **chapter 4**, a combination of promising techniques, which lead us towards an LCA-based data-driven method in order to handle obstacles identified in chapter 2. The theoretical framework of this new method is proposed and detailed step by step.

A first computer-based prototype is implemented and presented in **chapter 5**. The whole workflow is detailed, from the algorithms to the graphical user interface. The architectural competition for a low carbon building aiming to reach the SIA2040 objectives- namely the future building of the smart living lab – is used as the case study.

Chapter 6 is dedicated to the usability assessment of the prototype. First, a method is proposed as building performance usability has not been really investigated so far. Then, a mixed-method using quantitative and qualitative approaches is applied to collect feedback from practitioners. This knowledge is discussed and synthetized into strengths and weaknesses.

We conclude the thesis in **chapter 7** by summering the main research findings. A discussion about prospective improvements is also proposed. Finally, the application potential of the method is discussed.

Chapter 2 Identifying the practice context

Disclaimer: Parts of this chapter are adapted from the following articles – with permissions of all co-authors and journals:

Jusselme, T., Rey, E., & Andersen, M., 2018. Findings from a survey on the current use of life cycle assessment in building design. 1, 138–143. Hong-Kong: PLEA 2018. My contribution: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Co-Writing – original draft

Jusselme, T., Rey, E., & Andersen, M., 2018. Surveying the environmental life cycle performance assessments: Practice and context at early building design stages. Sustainable Cities and Society 52, 101879. https://doi.org/10.1016/j.scs.2019.101879. My contribution: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Co-Writing – original draft

In the introduction, we presented our research motivation to increase the LCA usability at early design stages. To tackle this challenge, this chapter will first focus on the usability concept coming from the User-Centered Design research field. We will then understand that the first step of user-centered design is the specification of the context of use of the method we want to develop. Accordingly, this chapter aimed at describing the practice-context in which life cycle performance assessment is used. The objective is to better understand the profile, needs and requirements of potential users of *LCPA* tools and methods as a first step towards a UCD approach. The work has been conducted in three successive steps. First, we conduct a literature review on current developments of LCPA and usability. Second, we develop a methodology to collect data about the usability context of LCPA. Finally, we analyze and discuss the collected data, highlighting key recommendations for the LCPA usability at the early design stage.

2.1 Towards a user-centered approach

Since the 1970s and its energy crises, countries have set up regulations to decrease the operative energy consumption of buildings. Their performance targets have been strengthened over the years, and the next generation of regulations will lead to generalizing Nearly Zero-Energy Buildings (*NZEB*) in 2020 within the European Union (EU - EPBD, 2010). Still, even the *NZEB* performance level will not be sufficient to reach the levels required to actually make a difference in terms of climate change mitigation at the international level, as the building itself has embodied impacts that need to be accounted for as well when assessing its environmental performance. This is specifically the purpose of life cycle assessments (*LCA*) that will become mandatory in future regulations (DHUP, 2016), and which are promoted by green building certification systems (e.g. LEED, BREEAM, HQE…). The complexity of the design process will significantly increase, as every building component and system will now have to be considered in the performance assessment. According to Häkkinen, integrating this complexity gradually and as soon as possible should be beneficial for the building design (Häkkinen et al., 2015). However, previous research about Building Energy Performance Simulation (BEPS) tools, a historically close field to LCA, highlight that early decision support tools are not really used by architects and didn't meet their specific requirements (Attia et al., 2012c, 2011; Weytjens et al., 2011). Bleil De Souza and co-workers summarized the situation with a very strong position:

> *"Current research in the field tends to be quite unilateral and seems to be based on interpretations of what the building physics/simulationists community assumes the building designer needs. As this community lacks a comprehensive understanding of the paradigms of knowledge and praxis of the building designer, it tends to be quite limited in terms of their propositions."* (Bleil de Souza, 2012)

> *"There is a lack of knowledge in BPS on user profiling, and on understanding user experience, user goals and associated task analysis."*(Tucker and de Souza, 2016)

Even if many researchers are today actively involved in the development of new Building Performance Simulation (*BPS*) tools at early design stages, the implementation of environmental assessments remains a challenge so far (Azzouz et al., 2017; Hamedani and Smith, 2015), and we suppose that this situation is partly due to the lack of knowledge about their context of use.

Any new method should of course carefully integrate a full understanding of the user context, which was the objective behind the User-Centered Design (*UCD*) approach developed in the 1980s by Donald Norman's research laboratory at the University of California San Diego (Abras et al., 2004). Although *UCD* and the concept of usability are widely used within the Human-Computer Interaction field, they are rarely mentioned in research and development publications of *BPS*. This observation is quite surprising as every BPS tool are dedicated to interact with a user. This is even truer when focusing on Life Cycle Performance Assessment (*LCPA*) tools where few usability context analyses have been conducted to the author's knowledge. As will be further detailed in section 2.4, there is a clear decorrelation between the increasing research activity on building and LCA methods, and on the other hand, the limited available studies on the LCA practitioner's context.

LCA having actually not yet benefited from a usability context analysis, we suggest within this chapter to do one from which we might learn how LCA tools could be more adapted to the practice context.

2.2 About usability

Starting from the seventies and the fast development of computer-based technologies, new research interests focusing on software usability have started to grow. They are namely User-Centered Systems Design (or ''human-centered''), User Experience (UX), User-Centered Design (UCD), Interaction Design (IxD) and Human-Computer Interaction (HCI) (Ritter et al., 2014). Within these fields, the UCD approach is specifically focusing on the integration of the usability requirements into the design process. A simple search on the Scopus website ("Scopus - Document search results," 2017) with the "*human-centered design*" keywords demonstrates that this field has an active research community which has already produced around 6,919 registered papers, publishing currently almost 700 papers per year with a first recorded paper written in 1974. There are two norms defining usability and UCD.

First, the usability concept is defined by ISO 9241-11 as the following: "*extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use*" (ISO, 2018). This norm defines key terms and concepts and identifies the fundamentals and the application of the usability concept.

Second, ISO 9241-210 norm (ISO, 2010) provides requirements and recommendations for a better understanding of *UCD* in practice. Here, the term "*Human-Centered Design*" is used, rather than "*User-Centered Design"* in order to pay attention to all stakeholders involved in the usability of a product, i.e., not only the user. However, as is suggested by the norm, we will use the term "*UCD*" which is widely used and considered as a synonym. According to this norm, the *UCD* loop (Figure 9) encompasses (a) the understanding of the context of use, (b) the specifications of the user requirements, (c) the production of design solutions and (d) the usability assessment of these solutions.

Iterations between all these steps allow continuous improvement of the design. The purpose of this thesis is to conduct a Human-centred research process. Then the research in this chapter will be focused on the context of use (a), which will define the user requirements (b). Later, Chapter 3 and Chapter 4 will suggest a new methodology (c) that will be evaluated in Chapter 5 (d).

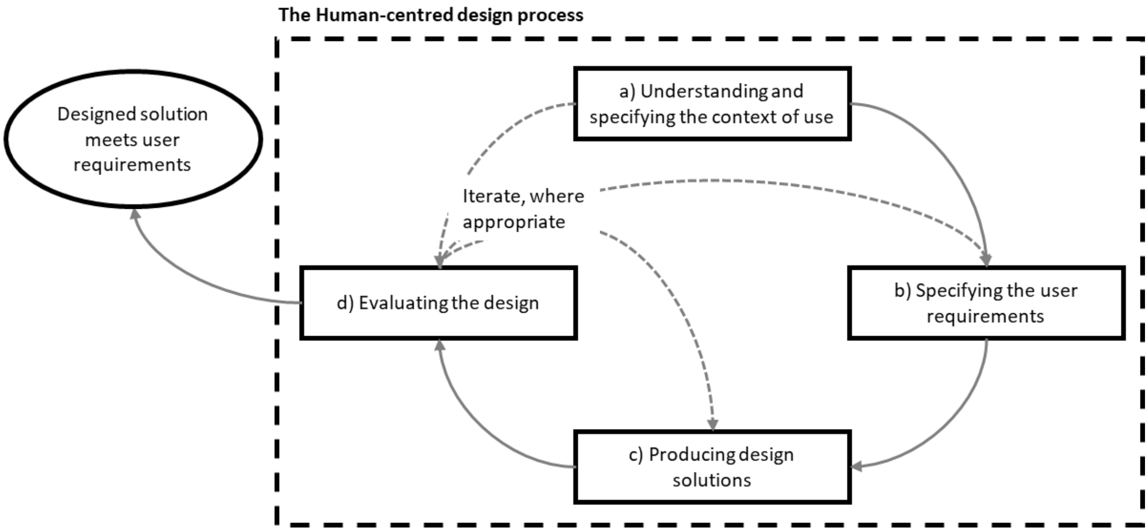


Figure 10: Human-centered design process, adapted from ISO 9241-210

Regarding the context of use (a), and following the ISO 9241-210 recommendations, its description should include the following:

- The definition of different users or stakeholder groups of users, (their relationship, goals and constraints…),
- The characteristics of the users (knowledge, skill, experience, education, training, physical attributes, habits, preferences and capabilities…)
- The goals and tasks of the users, (frequency, duration, interdependencies…)
- The technical, physical and social environment (hardware, software, work practices, organizational structure and attitudes…).

When it comes to evaluating the solution (d), the norm suggests collecting feedbacks from potential user through a case study, or from usability experts. In this thesis, we performed the assessment of the newly proposed method thanks to a case-study and practitioner's feedback.

Hence, this chapter and Chapter 5 called for specific social research methods to collect and analyze data about LCA in practice. Accordingly, the next section focused on techniques that could be used for this purpose.

2.3 Techniques of usability and context analysis

2.3.1 Context of use (a)

In 2001, Maguire compared six different context-of-use methods (Maguire, 2001), described hereunder:

- Identify stakeholders
- Context-of-use analysis
- Survey of existing users
- Field study/user observation
- Diary keeping
- Task analysis

Among them, the "survey of existing users" seemed particularly suitable to collect the data specified after the literature review in section 2.5.1 as it allows reaching out a diverse and difficult-to-access population, in our case the EU scale with different professional profiles. Indeed, the other techniques propose deeper but qualitative analyses on smaller samples of population. Maguire describes briefly the survey method, consisting of a set of written questions targeting a sample population of users and recommends to define a combination of open and closed questions to gather quantitative and qualitative data. It is quite time-consuming for its preparation and should thus be kept as short as possible for the respondents.

2.3.2 Evaluation of the solution (d)

Assessment of usability is an important exercise in the domain of human-machine interaction. It is generally conducted during the development process and requires experts, developers and real user tests (Lewis, 2006). It aims at a constant improvement of the interaction between users and a system, by obtaining information about its efficiency, effectiveness and satisfaction of use. It highlights the likes, dislikes, needs, emotions and understandings of real users interacting with a system in a real operational environment (ISO, 2010). It is important to guarantee that these needs and limitations are taken into account to ensure the development of tools that are easy and satisfying to use,(Rubin and Chisnell, 2008).

Amongst the main usability assessment methods, we can cite cognitive walkthroughs, heuristic evaluations, checklists or interviews, and focus groups (Jordan, 1999; Kuniavsky et al., 2012). Each of these methods features some advantages and disadvantages. Nevertheless, usability tests and focus groups are the only methods that consider representative end-users and provide empirical data as requested in the user-centered design principles (Gould and Lewis, 1985). Therefore, usability testing and focus groups are among the most important and widely applied methods in usability practice.

The focus group method is a qualitative method of data collection. It is a group interview technique, thanks to a semi-structured discussion, moderated by a facilitator in the presence of an observer. It is usually composed of 8 to 12 participants and lasts between half an hour to two-and-a-half hours (Masadeh, 2012).

When it comes to usability testing, two different approaches can be distinguished: formative and summative techniques. Formative testing is conducted in an iterative design process with the goal to gather qualitative information about weaknesses and operation problems of a product. Summative testing, on the other hand, aims to collect quantitative data about the accomplishment of task goals. It is often conducted at the end of specific phases in the product development process or at the end of the development process (Lewis, 2006; Rubin and Chisnell, 2008).

While usability assessment is well established and widely used in Human-Computer Interaction, its application to the BEPS tools remain sparse. Only a few publications relate usability engineering to BEPS software (Holzinger, 2005; Hopfe and Hensen, 2009). Previous work has focused on assessing the usability of a BEPS tool through a heuristic evaluation demonstrating the feasibility of this expert-based evaluation method (Struck et al., 2010). The System Usability Scale (Brooke, 1996) is a summative approach that has been applied recurrently on BEPS tools (Attia et al., 2012a; Cozza et al., 2018; McGlinn et al., 2017; Nault et al., 2018b).

The System Usability Scale (SUS) is a summative approach used to rate the perceived usability of a tool by its users (Brooke, 1996). This instrument is considered as an industry standard and offers several advantages: it can be used on small sample sizes, it is reliable and it can effectively differentiate between usable and unusable systems (Bangor et al., 2008). It consists of a 10-items questionnaire with a Likert scale. SUS scores have a range of 0 to 100, calculated as follows:

"*To calculate the SUS score, first sum the score contributions from each item. Each item's score contribution will range from 0 to 4. For items 1,3,5,7, and 9 the score contribution is the scale position minus 1. For items 2,4,6,8 and 10, the contribution is 5 minus the scale position. Multiply the sum of the scores by 2.5 to obtain the overall value of SU.*" (Brooke, 1996)

A SUS score is considered to be acceptable starting from 70 (Bangor et al., 2008), good at 73 and excellent at 85.

In the end, the usability assessment of the newly proposed method will combine in Chapter 5 a focus group and a System Usability Scale approach.

2.4 LCA in practice: a literature review

2.4.1 Early design characteristics

In the earliest phase of a design based on the RIBA plan of work, i.e. design concept, the first project strategies are being built up, with structural design, building systems proposals and first cost information (Sinclair, 2013). According to the literature, we can describe the early design phases as following:

- The level of detail available about the project at that stage is very low and does not allow an accurate prediction of the life cycle performance of the project (Malmqvist et al., 2011). This is a common issue every assessment method has to face at early design stages (Attia et al., 2012c; Riether and Butler, 2008) and that might explain the lack of usability of BEPS.
- The design process is iterative between building specifications and architectural options (Prost, 1992). It is characterized by a loop where solutions are first generated, then analysed according to some objectives, and third, implemented into the project according to their compliance with these objectives.
- All these iterations are time-consuming, around five to seven weeks for each according to Flager et al., (Flager and Haymaker, 2009). As a result, they found that architects and engineers can spend more than half of their time managing project information rather than executing, reasoning and specifying the project, though this statement should be taken with a grain of salt as it was performed on fifty professionals from a single company from which only 10% were architects.
- The main focus during early design is to "*align the preferences, targets and work methods of architect and client and to check the budget and regulation limitations*" (Meex et al., 2016). The construction type is mainly discussed et that stage however some preferences are expressed about U-values, Heat recovery systems, Light/heavy construction, Air change rate, Space usage, Glazing area, Floor plan depth and Fuel type (Morbitzer et al., 2001).

This description helps us to better understand the early design context, supporting the review of the previous context of use analysis we realized in the next sections.

2.4.2 Outcomes of prior surveys about the context of use of LCA

This section provides a literature review of research about *LCA* practices within the construction industry. The review has been limited to the past fifteen years, considering that older studies would not have been relevant nowadays according to the major improvements that the field has benefited from in terms of methodology and software these past few years. It did not focus on methodological developments of LCA but on its context of use, targeting surveys about practitioner's feedback. This is why surveys of practitioner's feedback about the method (e.g. impact weighting, normalization interpretation, etc.) have been excluded. However, published surveys have so far been mostly centered on the scientific issues of the *LCA* methodology rather than on user practice (De Wolf et al., 2017). As an example, the biggest survey to date (Hofstetter and Mettier, 2003), with 566 survey participants, and also the oldest one, targeted a better understanding of user wishes in terms of weighting the environmental indicators and about impact aggregation methodology, but without attention paid to the decision-making process itself, or the context of use. The survey was limited to the people who had downloaded BEES 2.0, an *LCA* software targeting the US building industry. Another survey with a large population (Pizzol et al., 2016), gathering the feedback from 216 valid answers, was also centered on normalization and weighting in the *LCA* methodology. Sibiude and co-authors, on the other hand, concentrated the survey on the interpretation and reporting steps of the *LCA* methodology, proposing to *LCA* tool developers some recommendations about the aggregation system that should be implemented (Sibiude et al., 2014). Cooper and Fava actually did investigate the benefits and barriers of *LCA* methods and software in North America (Cooper and Fava, 2006), and identified the complexity of the method as one of the main barriers for practitioners. They particularly emphasize the input data collection as the most time-consuming step of LCA.

Indeed, there is an important distinction between the user wishes regarding metrics and the user practice regarding the tool they use, the latter being specifically what we want to discover.

Other studies focused more specifically on defining and characterizing users. Han and Srebric, for instance, established a relationship between the respondents' background and the use of *BEPS* or *LCA*. According to them, the larger the size of a company, the greater its use of LCA. They also found another correlation: the more the user professional experience is important, the lower its use of LCA. They also discovered that *LCA* is rarely used by professionals compared to energy simulations (Han and Srebric, 2015). Similarly, Olinzock et al. found a high degree of interest regarding sustainability issues within the AEC industry (Olinzock et al., 2015), but they also found that only 12% of the respondents were actually using *LCA* on the majority of their projects. For Olinzock, the lack of client demand is one of the main barriers of *LCA* practice. According to Bruce-Hyrkäs, the purpose of use of LCA is mainly because fo green building certification for 84% of the sample he collected data (Bruce-Hyrkäs et al., 2018).

While the first surveys cited previously were quantitative and targeting a large population, other studies have been found with a qualitative approach. The first one (Saunders et al., 2013) applied the focus group technique, which allows in-depth discussion with qualitative data emphasizing open discussions. This study focuses on the main barriers and benefits of *LCA* methods. Complexity, time, and accuracy were highlighted for the barriers, and "*providing information about environmental impacts*" for the main benefits. The authors also highlighted the necessity to combine their research with a national survey relying on a larger sample size.

The second study (Schlanbusch et al., 2016), limited to Nordic countries, focused mainly on gaps and issues within the *LCA* methodology. In their work, they highlighted that building *LCA* is time-consuming in finding and collecting data, and thus expensive. Also, the following points were evaluated as still challenging for LCA users: handling the end-of-life phase, the time-aspect, the weighting factors, the discount rates. They concluded that more research on efficient ways of performing LCA in the early design stages is still needed.

Bruce-Hyrkäs et al conducted interviews with LCA practitioners highlighting multiple challenges of performing LCA, upon which the difficulty to understand LCA results, the low availability of building LCA background data with locally relevant and product-specific data, and the low level of details at early design stages (Bruce-Hyrkäs et al., 2018).

Table 2: A literature review of previous LCPA practice surveys.

Survey participants	Main geographical scope	The technical, physical and social environment	The goals and tasks of the users	The characteristics of the users	Definition of the different users	References
65	North America			x	x	(Cooper and Fava, 2006)
96	US			x	x	(Han and Srebric, 2015)
566	US		x	x	x	(Hofstetter and Mettier, 2003)
250	US		x	x	x	(Olinzock et al., 2015)
216	World		x			(Pizzol et al., 2016)
37	US		x		x	(Saunders et al., 2013)
57	Nordic countries			x	x	(Schlanbusch et al., 2016)
121	France		x	x	x	(Sibiude et al., 2014)
151	EU, Middle-East, South-East Asia.		x			(Bruce-Hyrkäs et al., 2018)
62	EU and US		x			(De Wolf et al., 2017)
3	UK		x			(Pomponi et al., 2018)
381	Belgium		x	x		(Meex et al., 2017)

In their survey, De Wolf et al. demonstrated that the literature provides a large body of case studies. However, the high discrepancies in terms of boundary conditions and assessment decrease their usefulness to be used as a reliable benchmark and design support (De Wolf et al., 2017). Pomponi et al. shared the same conclusions in their examination of 15 detailed assessments (Pomponi et al., 2018).

When it comes to the time spent conducting LCA, most of the surveys highlighted the time consumption issue of the method. More specifically, Meex et al. defined some requirements for applying LCA at early design stages based on a large-scale survey and 5 interviews. They suggested keeping the time-investment as low as possible, targeting evaluations that should not take over half an hour per design solution in early design (Meex et al., 2017). They also recommend using interoperable tools to facilitate the data inputs and real-time assessment with calculation lengths no longer than 0.1s (Meex et al., 2018).

All these publications are listed and qualified in Table 2, according to the context of use description items of the ISO 9241-210 and their main geographical scope. The participant numbers reflect the size of the study. When mixed approached have been used (e.g. focus group and online survey) the sum of all participants is proposed.

Several important lessons emerge from this review. First, the time-consumption problem was revealed by almost all the previous surveys. They concluded that this issue was strengthened by a lack of client demand, which might make it even more painful if no engineering fees support this work. The time efficiency issue was also emphasized by the LCA method, which was perceived to be complex. However, researchers and practitioners seemed to be convinced about the potential benefits LCA could bring to integrate life cycle performance objectives as soon as possible within the building design.

One should also note several important limitations to these studies. First, a large majority of previous studies have been performed in the US and few within the EU boundaries with a limited number of participants. Second, there is not yet a comprehensive survey that would address the four key items that have to be described in the previous section according to the ISO 9241-210 recommendations. Although some of the studies mentioned that providing guidance to software developers was one of their main objectives, the *UCD* methodology was never cited by their authors, and they were mainly focused on the scientific issues of the method rather than on its use in practice. The lack of knowledge about interactions between LCA and the design process in practice is particularly pronounced for the technical, physical and social environment, i.e. all the things that have an influence on the LCA use, and more generally for the context of use of *LCPA* methodology and tools within the design process in practice. Indeed, most of the surveys were focusing on LCA methodological issues (e.g. weighting the indicators, rather than on the design process, or the users' needs and environment. For instance, none of the following questions has been answered yet when it comes to the use of *LCPA* tools:

- What are the roles, responsibilities and interactions between *LPCA* tool users?
- When and how are users questioning the life cycle performance of their project within the design process?
- How much time do they have/need to perform an *LCPA* analysis?

It is also worth to note that these practice surveys represent a very small minority of the research conducted on *LCA* and buildings, as it is illustrated in Figure 11. Indeed, out of the 2346 scientific articles published since 2003 and identified by the scopus.com website, only fey of them illustrated in Table 1 focused on understanding the LCA context of use, despite their fundamental role in increasing usability according to the UCD concept.

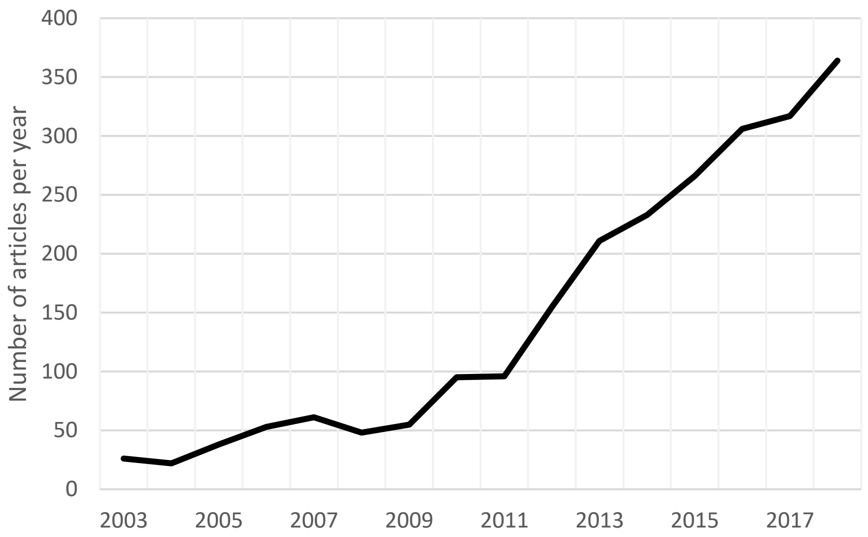


Figure 11: Evolution of the scientific articles (black line) yearly published since 2003 and related to Building LCA. Information obtained from Scopus for the keywords "LCA+building".

In this section, we focused the review on surveys about the LCA context of use. The following section will extend the scope of the review more broadly to BEPS tools pertaining to energy use in buildings, to see if any additional information about the context of use in a historically very close research field might be relevant.

2.4.3 Outcomes of prior surveys about the use of BEPS tools

Several studies also point out the limited use of BEPS in building practice, specifically by architects and at early design phases, because of their low usability (Attia et al., 2009; Bambardekar and Poerschke, 2009a; Hong et al., 2000). Alsaadani and Souza They point to a negative perception of BEPS tools by Architects, probably due to a misperception of the BEPS, understood more as compliance decision support than a source of creativity (Alsaadani and Bleil De Souza, 2016; Alsaadani and Souza, 2017).

These prior studies confirmed that BEPS tend to be performed late in the design process and associate this unfortunate timing to the client's underestimation of the importance of BEPS, budget constraints (e.g. limiting the engineering fees, or simply lack of interest). Tucker and de Souza (Tucker and de Souza, 2016) actually state that while *HCI* techniques have the potential to develop more usable interfaces, there is not enough knowledge so far in BEPS user behavior, goals and profiles for this potential to turn into reality.

In synthesis, the outcomes of prior surveys about the context of use of BEPS tools highlighted the time-consuming and low usability issues, similarly to the previous section focusing on LCA.

2.4.4 The need for a survey

Many researchers point out the mismatch between designers' requirements at the early design stage, and LCA tools available on the market. This gap is particularly important for architects, who are oftentimes dissatisfied with the current tools and methods developed by engineers. Increasing the usability of LCA at early design, means understanding the concept of usability, which is part of the User-Centered Design field (UCD). According to section 2.2, the first step of a *UCD* approach is the specification of the context of use, which has not been done exhaustively for LCA tools at early design, even if *UCD* is widely recognized as an important research activity in the frame of Human-Machine Interaction. To cover this lack of knowledge, we propose to conduct a survey about the LCA practice context within the next sections.

2.5 Framing a survey about the LCA usability context

2.5.1 Survey objectives

The three main objectives of this survey are the following. First, the overall purpose is to offer to *LCPA* developers a comprehensive and context-oriented study, guiding them towards more usable tools. Second, the ambition of this survey is to target the European level to be representative enough of a large design community. It will also complete the state of the art where a large majority of previous studies were performed in the US. Third, the goal is to target specifically early design phases, as the state of the art mentions that integration of life cycle performance targets is crucial and that current BEPS tools seem to be particularly ineffective at this stage. For this early phase, three types of practitioners are targeted (Zabalza Bribián et al., 2009)**:** architects, engineers/consultants and real estate developers. According to section 2.3.1, the survey of existing users is the technique that has been used.

2.5.2 Survey methodology

The prepared survey included 40 questions and took about 4 minutes to fill out. Most of the questions used a Likert-scale, i.e. a scale from 1 to 5 in integer steps, so as to make answers short and data analysis efficient. Whenever a Likert-scale was not appropriate, multiple-choice questions have been used instead, which gives the possibility to the respondent to choose the "*other*" choice and then formulate an answer him/herself. The Survey Monkey software (Finley, 1999) was used to set up an online questionnaire. The closed questions were framed to make answers easy with a pull-down menu encompassing categorical data (e.g. country), ordinal data with Likert scales (e.g. not at all satisfied to very satisfied), and interval data (e.g. age: 35 to 44).

Once a first survey version was completed, and according to the rule of five (Hubbard, 2010), a test on five participants was performed to check the understanding and the length of the questionnaire. The feedback of these first participants validated the duration of the survey, and allowed to specify some of the questions that were misleading in terms of interpretation. Then, the questionnaire was spread to more than 33,000 European people from the *AEC* community through the author's network and commercial mailing lists, mostly targeting architects. The professional network LinkedIn was also used to share the survey among green building communities of practitioners using *LCA* tools or interested in sustainable construction and green label discussions. At the EU level and to the best knowledge of the authors, it is impossible to evaluate the actual size of the *LCPA* tool users' community so as to define a target number of respondents. Thus, the targeted population size has been defined according to the previous best practices and set to 500 respondents. Indeed, the largest survey so far was conducted fifteen years ago with 566 participants in the US (Hofstetter and Mettier, 2003).

The answers were collected after two successive reminders and a four-month period between 06/21/2017 and 11/08/2017. In the end, only the respondents fitting with the scope of the survey have been kept, that is to say, the one working as architects, engineers/consultants or real estate developers within the EU boundaries.

Regarding data analysis, bar charts and box plots with averages and deviations were used to highlight the survey results. To reinforce the analysis, and considering that the collected data are mostly categorical, a Chi-square test (McHugh, 2013) for independence has been performed additionally to show the bivariate associations. To determine whether the variables are independent, the p-value of the Chi-square test has been compared to the significance level considered to be 0.05. In other words, when the P-value is below this threshold, the variables are considered to be statistically associated. When calculated, this P-value is noted in the legend of the related graphics.

2.5.3 Content of the survey

As this survey had an explicit focus on the context of use, it was set to answer the following overarching questions:

- What is the **purpose**-of-use that *LCPA* methods and tools have to address? Here the point is to collect users' feedback about their needs and their vision of what objectives the methods should achieve.
- What is the **audience** that will benefit from these methods and tools?
- What is the **context** of use? What situation induces the method's needs?

These three major questions have been detailed and subdivided based on the understanding of *LCPA* specificities, on the previous literature review, and on the literature recommendations about usability context analysis (Thomas and Bevan, 1996). Forty questions came out of this work, represented in Figure 12. They have been reordered to be asked in a logical way to the participants. The questions were grouped by theme, starting with demographic questions. The specific list of questions (cf. Appendix A) was inspired by ISO 9241-210 and previous research (Maguire, 2001; Thomas and Bevan, 1996). The survey includes questions about the participants' profiles, their companies, their practice of LCPA, their practice of LCPA, how they characterize the early design stage, and their expectations regarding LCA tools.

As we targeted the EU scale, questions were written in English. No translation in other languages was proposed to avoid a different understanding of the questions based on language. For multiple-choice answers, a random function was used to change their order and thus lower the influence of answer position.

2.6 Results of the survey

The survey was answered by 495 participants, which is a high population compared to the previous studies in which the average number of respondents was below 200. After cleaning the data, 414 of them matched the target population of the survey, i.e. working in Europe, and practicing as either engineers, architects or real estate developers. According to their answers, participants were directed differently to subsequent questions, which explains why not all questions have the same number of answers. In addition, some participants quit the survey before the end, but their answers up to the point of leaving have still been considered.

Among the 414 participants that fulfilled the survey criteria, 82.3% of them were architects, 13.3% were Engineers, and 4.4% were Real Estate Developers. This reflects the networks used to distribute the survey. Therefore, the survey results present a very architectural perspective. However, this distribution is in a way coherent with the objectives of this survey that targeted the early design stage, during which the design team is often reduced to the architect only. As a consequence, the results highlighted in this thesis will not discriminate architects vs. engineers, as engineers are not well represented. Moreover, there is a high diversity of engineers working with architects, such as environmental consultants, structural, mechanical and electrical services engineers, which would have led in a lack of robustness into the result interpretation. On Figure 12, the number of participants having filled a given part of the survey is provided, and is repeated in each graph interpreting the answers received (Figure 13 to Figure 30).

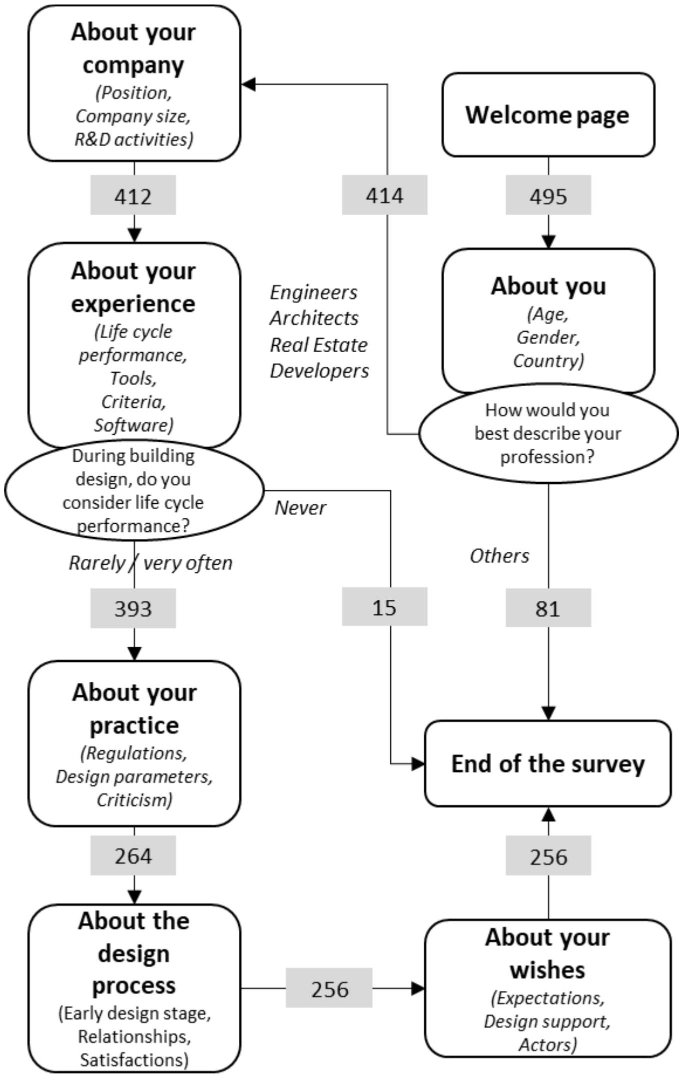


Figure 12: Presentation of the Overall Survey. The numbers in the rectangular grey boxes correspond to the number of participants that reached a particular point in the survey.

2.6.1 Sociological profile of the life cycle performance assessor

2.6.1.1 A pro-active community

The survey reached its ambition in terms of geographical scope: the participants that answered were working in 26 different countries within Europe. However, more than 80% of them were located the Western part of Europe (either in the UK, France, Switzerland, Germany, Italy, Spain or the Netherlands), as detailed in Figure 13. This might be the result of both the fact that the author's network happens to be better connected to this part of Europe and that the level of interest towards environmental questions may vary within Europe. From some of the participants' feedback in open questions, it was clear that economic and social issues have an explicit priority over environmental questions in certain countries.

Regarding gender, females were clearly a minority in the surveyed population, representing only 18% of the participants. This, unfortunately, reflects the current situation of architects in Europe, which exhibits a disproportionately low ratio of female practitioners: 25% in France and 21% in the UK (Fulcher, n.d.; "La profession en chiffres," 2006).

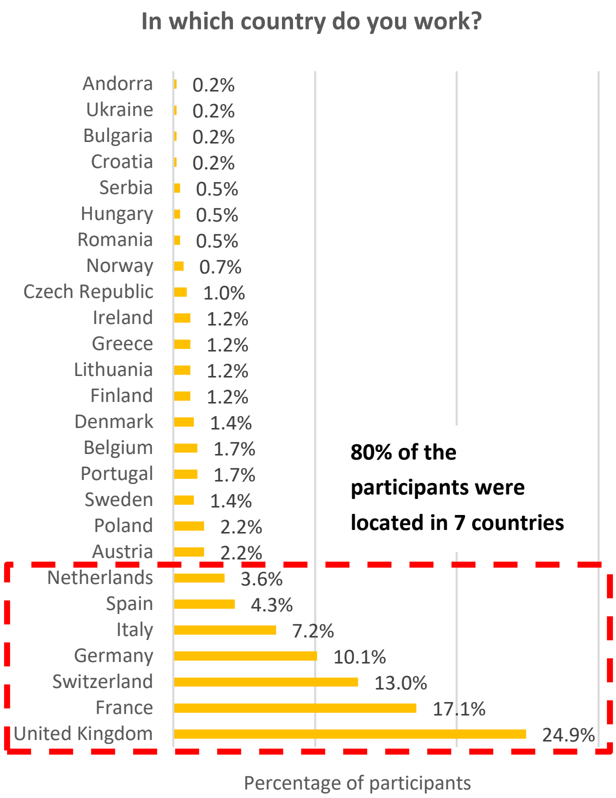


Figure 13: Working countries of the 414 participants answering the survey.

An interesting finding was that only 41% of the participants reported they had to consider life cycle performance because of the client's requirements, and yet 77% of them consider the life cycle performance of building designs (qualitatively in most of the case, see Figure 26) because it is common practice in their company (this was a multiple-choice question allowing cumulative answers). What this means is that dealing with *LCPA* during the design process is first a pro-active behaviour of the design team, before being a request of the client.

The survey also revealed that 74% of the respondents consider the environmental performance of their building project as fairly critical (41%), critical (24%) or very critical (9%) compared to other constraints. Therefore, despite the low demand from the clients, environmental performance seems to be an important enough success factor of a building project to encourage such a pro-active behaviour, combined with pressure from the civil society or from the end-users, and the environmental convictions of the designers themselves.

To gauge the practitioners' sensitivity to future regulation needs, a question was asked about the EU regulation about to be enforced, in which all new buildings starting from 2020 will have to be nearly zero-energy (EU - EPBD, 2010). On average, 50% of the respondents were aware of this future regulation, which is quite a low percentage considering that the survey was performed eight years after the directive publication, and only two years before its application. We could also observe large disparities between countries. Among the seven countries that have the highest number of answers, the awareness rate varies from 90% in Italy to 36% in the UK (Figure 14). Additionally, with a P-value of 0.003, the Chi-Square test demonstrates a significant influence of the country variable on the EU regulation awareness.

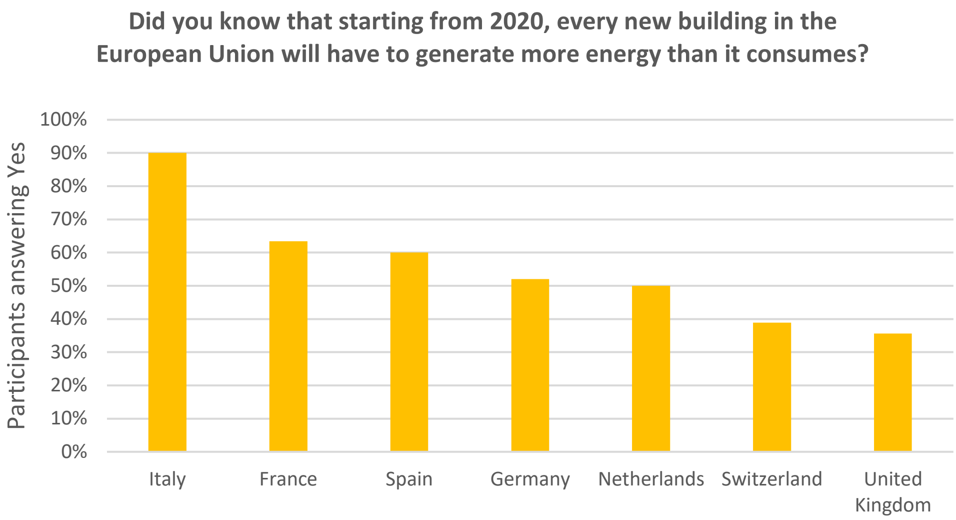


Figure 14: Awareness of the practitioners, according to their working countries, about the future nearly-zero energy building regulation in Europe, out of 264 answers.

2.6.1.2 A high interest in life cycle performance

Within the survey population, it is worth mentioning that according to Figure 15, most of the practitioners (59%) claimed that they often or very often consider *LCP* during the building design. Only 4% (i.e. 15 people) never consider it but agree that they will have to in the future. The main reason for those that answered "*never*" was the absence of the client's requirement regarding this type of analysis. This enthusiasm might be explained by the fact that the environmental constraints are largely perceived as an opportunity (by more than 70% of the respondents as shown in Figure 16). It is rarely considered a threat (only by 7%) and was reported as a potential source of innovation and creativity. Also, the question was very open on purpose, in order to reveal the interest of practitioners when it comes to LCP. As it is later confirmed by Figure 26, only 27% of them are using computer software to perform LCA, while most of them used qualitative methods.

The answers to these two questions highlight a very high interest from architects and engineers regarding environmental issues, and a fundamental wish to integrate this performance criterion into their design process.

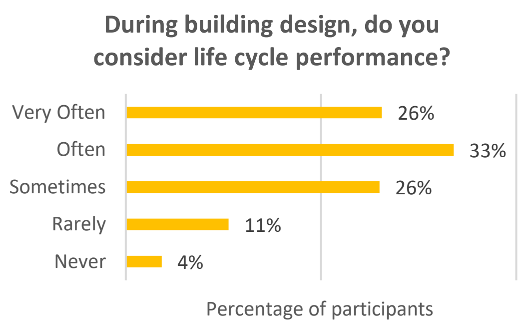


Figure 15: Consideration of life cycle performance by practitioners, out of 408 answers.

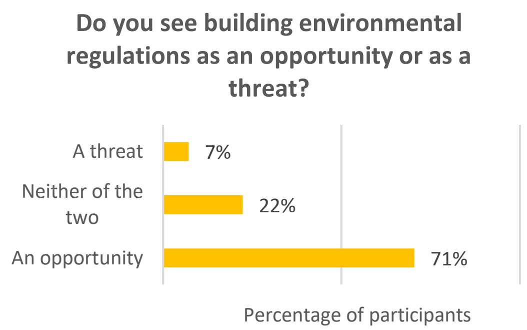


Figure 16: Perception of environmental regulations by practitioners, out of 264 answers.

Amongst the seven countries that represent 80% of the answers, a quite steady majority of practitioners seem to consider *LCP* when designing a building (from 72% in Spain to 51% in Germany) although how well a given country was represented amongst respondents could be quite variable as highlighted by the black line in Figure 17 (e.g. only 4.3% of them were coming from Spain). The question was actually very open on purpose, so as to include every method that allows consideration of the *LCP*. In other words, although awareness to life cycle performance should not be doubted, the practice behind this objective involves a large diversity of methods and tools (cf. section 4.2), and probably of *LCP* definitions.

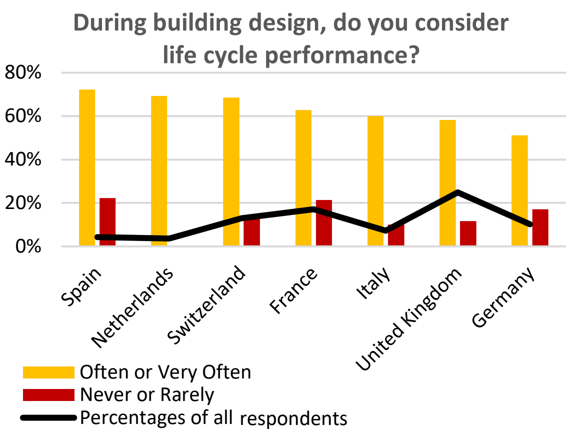


Figure 17: Life cycle performance considerations, out of 408 answers. Bars represent the respondents of each country that considers LCP, and the line represents the country distribution of 80% of the respondents.

2.6.1.3 Life cycle performance assessment and social interactions

When it comes to life cycle performance assessment, 46% of the respondents are working with external consultants, and 16% with an internal consultant. Thus, it leads in many cases to interdisciplinary collaborations between people with different skills, backgrounds and languages, and a section of the survey was dedicated to analysing these social interactions between architects and engineers.

The first question was about the collaboration rate between them at the conceptual design stage. Figure 18 highlights that 74% of the engineers are used to collaborate at early design stages with architects. This number drops to 54% on the architects' side, which shows that architects don't always have the time or the budget to involve a specialist in *LCPA* for every project. On the contrary, as it is its main objective, an engineer in charge of the LCA calculation might have a higher willingness to collaborate as early as possible in the design process.

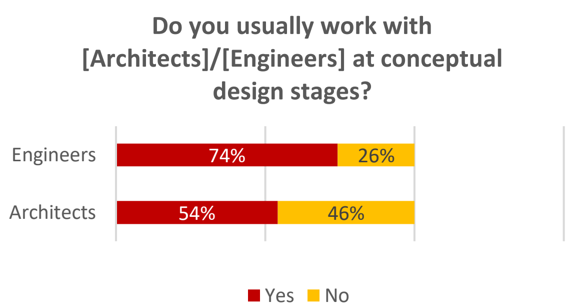


Figure 18: Collaboration rate between architects and engineers at the conceptual design stage, out of 227 architects and 35 engineers. (P-value = 0.03)

A specific question was asked to determine the architects' and engineers' positions regarding the responsibility of integrating the life cycle objectives into the design process (Figure 19). Overall, 74% of the survey participants agreed that both architects and engineers should be concerned. This demonstrates a strong awareness of practitioners of the collaboration necessity when dealing with environmental issues. It is also interesting to note that the rest of the respondents were clearly split into two groups: architects were convinced that it is their own responsibility only, and engineers thought the same about themselves. Although this does not reveal any tendency to “blame it on the other”, it still shows that a good 25% of practitioners seem to be more comfortable managing such issues alone rather than have to worry about collaborating with the other.

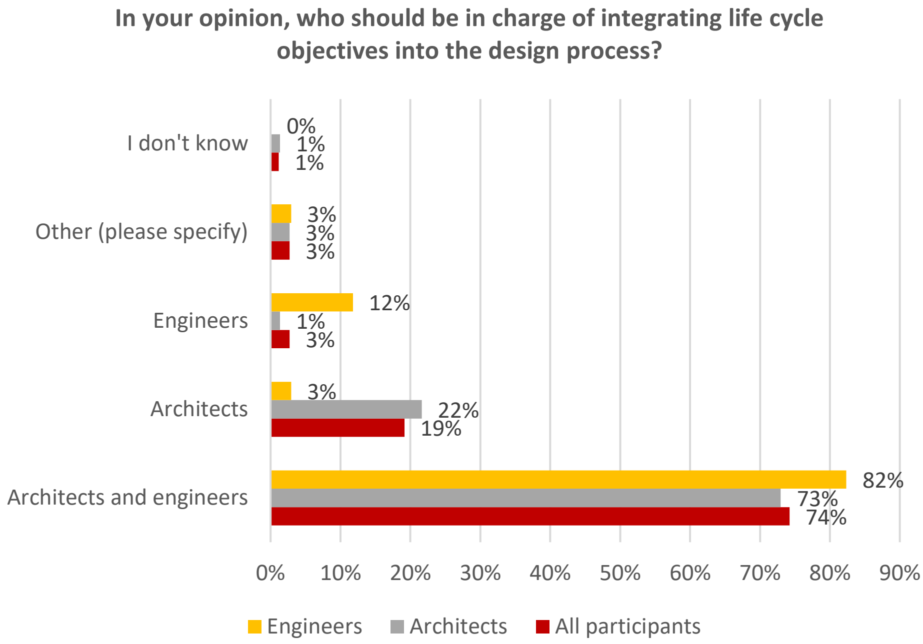


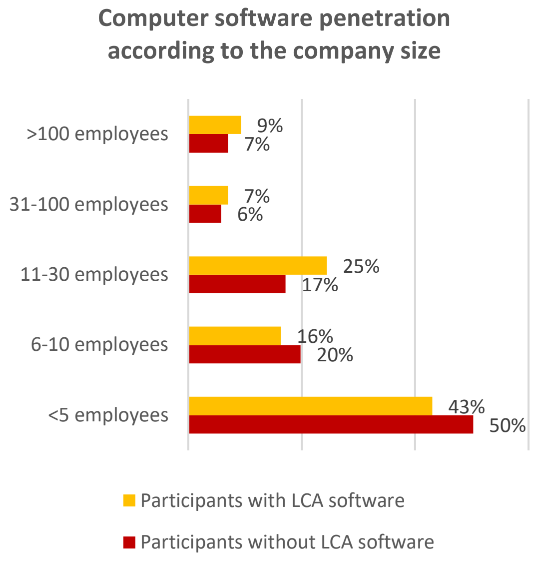
Figure 19: Architects’ and Engineers’ opinions about the life cycle performance responsibility within the design process, out of the answers of 222 Architects and 34 Engineers. (P-value = 0.001)

2.6.2 The mismatch between LCA tools and the early design process

2.6.2.1 A low software penetration

“*Do you consider life cycle performance?*” is a broad question that let the participants answer with different interpretations of what life cycle performance may be. Indeed, practitioners use a large variety of tools and methods to assess life cycle performance and only 27% among them are using *LCA* software (Jusselme et al., 2018a). This is a very low rate, considering that the complexity of a life cycle assessment decreases the efficiency of qualitative approaches (e.g., guidelines or technical references). Moreover, this question did not specify what was understood as LCA software. As a result, positive answers might include conventional BEPS targeting the operational impacts only, and not the full life cycle impacts, leading to an overestimation of this rate. As a comparison, 85 respondents out of 322 claimed to use software when answering this question, while they were only 38 specifying later which one they used (see Figure 25).

This penetration rate has been further analyzed according to two discrimination factors: the company size and its R&D activities. In Figure 20, one can note that the companies with *LCPA* software are slightly under-represented below 11 employees, and over-represented above. Companies involved in R&D activities have a penetration rate of *LCA* software 7% higher than the others: 59% instead of 52% (Figure 21). However, the Chi-square test did not allow to draw any significant dependence between these variables. Thus, using *LCA* software is not a common practice for the respondents, and although one can note small variations in the answers, it is not possible to observe different behaviors according to the company competencies and size.



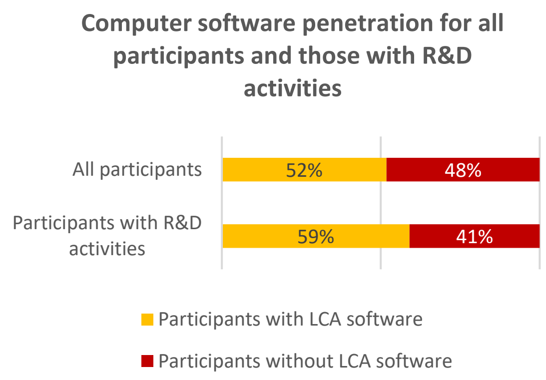


Figure 20: Computer software penetration according to the company size, out of 414 answers. (P-value = 0.99)

Figure 21: Computer software penetration according to the R&D activities, out of 411 answers. (P-value = 0.91)

2.6.2.2 A high cost of use

One of the goals of this survey was to define the cost-of-use of a life cycle performance assessment. To that end, the survey characterized first the time spent during conceptual design stages thanks to Figure 22. This figure is a Tukey boxplot highlighting groups of design process durations through their quartiles. Despite some extreme values in the high range, the results show that the conceptual design phases typically take less than 17 weeks (for 75% of the population), and last 12 weeks on average for a building. When looking at the median of the answers, the duration is even shorter, with 8 weeks. During this time, designers typically produce about three different alternatives on average, which confirms the necessity to develop an iterative design process and explore different variants of their projects. As can be seen in Figure 23, Architects and Engineers actually agree on the number of alternatives, respectively 3.3 and 3.2 on average, or 3 for the median. Some participants commented that this question was hard to answer, as it also might depend on the context or the size of the project, but this answer could be considered as an order of magnitude.

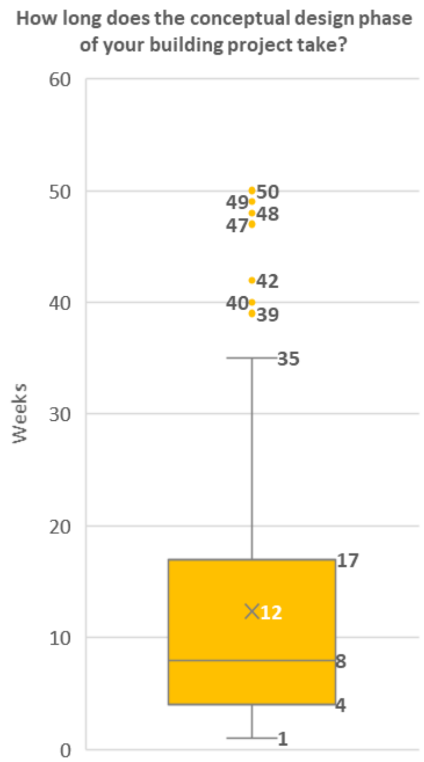


Figure 22: Length of the conceptual design phase in weeks, out of 264 answers

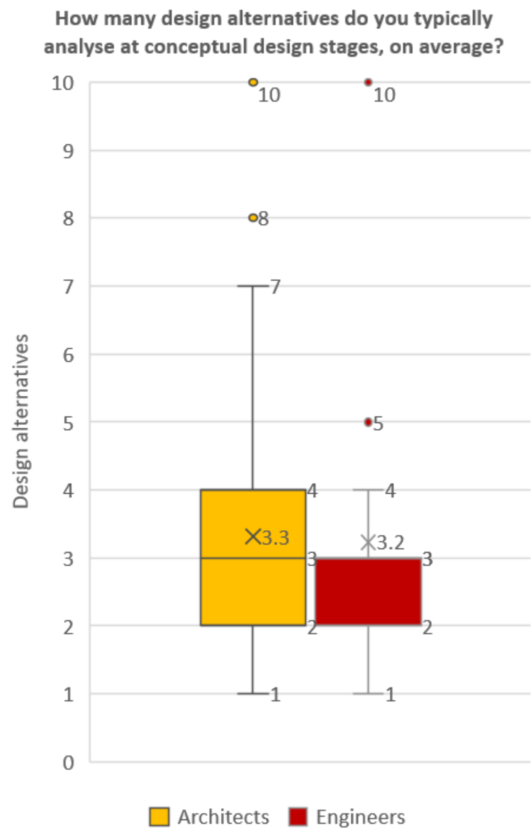


Figure 23: Number of design alternatives of the conceptual design phase, out of 264 answers

Figure 24 highlights the time spent to assess the life cycle performance of a design alternative. It is on average 24 hours, i.e., around 3 days of work. Furthermore, the global wish is to extend this length to 28 hours, which means that the current time allotted to the assessment is not enough. Looking deeper into the data, the tools and methods used are a strong discrimination factor as they change this average length from 18 hours for the ones using rules of thumb to 34 hours for the ones using computer software. This analysis seems to show that quantitative techniques tend to be the most time consuming, followed by working with external or internal consultants as the latter need to be provided with the project details. Finally, the quickest methods are the qualitative ones.

We have to say that the large range discrepancies in these quantitative answers might reflect the differences in what the questions mean for the respondents, the difference in size and complexity of projects, but also reflects people's different estimates. This is why all these estimations have to be carefully considered. However, they give a first range of calculation lengths and frequencies that might be helpful to specify the time-consuming issue, well acknowledged in the literature review (section 2.4.2), but not really specified yet.

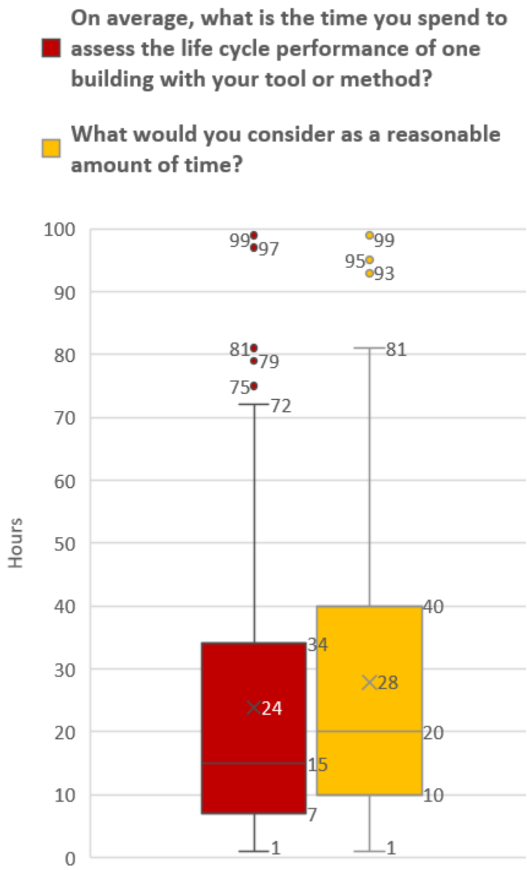


Figure 24: Lengths of a life cycle performance assessment, out of 322 answers.

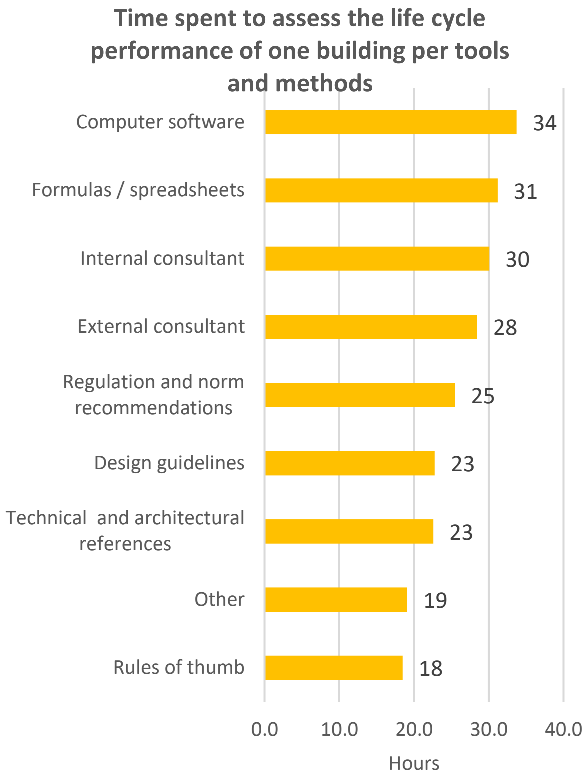


Figure 25: Lengths of a life cycle performance assessment, according to different tools and methods, out of 322 answers.

In summary, a practitioner using *LCA* software to assess the life cycle performance of its building project at the conceptual design stage will need 34 hours (Figure 25) as an order of magnitude for each design alternative. As practitioners usually design three alternatives at that stage, the theoretical assessment length of the three alternatives grows up to 100 hours, that is to say, two and half weeks full time for one person, mostly without any demand from the client, and for a design phase duration of 2 to 3 months. This estimation might be pessimistic as we linearly upscale this answer for assessing more than one alternative. Indeed, the first assessment might be typically more time-intensive than the others as part of the collected data can be reused for the assessment of the other ones.

2.6.3 Practitioners and *LCA* software

The participants of the study happen to mostly work in small architecture companies (<10 employees for 70% of the participants). This kind of company size seems rather small, but is representative of the situation in France for instance, where 94% of the architecture offices have less than 10 employees (RIBA, 2017). This has a direct impact on the skills and tools that designers can handle. In the UK, it was pointed out that companies with more than 100 employees use Building Information Modelling on half of their projects while for companies with less than 10 people, this ratio drops to 17% of the projects (RIBA, 2017). Following the same trend, Figure 26 illustrates the very low penetration rate of computer software dedicated to *LCA* amongst professionals (27%). Overall, the participants are actually more likely to use rules of thumb (33%) or guidelines (43%) for instance.

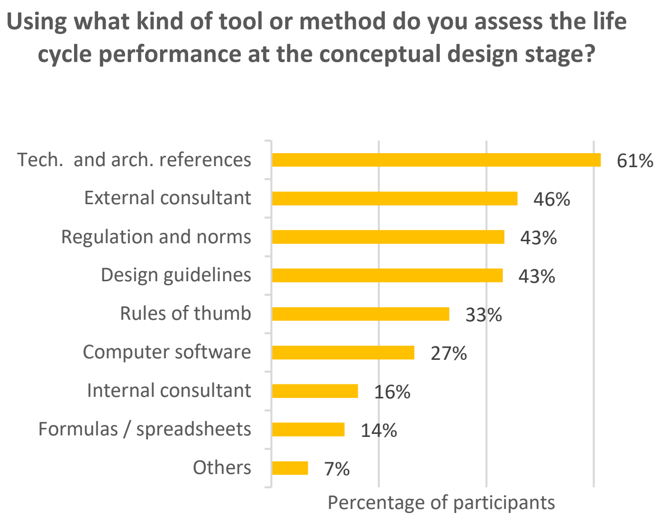


Figure 26: Answers about the tools and methods used to assess life cycle performance at the conceptual design stage, out of 323 answers.

The most popular approach is the use of technical and architectural references (61%). Indeed, according to Jusselme et al. (Jusselme et al., 2016), they are commonly used by designers to feed the iterative design process between problems and solutions. However, considering the still small corpus of reference buildings in terms of *LCP*, its complexity and context-dependency, one may start to wonder about the efficiency of such methods. The fact that 46% of the respondents work with an external consultant also highlights the difficulty of internalizing this competence.

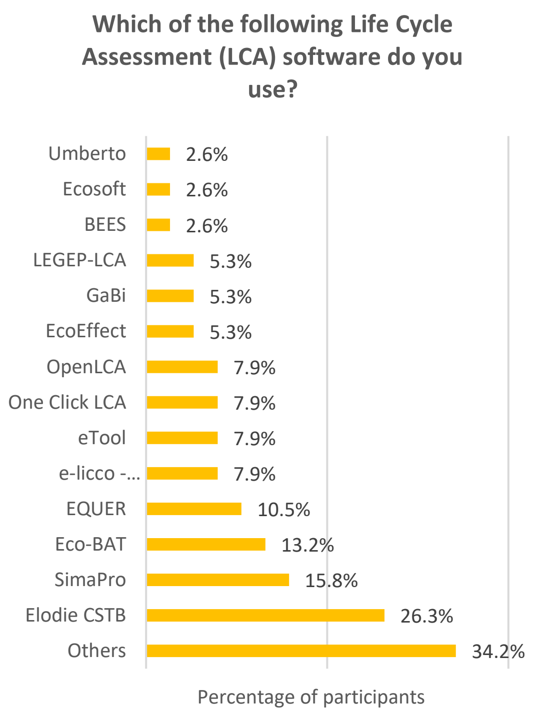


Figure 27: LCA Software distribution, out of 38 answers.

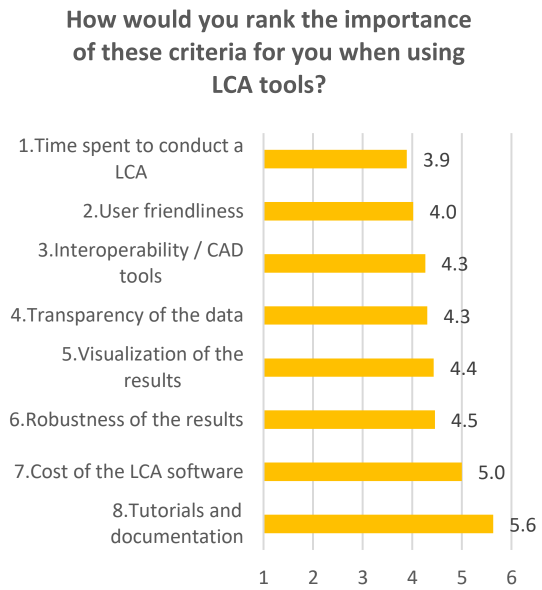


Figure 28: Average ranking of several criteria when using LCA software, out of 46 answers (1=highest importance; 8=lowest).

In Figure 27, 38 respondents specified what software they use. It is interesting to note that they use more than 14 different types of software, and the most popular (*Elodie*) is used by no more than 26% of them. Although this statement has to be moderated based on the country distribution of the survey participants, it means that there is no clear leadership of one of the tools in Europe, probably as a result of country-specific Environmental Product Declaration (*EPD*) databases used to perform the *LCA*. *Elodie* software, for instance, is dedicated to the French building context, using a French *EPD* database (INIES) and 90% of its users, within the frame of this survey, are located in France. Among those who answered "*Other*," Brightway, Smeo and an in-house Excel file were mainly cited.

Several criteria have been ranked by *LCA* software users in order of importance, as shown in Figure 28. Among the three first-ranked criteria, we find the time spent conducting *LCA,* the interoperability with *CAD* tools, which are both related to a willingness to reduce and lighten the time consumption of filling in input data or more generally of using the software. Indeed, architects and engineers spend most of their time managing existing information (Flager et al., 2009), rather than creating new information.The user-friendliness also emerges as a major concern, which might be related to the desire for an easier interpretation process. This could be improved with the use of data-visualization techniques of the results as suggested in Jusselme et al. (Jusselme et al., 2017).

These criteria have also been rated in terms of satisfaction levels thanks to a Likert scale with five levels from "*not at all satisfied*" (1st level) to "*completely satisfied*" (5th level). In the end, the time spent and the interoperability have lower satisfaction with a score of 2.84 and 2.49, respectively.

Overall, a major issue regarding the use of life cycle tools is their cost of use, which is too high for practitioners. This is also clearly reported in several open answers. This survey found out that the *LCP* is a voluntary approach for 71% of the practitioners, while it is a client's requirement for only 41%. In this context, and especially with the early designs, the engineering fees might fail to make up for the time consumption of current software.

Figure 28 also highlights a lower emphasis on the importance of tutorials and documentation. This is paradoxical, as the survey shows on another note that they are used by 82% of the respondents, while 44% are helped by colleagues, and 38% have internal or external training courses. Thus, tutorials are highly popular but are probably considered a basic feature of the software compared to the other criteria.

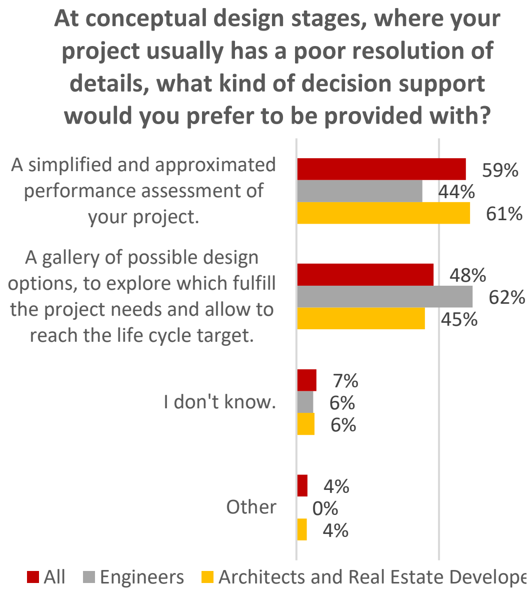
2.6.4 Practitioners' wishes

Regarding the services expected by the participants, more than 50% of the practitioners are willing to perform the following:

a) to check the compliance of the project with the objectives;
b) to assess the performance of the building project;
c) to evaluate the sensitivity of the design parameters;
d) to know what would be optimum in terms of sustainability;
e) to explore which design alternatives fulfil the objectives;
f) to compare the performance of different building design alternatives.

While current software is able to meet requirements (a) and (b), this is commonly not the case for the others, which highlights a major gap with practitioner's needs that expect much more than a simple life cycle performance assessment. Indeed, although the compliance of a project with a specific environmental target is a fundamental need, it does not efficiently support the design process and its iterations. On the other hand, the sensitivity analyses of design parameters and design alternative explorations, for instance, are much more powerful (Jusselme et al., 2018b, 2016). When focusing specifically on early design stages, 59% of the respondents agreed to use simplified performance assessment to handle the low resolution of details of these stages (Figure 29). Still, the ability to explore a gallery of possible design options is acclaimed by 48% of them, with a higher rate among the engineer's sub-population (62%).

The survey actually reveals a strong willingness to perform multi-criteria assessments as most of the respondents also take care of acoustics, lighting, thermal comfort and energy consumption. This finding is in line with the need for interoperability compliancy of *LCA* software, and it demonstrates the will to have more holistic tools to integrate the complexity of multiple performance targets into the design process.



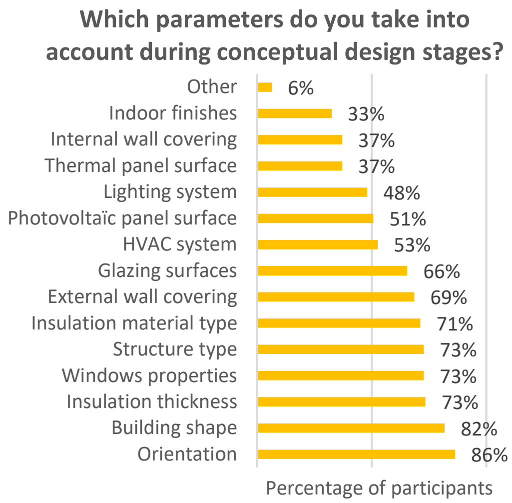


Figure 29: Comparison of exploration and assessment approaches, out of 256 answers.

Figure 30: Consideration of design parameters at conceptual design stages, out of 263 answers

Regarding the design parameters, Figure 30 highlights that more than 80% of the practitioners consider the building shape and the building orientation at the conceptual design stage. There is a decreasing interest in the design parameters from macro (building shape and orientation) to micro (indoor finishes and internal coverings). Yet, all proposed parameters are considered by more than 30% of the participants, which is counter-intuitive at the early design phase. In fact, life cycle performance assessments consider all the building components in their calculations. This means that using a low performing structure will perhaps lead to a decrease in design options by choosing only the best products in terms of indoor finishes. Reciprocally, if the client's brief specifies low performing indoor finishes, this may have an impact on the building shape or structure possibilities. In that sense, it is interesting to note that designers want to understand the consequences of design choices commonly made at early stages, but do this based on details with high environmental impacts that will actually be fixed only in later phases.

2.7 Discussion

Literature suggests (section 2.4.2) that previous surveys targeting practitioners in the field of *LCA* were limiting their participant sample around 170 on average. With 495 answers, our sample size is almost equivalent to the biggest survey of Olinzock et al (Olinzock et al., 2015). However, the representativeness of the sample has not been demonstrated, as its distribution has not been compared to the targeted population. Indeed, the targeted population was architects, engineers, and real estate developers at the EU level, but no global database identifying such populations by country was identified. Due to the low participation of engineers, we decided to analyze the answers as a whole, without specific analyses for the engineer's sub-population itself. In terms of language, the survey was proposed in English only, to prevent any bias in the translation of the questions. On the other hand, it might have limited the participants to the ones knowing this language, which distribution varies from one country to another.

In addition, we can safely assume that there might be a bias in the sample of participants, as the willingness to answer this survey might be higher for those already interested in *LCP* than those currently ignoring this field. Therefore, the results may actually be slightly optimistic in favor of *LCPA* practices. Olinzock et al., for instance, noted a large gap between the sustainability interest of the AEC industry and the real *LCA* practice (see section 2.4.2). They estimate the practitioners using *LCA* on a majority of their project to 12%, even if everyone recognizes it as beneficial. In comparison, 60% of our respondents considered life cycle performance often or very often, while 27% of the respondents only were actually using *LCA* software. There is thus clearly still a gap, but it tends to be smaller over the years than the Olinzock et al. study, which was realized in 2012 and targeted the US only.

There might also be another bias in the answers to the survey that might reflect what respondent think they should think, rather than what they base their decisions on in general practice.

Still, it is possible to compare the answers to the ones that have been already provided by the BEPS community. In 2007, a survey on a single office population pointed out that it takes more than a month for designers to complete a design iteration between the stakeholders, with no more than three of these design cycles at the conceptual design phase (Flager et al., 2009). This is fully consistent with the present study where the average early design phase lasts three months and handles three design alternatives. It really strengthens the point that the cost-of-use of *LCA* software is far too expensive. As an example, let's consider the following figures:

- a daily consultancy fee is 800€ per day as a European average,
- an *LCA* with software requires around 4 days (Figure 24)
- an *LCA* should be done for each of the three alternatives that are proposed on average (Figure 23).

Thus, the cost of use should represent roughly 10,000€ only for the early design stage. These elements may partially explain why *LCA* is still not amongst the clients' requirements, and why, even if there is an increasing interest from practitioners, why the use of *LCA* into practice is so limited. This is particularly true at the early design phase, which often happens in the form of an architectural competition with a very limited budget, or even no budget sometimes. It is interesting to note that in comparison to the cost of use, the cost of the software itself does not seem to be an issue, as no significant influence of the company size to software penetration (Figure 20) has been observed, unlike the positive correlation to company size that was observed by Han and Srebric (Han and Srebric, 2015). The cost-of-use of LCPA techniques, however, seems to be of major importance, as even qualitative approaches like "*rules of thumb*" or "*technical and architectural references*" fail to be quick enough and probably remain hardly usable as they still represent 6,000€ for the early design phase (assuming the same hypotheses).

2.8 Findings and recommendations

This survey identifies a real willingness of engineers and architects to use *LCPA* but highlights that there is a major gap between their context of use and the method's abilities to fit this context.

The study reveals that the *LCPA* user community is **pro-active** and considers environmental constraints as an **opportunity**. They use life cycle thinking as a **best practice** that they have to follow and are largely convinced by the **integrated design** principle, considering that life cycle performance should be the responsibility of both engineers and architects, who have to tackle this issue early in the design process.

However, it is clear that the daily practice of *LCPA* does not reflect this enthusiasm, as most of the respondents use qualitative approaches, leading to a software penetration rate as low as 27%.

Quantitative life cycle performance assessment is facing major obstacles, which prevents current software from being widely used, specifically for the early design phase. We would like to highlight three of them here.

The clear lack of *LCP*-based requirements from the clients. The market demand is very low, contrasting with the scientific community warnings about climate change, and the engineer and architect's empathy. Fortunately, future EU regulations about greenhouse gas mitigation may become very powerful market traction.

The high cost of use that makes *LCPA* tools unsuitable to use at early design stages. In fact, the cost of use is much higher than the cost of the LCA software itself: engineering fees – estimated on average at 10,000€ at the early design stage – represent a strong barrier for real estate developers to engage LCA expenses at a financially risky stage. *LCA* software should also be more interoperable with CAD tools in order to decrease their cost of use, i.e. the time for processing the input parameters and interpreting output data. This compatibility with the BIM environment might extend the boundaries of current *LCA* software with more functionalities. Indeed, the increasing performance-oriented trend of building specifications calls for designers to adopt a multi-criteria approach, assessing other metrics such as energy, lighting, acoustics, etc.

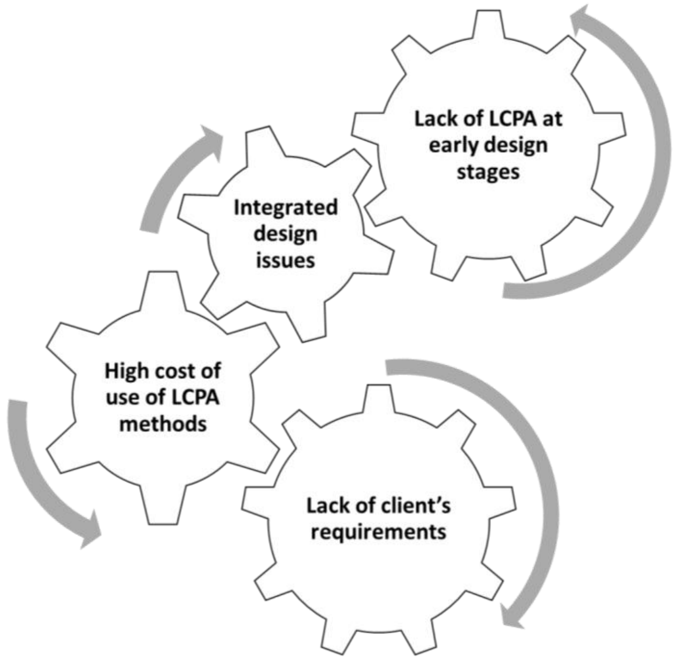


Figure 31: Mechanisms decreasing the use and the usability of life cycle performance assessment methods at the early design stage.

There are major issues in the integrated design process. Collaborations at conceptual design stages, such as required for an *LCPA*, are acknowledged as a necessity for 74% of the participants. However, architects do not involve engineers in more than 54% of their projects at the conceptual design stage. There is also a mismatch between LCA software and the context of a design process. Indeed, current tools are mainly limited to the assessment functionality. Within the survey, practitioners call for many other techniques such as sensitivity assessment, exploration mode, etc., to fit better with the design iterations. These iterations are currently fed by the use of architectural references, which are highly popular among architects and engineers during the iterative design process, but are very limited in term of quantity from when it comes to the *LCP* issue.

These three major obstacles together work against the practitioner's willingness to use *LCPA* at early design stages, in a pattern of causes and effects illustrated by Figure 31. To overcome these obstacles and attempt to promote LCPA at early design stages, some overarching principles might be helpful to consider.

First, to increase the real estate developer's willingness to include LCPA into their building specifications, there needs to be an economic incentive. As the construction sector is a highly constraining and cost-driven industry, we envision that there will be low interest in carbon mitigation by decision-makers until the carbon emissions themselves have **no economic impact** that will affect the construction cost. There is little doubt that *LCPA* will become of high interest by all construction stakeholders once the economic impacts will be as high as the environmental damages. Another powerful leverage to increase the market demand might be the **EU regulation**, that could extend the current energy consumption requirements to life cycle performance requirements. A first step towards this direction has been proposed with a framework for LCPA at the EU scale (Dodd et al., 2017). In line with the greenhouse gas international agreements, it would make *LCPA* de facto mandatory in the client's requirements.

Second, there is a need to develop new *LCPA* methods with **high efficiency at early design stages**. On the one hand, the digitization of the construction sector thanks to the Building Information Modelling methods (BIM) will allow input collection to be made more time-efficient, as it will allow real time-assessment for the detailed design phases as soon as the material quantities are available. Simplified LCA and parametric approaches will also make LCA usable at early design as suggested by Hollberg's work (Hollberg, 2017). On the other hand, LCPA outputs must deliver higher benefits with insights fitting the design process in terms of uncertainty and level of details, as most of the design choices are not defined yet.

Finally, we envision that **mixed approaches** are needed when it comes to communicating between architects and engineers about the *LCPA* results. Both quantitative and qualitative approaches must be proposed to make reconcile the necessity of engineers being able to verify the compliance of a conceptual design option with quantified thresholds (e.g. kg CO_2-eq/m²) with the necessity of architects being able to effectively make use of the results in their design process, and support decisions to be made regarding space, materiality, light, etc.

Chapter 3 Combining promising techniques towards a new LCA-based data-driven design method

Disclaimer: Parts of this chapter are adapted from the following articles – with permissions of all co-authors and journals:

Jusselme, T., Rey, E., Andersen, M., 2018. An integrative approach for embodied energy: Towards an LCA-based data-driven design method. Renewable and Sustainable Energy Reviews 88, 123–132. https://doi.org/10.1016/j.rser.2018.02.036. My contribution: Conceptualization, Investigation, Methodology, Visualization, Co-Writing – original draft.

Hoxha, E., **Jusselme, T.**, Brambilla, A., Cozza, S., Andersen, M., Rey, E., 2016. Impact targets as guidelines towards low carbon buildings: Preliminary concept, in: PLEA. Los Angeles, USA. My contribution: Conceptualization, Methodology, Supervision, Validation, Co-Writing – review & editing

Jusselme, T., Tuor, R., Lalanne, D., Rey, E., Andersen, M., 2017. Visualization techniques for heterogeneous and multidimensional simulated building performance data sets. Proceedings of the International Conference for Sustainable Design of the Built Environment 971–982. My contribution: Conceptualization, Investigation, Methodology, Supervision, Validation, Visualization, Co-Writing – original draft

This chapter proposes a review of promising techniques that have the potential to support architects and engineers during their practice of life cycle performance assessment, to face obstacles that were identified in Chapter 2. The review does not pretend to be exhaustive but is necessary to understand their potential integration in a new LCA-based method at the early design stage that is described in the second part of this chapter. Each reviewed technique has some inherent limitations that are identified and indexed as *L1*, *L2*, etc. Hence, based on the understanding of the context of use and the identification of the most promising techniques to support the use of LCA at early design stages, this chapter presents a new methodology that was developed towards an *LCA*-based data-driven design of low-carbon buildings.

3.1 A review of promising techniques

3.1.1 Latest researches in Life Cycle Assessment and early stage

LCA applied to buildings is used to assess the environmental impact during its lifetime, including five major life cycle stages according to the European Committee for Standardization: production, construction, use, exploitation, and end of life (European Committee for Standardization, 2011). Within the architecture, engineering, and construction (*AEC*) fields, this is a complex process as each building is unique, with long lifespans and multiple functions. As a consequence, performing *LCA* is time consuming (*L1*), especially at the early building design stage (Basbagill et al., 2013).

Recent improvements in interoperability between computer-aided design software and building performance simulation tools allow facilitating the life cycle inventory thanks to a common file exchange format. With building information modelling, it is now possible to assess the life cycle performance by coupling a 3D modelling software with an *LCA* tool at the early design stage ("Tally," 2016; "Tortuga - LCA in Grasshopper," 2016). Indeed, it is at the beginning of the design process that designers have the largest range of options to influence their project. Hollberg et al. and Basbagill et al. (Basbagill et al., 2017; Hollberg et al., 2017) developed real-time *LCA* techniques. Their works provide quasi-real-time feedback thanks to a parametric approach and simplified assessment algorithms. As a result, you can modify a drawing, and directly observe the consequence of this change on the building life cycle performance. The Building Information Modelling (BIM) process provides the necessary inputs to LCA methods and allows this real-time assessment.

However, while a robust *LCA* needs a high resolution of details to be applied on a building project, the early design stage typically relies on a low resolution of details (Malmqvist et al., 2011; Marsh, 2016), which results in a co-existence of high incompatibility at early stages (*L2*). If the BIM process appears to be a powerful leverage to shorten the data collection of detailed design phases, it is not solving this detail resolution mismatch (Hollberg et al., 2020). As shown in previous work (Attia et al., 2012b; Riether and Butler, 2008), every method used in early design stages has to face the problem of system resolution. Two different possibilities have been identified so far to solve this problem. The first one is an over-simplification of the building, based on macro-component descriptions to easily reach a rough assessment of the project (Sibiude et al., 2013). The second one is a high definition of the building usage and characteristics that will obviously lead 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. Simplified techniques can provide results that deviate up to 70% when compared with a detailed *LCA* (Lewandowska et al., 2015).

Another identified obstacle is the non-reproducibility of *LCA* results (Bonnet et al., 2014) (*L3*). This is due to the method itself that allows practitioners to define their own system boundaries (*Figure 32*) and functional unit, and to freely choose among different life cycle inventory databases. Thus, two practitioners that perform an *LCA* on the same building may get different results (Dixit et al., 2012; Pomponi et al., 2018). In addition, results will not be applicable from one case study to another if they are not considered within the same boundaries (Anand and Amor, 2017).

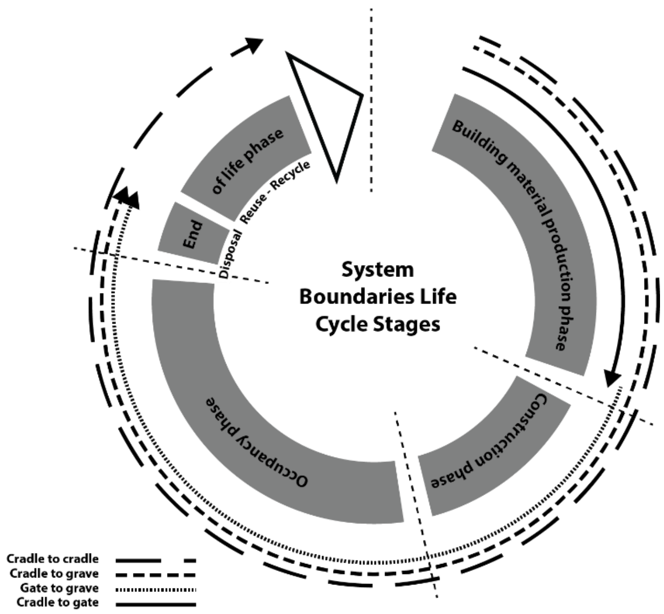


Figure 32: System boundaries and life cycle stages of a building, according to different approaches, adapted from (Dixit et al., 2012)

As a conclusion, the non-reproducibility of *LCA* results basically prevents *AEC* actors from being able to use results from other case studies. Furthermore, the early building design stage and its low-resolution regarding the level of detail remain an obstacle to performing *LCA* with trustworthy results. To address this resolution issue, increasing the number of simulations without negatively impacting time-consumption seems promising – if feasible – to better understand the consequences of design choices made at the early design stages on variables that will have to be chosen later. This approach will thus be investigated further in the next section, based on parametric assessment methods.

3.1.2 Parametric assessment

On the one hand, the literature review of current early design simulation tools has pointed out that most of them guide designers through an optimization process, assessment after assessment (Crawley et al., 2008; Maile et al., 2007). They suggest one optimized solution according to the environmental performance criteria, but this solution might not be seen as optimal by designers, who also have to consider other requirements, both quantitative and qualitative. Thus, there is a risk that an optimized project in terms of environmental constraints does not fit comfort and cost objectives or even aesthetical preferences for instance. As a result, suggesting only one optimized design option might be useless if this option does not match all the requirements.

On the other hand, architectural design is an iterative process between problems and solutions allowing to integrate also qualitative aspects (Claeys, 2013; Prost, 1992). Many types of references (i.e. case studies, design alternatives) can be used to go from building specifications to solutions, but it is not always easy to produce or find a quantitative or technical one at the building level.

Considering the complexity of the building design process as a multi-criteria approach, it thus seems interesting to consider pools of solutions rather than optimized ones, and feed this multi-criteria, iterative design with a wide range of design alternatives. If the information overload is not a limitation itself, the higher the number of design alternatives, the easier for designers to match every constraint (Akin, 2001).

However, to be useful, the carbon emissions of these design alternatives have to be assessed, and *LCA* applied to buildings is time consuming (*L1*) because of the necessity to describe dozens or hundreds of building elements (Bonnet et al., 2014). This current limitation reduces the possibility to develop an iterative process, which is crucial for project quality. In 2007, a survey demonstrated that it takes more than one month for designers to complete an iteration, and these design cycles are up to three at the conceptual design phase (Flager et al., 2009). This probably means that the LCA calculation will have to be repeated three times, for each iteration. Accordingly, fast feedback on the project assessment is without any doubt one of the most important features of a decision-making tool (Athienitis et al., 2010; Clarke and Hensen, 2015).

A solution to the time-consuming issue of LCA and to the need to the fast generation of design alternatives might be the use of parametric assessment methods. A comparison between a manual optimization process and an automated approach using cloud computing carried out by Naboni et al., for instance, showed that within the same period (71 hours), an architect with a standard dual-core PC was able to manually test 64 design options (Naboni et al., 2013). In the meantime, the parametric approach with cloud computing was able to provide 221,184 options, and the best solution to this approach was 33% less energy-consuming than the best one from the conventional approach.

Pomponi et al. used a parametric approach to provide the life cycle assessment of 128 different configurations of double skin facades for office refurbishments. Thanks to this knowledge database, the authors were able to demonstrate that double-skin facades were more energy-efficient than single-skin in 98% of the cases, and more carbon-efficient in 85% of the cases (Pomponi et al., 2015). In a similar way, Allacker et al. assessed the life cycle performance of 13,440 variants based of 16 representative dwellings in the Belgian context to demonstrate that the passive standard was not always having the lowest life cycle impacts. Indeed, most of the dwelling had an optimum characterized by a net heating demand between 15 and 30 kWh/m² floor (Allacker and De Troyer, 2013).

In such a way, the fundamental benefits of the parametric approach are the potential to increase energy savings by multiplying the design options and providing a knowledge database, with a possibility to have a deeper understanding on how these alternatives guide towards a performance threshold. Also, the assessment automation allows spending more time evaluating the results rather than modelling and assessing alternatives (Flager et al., 2009). It seems of major importance in the early design context, where the time-consumption issue of LCA is one of the main LCA barriers, to give more space to the engineering tasks that really support the design, rather than spending time gathering and processing information.

Hollberg et al. developed a parametric model to easily compare building variants and their relative operational and embodied impacts (Hollberg et al., 2016). Their first model with EnergyPlus (Crawley et al., 2001) had a calculation time ranging from 20 seconds to 3 minutes, which has been considered as too long by the users. A second model (Hollberg and Ruth, 2016) was able to perform the assessment in only 10 seconds using a simple energy simulation based on the German norm DIN V 18599-2. However, in the discussion, the authors underline that a tool like EnergyPlus may still be necessary for complex buildings (i.e. multi-functionality of the building and high performance). Recent research illustrates the possibility to increase the computational power thanks to cloud computing services. It allowed performing large and customized parametric studies even with complex simulation engines as EnergyPlus (Macumber et al., 2014; Richman et al., 2014). According to the literature, another promising path towards fast LCA calculation might be the use of machine learning techniques thanks to algorithms that would be trained a large database. Multivariate regression has already been used to quickly assess the results of a project, avoiding the use of heavy simulation engines (Hygh et al., 2012). Similarly, Artificial Neural Network has been used to develop surrogate models and predict building energy consumptions (Li et al., 2019; Sharif and Hammad, 2019; Westermann and Evins, 2019).

Victoria et al. developed a parametric embodied carbon prediction model thanks to regression analysis aiming at embodied carbon estimation at the early stages of projects when detailed design information is not available (Victoria and Perera, 2018). They successfully collected data of office buildings in the UK from different sources and used the wall to floor ratio and the number of basements to predict embodied impacts with an accuracy of ±89.35%.

As a conclusion, the parametric approach allows going beyond the single performance assessment or the optimization process. It also opens the door to an exploration approach with the generation of alternatives that could be considered as references to feed the iterative design process. Automation of the workflow based on a simple 3D volume might decrease the time-consuming issue of the LCA method at early design. Actually, exporting these alternatives in a specific knowledge database to get a deeper understanding of a project seems to be a promising way to support the designers. To that end, one should be able to face the overload information and to extract knowledge from this database, in a useful and understandable way for designers, which constitutes our fourth challenge (*L4*). Accordingly, the following sections will focus on methods valuing the database as a source of knowledge for early decisions.

3.1.3 Sensitivity analysis

The main purpose of a sensitivity analysis is to rank design parameters according to their influence on the result (Heiselberg et al., 2009), so that, for instance, one can remove parameters unlikely to affect the result from a simulation model, thereby simplifying it and increasing its efficiency in providing relevant information. Sensitivity analysis has been already used extensively for decision-support but still lacks integration and easy to use connections with building performance simulation tools (Hopfe and Hensen, 2011).

Adapted from Heiselberg et al., a sensitivity analysis follows four steps:

- Determine the model inputs (design parameters) and their sample range.
- Run the sample function to generate the model inputs.
- Evaluate the model using the generated inputs, saving the model outputs.
- Run the analyze function on the outputs to compute the sensitivity indices.

One of the main differences between sensitivity analysis methods is the computational cost of their assessment model (Tian, 2013a). The Morris method (Morris, 1991), for instance, is a screening-based technique particularly well adapted when a large number of input variables are involved in the analysis, but involves one important limitation to overcome, namely that results can only be expressed in a qualitative way, with effects of different parameters on outputs that cannot be quantified (Tian, 2013a). A very interesting aspect of the Morris method, however, is that it provides two sensitivity indexes: μ that assesses the sensitivity of the results regarding one input, and σ that evaluates the interaction between a parameter and the others. The method was thus used in (Jusselme et al., 2015a) to analyze the sensitivity of *GHG* emissions to design parameters, and identify μ and σ in this context.

As quantitative results are clearly also needed for LCA, the Sobol method can be used. It is a global sensitivity analysis and a variance-based approach using the Monte-Carlo strategy (Saltelli et al., 2012). It provides quantitative Sensitivity Indices (SI) to the user and thus more readable results than using Morris alone. According to Saltelli, the SI gives the decomposition of the variance of the mathematical model into terms either due to each input factors. When these factors are considered singularly, they are named first-order indices. The second-order SI gives the possibility to understand interactions between parameters. Another advantage of Sobol over Morris is the low-discrepancy sampling of the method that covers evenly the input combination possibilities. This is an advantage for an exploration process where one wants an equal distribution between the design parameters. Its main drawback compared to the Morris method is that Sobol increases the computational time by a factor of about 100 (Campolongo and Saltelli, 1997). A recent comparison of Sobol with other sensitivity analysis methods (regression-based, FAST and Morris) pinpoints that Sobol was the most suitable when using LCA calculations, because of its ability to manage heterogeneous and discrete values as inputs and because of its accuracy (Duprez et al., 2019). Also, the fact the Sobol need a large dataset to be performed was revealed as an advantage by the user point of view, as it means the possibility to explore a large knowledge-database if the computational issue can be solved. As an example, the Sobol method was used to identify the most influential parameters affecting the final energy consumption in office buildings (Ruiz et al., 2012). Even if this case study involved 68 parameters, it showed that only eight were responsible for 80% of the variance (*Figure 33*). In this case, the SI of the Appliance load density is the highest with 26.8% of the total variance of the sensitivity analysis.

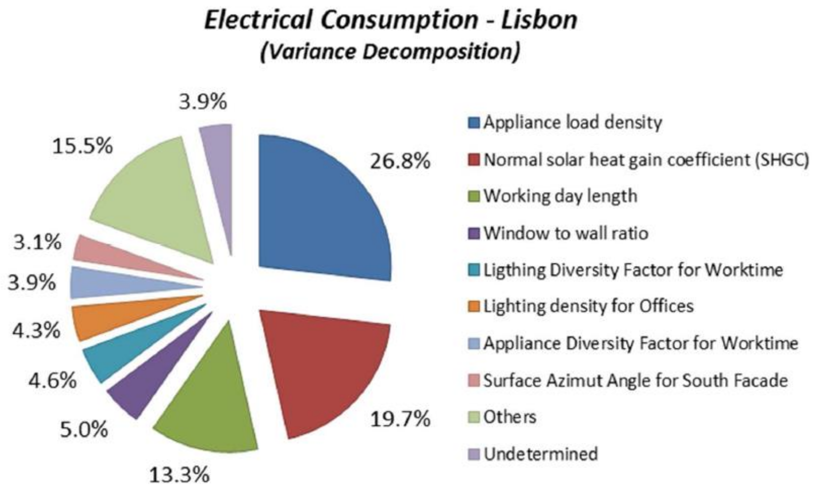


Figure 33: Variance decomposition for annual electrical consumption with the Sobol method. Image courtesy of (Ruiz et al., 2012)

This section allowed highlighting the Sobol method as suitable for the calculation of sensitivity indices based on LCA calculations. However, while a sensitivity analysis supports the design process, it does not necessarily allow one to quantify the environmental impact of design parameters to the extent they can be specifications useful to designers. In other words, if a design parameter varies with options that have high but equal impacts, its sensitivity index will be low considering the fact that changing the options will not affect the building performance. The next section proposes the target cascading technique to face this issue.

3.1.4 Target cascading

The mitigation of environmental impacts requests a well-coordinated improvement of all the environmental impacts related to the components and systems of a building. In general, in the design process, the minimization of the environmental impacts of buildings is directed towards optimal objectives by an iterative process. During this process, the most appropriate combination of components and systems is found by testing different proposition and solutions. This is both time- and effort-consuming, due to a large number of variables that, combined, provide a multidisciplinary analysis on a building's ability to respond to needs of accessibility, safety, well-being, durability, energy efficiency, and to be environmental friendly by emitting as little greenhouse gases as possible (Peuportier, 2013).

Existing studies found in the literature often aim to a simplification of the building's LCA (Bonnet et al., 2014). To reduce the calculation time of environmental impacts, Bonnet et al. proposed a simplification in a building's LCA based on the Pareto principle, according to which roughly 80% of the effects come from 20% of the causes. They proposed to assess the impacts of 20% of the major causes and the rest to be considered in the form of a ratio. One of the acknowledged limitations of that study is that the results of the simplified LCA actually embed a substantial uncertainty. Other simplifications aim to guide the design process towards optimal targets. The targets provide the objectives that a product or system has to reach. Rivallain proposed a methodology based on genetic algorithms to set optimal targets in the rehabilitation of existing buildings (Rivallain, 2013). This methodology offers the advantage of guiding designers towards efficient strategies but is complex and time-consuming.

Allacker et al. propose a database of environmental profiles of 115 variants of building elements offering transparent information, specific to the Flemish-Belgian building context. Doing so, the database offers the possibility to architects and material producers to narrow down the building life cycle impact issue from the building scale to the building elements (Allacker et al., 2013). However, if this approach decreases the scope of the problem to a relative comparison of the building elements, it does not allow to compare these building elements to an impact threshold that would ensure that the sum of all these element impacts would be compliant with an overall threshold usually defined at the building scale.

Hence, there is a need to propose a method that would simplify the building's LCA by reducing the scope of analysis to the building component scale, proposing carbon targets for each. In that way, a simple comparison between a building component and its target would allow a designer to evaluate the compliance of this component with a carbon budget at the building scale.

In mechanical engineering, the complexity issue of a system has already been addressed by the target cascading approach (Kim et al., 2003). Target cascading can be defined as a process which splits top-level design requirements into subsystems and components targets in order to design these subsystems and components at the same time, without considering the complexity of the whole system. It guides designers towards optimal targets at the component level, allows them to assess smaller perimeters than the entire system, and attributes responsibilities to each design team member (e.g. definition of the cost target of the wings in accordance to the cost of the entire aircraft). The possible links that components can share with others have to be identified during the splitting process of a system in sub-components. For a building, for instance, it might not be relevant to split the façade insulation from the façade structure, as the kind of insulation that can be used is highly dependent on the kind of structure. As a result, insulation and façade structure should be kept in the same component with a common carbon budget. From a design viewpoint, the main benefits of resorting to target cascading include time-savings by the reduction of the design iterations. Decomposing the system into subsystems and components reduces the complexity of the overall design problem, and have higher benefits especially when applied to large scale multidisciplinary design problems (Liu et al., 2006).

Within the context of the built environment, target cascading has already been used in the past. It has, for instance, been applied to spatially decompose top-level building objectives of energy performance and comfort into two sub-objectives, for the office and workshop areas (Choudhary et al., 2005). Regarding *LCA* targets, only little research seems to have been conducted so far, although the concept can be considered embedded in the 2000-Watt society vision, that defines targets per capita (Jochem, 2004). The SIA, on the other hand, defines sub-targets for buildings and mobility (SIA, 2017a), and Kellenberger et al. assign targets for every building function (Kellenberger et al., 2012), in order to discriminate dwellings, offices, schools, hotels, etc. In all these cases, the focus is placed on the definition of objectives that the buildings will have to reach in the future, but in none of them have targets for individual components and systems of buildings been defined. Moreover, none of them has treated the definition of the targets as a way to simplify the design process of the building, or to guide the project towards demanding objectives. And yet, the target-cascading process could be considered as a way to increase the operationality of the problem formulation as described in section 1.3.2, while the targets themselves can help to save time in the design process by making the problem understandable and already part of the solution.

One major drawback of this approach might be that the designers' ability to have a holistic approach might decrease. Indeed, reasoning at the building component, rather than at the building itself might prevent to suggest a solution that is effective at the building scale but not at the component level. In a building, for instance, triple glazing will increase the embodied impacts of the building comparing to a double one, but the heating consumption will decrease as a result. Looking at the component only would lead to choosing the double-glazing, while at the big picture; the triple glazing could be a better strategy to decrease the carbon emissions. This is actually what can be observed in most of the current energy label and certifications where a global energy target is requested but also supplemented by other sub-targets as design guidance. As an example, the Minergie P label widely used in Switzerland applies the target cascading principle by setting up an overall target, namely a net-zero energy balance (*NZEB*) for the building. But it also imposes two sub-targets: to decrease the heating demand 10% below the Swiss building regulations and to limit the embodied non-renewable primary energy below 50 $kWh_{EPnren}/(m^2a)$ (Hall, 2013). As a consequence, a designer actually would not be allowed to choose to produce more renewable on-site energy to meet higher heating demands, even if the overall *NZEB* target is respected. This obviously decreases design freedom, and limits creativity in adapting a project's strengths to local specificities.

This literature review thus highlights that target cascading is a powerful approach to simplify the design process by reducing the scope of the carbon mitigation problem to the building element scale. Doing so, it might decrease the number of iterations between the design team members as they would be able to work separately on the different building elements. However, special attention has to be paid so that it is not at the expense of a holistic and creative design approach, where finding solutions at the element scale might also decrease the freedom to propose a design that would fit the building carbon objective but not the thresholds at the building element scales (*L5*).

3.1.5 Exploration methods

Increase in computing power, and now cloud computing dramatically reduces the time consumption of energy and LCA calculations. Thus it becomes possible to increase the method usability at the expense of the calculation complexity (Malmqvist et al., 2011). The parametric approach described in section 3.1.2 illustrated the possibility of generating a knowledge database as a source of references for the design iterations. However, the information overload was identified as a potential risk of this method. To face this issue, parametric assessment started to be associated with interactive visualization techniques, as proposed through exploration methods. As an example, Miyamoto et al. developed a visualization tool to highlight the effect of design parameters on the heating demand in early design phases. They reduced a building energy model to seven parameters (e.g. thermal transmittance or U value) to assess heating energy demand with a parametric approach (Miyamoto et al., 2015). In their approach, each parameter was quantified with three levels of performance (e.g. 0.2; 0.5; 0.8 W/m^2K for the U value) which meant that exploring all design solutions requires to perform and analyse $3^7 = 2{,}187$ energy simulations. They used the Excel software to generate all possible combinations and to simulate the heating energy demand with a simplified estimation method called "*Dynamic Equivalent Degree Day*". To make this database understandable and valuable for designers, a Parallel Coordinate Plot (*PCP*) (Inselberg and Dimsdale, 1991) was used as a visualization tool to explore the design possibilities and their heating demand consequences. Miyamoto's pioneering paper helps to demonstrate that the combination of parametric simulations with data visualization techniques can prove very powerful to allow architects to translate numerical language into visual representations. In addition, it shows that such an approach can be very useful for a quick understanding of each parameter's impact on the results and the interaction between them at early design stages.

Thanks to the literature, we can cite other research the combined successfully parametric approach and visualization techniques. Asl and co-workers, for instance, also used parametric simulation and a visual programming interface to tackle a multi-objective optimization process (Asl et al., 2014). Coupled with a cloud-based energy analysis tool, trade-offs between daylighting and energy were highlighted thanks to an optimization algorithm and an interactive *PCP*. Cianfrone, on the other hand, implemented a parametric analysis with more than 100,000 simulations performed with the EnergyPlus software to design low energy high-rise residential buildings (Cianfrone et al., 2016). They explored solutions outside the fundamental thermal principles for reducing loads, but according to architect and client desires (e.g. maximum glazing surface). This type of research illustrates that performance is not the only driver that leads the design, and that tools should also be able to propose alternatives that are not optima, but still achieve the client's objectives. The graphical display proposed through a *PCP* is effective at filtering parameter combinations according to targeted performance. The *PCP* highlights the diversity of the possible parameter combinations, according to a specified performance threshold.

Ritter and co-workers further proposed the "*Design Space Exploration Assistance Method*" (DSEAM) (Ritter et al., 2015). This research highlighted the necessity to propose an alternative to optimization algorithms, which do not help designers to find solutions that fit their own requirements. First, parametric and time-consuming simulations with the EnergyPlus software were performed to generate a first knowledge database. Then, on this basis, a metamodel was trained to enable rapid design space exploration thanks to a *PCP,* and to draw response surfaces with 3D charts to visualize two parameters and their related impact on energy consumption (*Figure 34*).

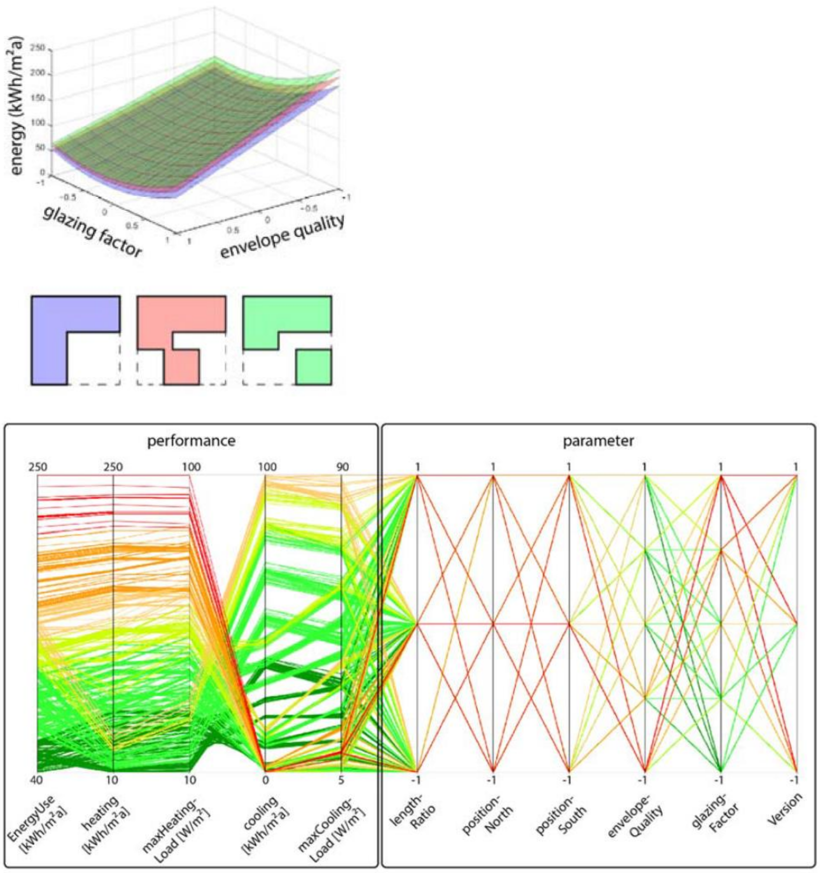


Figure 34: Visualization of the meta-model with the response surfaces (left) and results of the different office building variants that form the supporting points for the meta-model in the parallel coordinate plot (right). Courtesy of (Ritter et al., 2015)

Comparing these two different ways of visualizing the meta-model clearly points out that the *PCP* is the one that allows the most effective understanding of all dimensions at the same time. In addition, this multi-dimensional visualization of *PCP* is not only useful for the parameter input, but also for the resulting output (which could be obtained with different analysis tools if necessary).

The literature includes several interesting examples of exploration methods (e.g. (Flager et al., 2009; Miyamoto et al., 2015; Naboni et al., 2013; Ritter et al., 2015). However, in order to decrease calculation complexity, the number of parameters involved in these studies were typically quite limited (*L6*), and operative energy was the only considered impact. Exploration methods applied to *LCA*, with a much higher number of parameters able to describe the full building life cycle, were not found by the author. Another limit of existing applications of exploration methods lies in the method itself, as its usability is dictated by the way the building is decomposed into design parameters. In other words, designers cannot explore solutions beyond the already defined parameters (*L7*).

Coupling parametric and visualization techniques seems to be a promising way to explore a knowledge-database, as it was highlighted in the previous exposed literature. In other words, visualization techniques are essential components of exploration methods and will be further investigated in the next section.

3.1.6 Data-visualization techniques

Building Energy Performance Simulation (*BEPS*) research includes the development of new methods and software able to couple energy simulation algorithms with visualization techniques (Østergård et al., 2016). The aim is usually to support the design process based on *BEPS* datasets, generated parametrically from a baseline architectural model (Eleftheria Touloupaki and Theodoros Theodosiou, 2017; Feng et al., 2019; Hollberg, 2017). But researchers have also started to consider the dataset exploration itself as a powerful decision-making process (Haymaker et al., 2018; Hester et al., 2018; Miyamoto et al., 2015; Rezaee et al., 2019). More proactive usage of *BEPS* tools by creating a knowledge database and interacting with it becomes possible thanks to the faster creation of design alternatives, their performance assessment and an exploration process using Data Visualization Techniques (*DVT*).

However, at the same time, the assessment of thousands of variants necessarily increases the complexity of data interpretation. A study based on 28 interviews of building performance optimization experts (Attia et al., 2013) highlights that 75% of them do not have a proper Graphical User Interface (*GUI*) to process the assessment results, visualize patterns and explore input and output data. Most of the experts develop their own custom script to interpret results, with basic visualization techniques such as Pareto front, scatter plot, line graph, bar chart and time series. From the interviewees' point of view, optimization techniques are mostly used to explore the design space of alternative solutions, which they consider more relevant than finding the best one. Despite this exploration emphasis, one can note that in Attia's paper, none of the cited *DVT* fits this exploration wish as they do not allow the user to interact with the Graphical User Interface (*GUI)* in a proactive way. Based on this, there seems to be a missing link between the *BEPS* engineering and the data visualization domains. It remains indeed unclear which would be the suitable *DVT* that should be integrated by *BEPS* tools in order to support a data-driven design.

To explore bridging opportunities between these two domains, we will start by characterizing *BEPS* datasets, so as to set up criteria to be fulfilled by *DVT* might be suitable to explore this kind of data. In the following sub-section, various *DVT* will be highlighted via a literature review. Finally, these techniques will be ranked according to their ability to satisfy the requirements defined in the first section.

3.1.6.1 Requirements for data visualization techniques

DVTs can apply to a large spectrum of data, but their usability is highly dependent on the characteristics of the data themselves. Thus, the purpose of this section is first to define the *BEPS* dataset specificities. Secondly, tasks that should be performed by decision-making tools to support the design process are identified. Datasets specificities and tasks will be used as requirements (*Rn*) for the data visualization techniques selection. They are identified from (*R1*) to (*R8*) within this section.

A. BEPS dataset characteristics

BEPS datasets are the result of simulations that estimate the output value for a given combination of dimensions. They usually include ten to twenty dimensions (Jusselme et al., 2016; Miyamoto et al., 2015) and several output values representing the performance of each design alternative.

A literature review of techniques that allowed to create *BEPS* datasets was first performed. Among these techniques, one can cite approaches involving parametric analyses (Hollberg and Ruth, 2016; Jusselme et al., 2016; Lolli et al., 2017), those dealing with sensitivity and uncertainty analysis (Heeren et al., 2015; Hopfe and Hensen, 2011; Tian, 2013b), methods that include a multivariate regression (Catalina et al., 2013; Hygh et al., 2012), and those that include meta-modelling (Eisenhower et al., 2012; Manfren et al., 2013).

Based on their method and findings, we can make the following statements:

- *BEPS* datasets are characterized by input values defining building parameters that are chosen to feed the workflow, and output values, which are the *BEPS* assessment results. Inputs are discrete values composed by either ordinal (e.g. thermal transmittance U=1 W/m2.K) or categorical data (e.g. type of insulation, say Rockwool). Outputs are either continuous (e.g. CO_2 emissions of 10 Kg CO_2-eq./m².y), discrete or categorical data (e.g. ‘good’ thermal comfort).
- Inputs and outputs can be correlated (e.g. photovoltaic panel surface and energy performance) or non-correlated (e.g. photovoltaic panel surface and heating demand).
- Datasets have a medium size: they are too big to be understandable with traditional graphical tools, but not large enough to be processed using “*big data*” methods, which deal with terabytes of information. Datasets coming from *BEPS* are generally sized from hundreds to hundreds of thousands of design alternatives. In Naboni’s research for example (Naboni et al., 2013), a parametric analysis involving 8 parameters required the calculation of 221’184 design alternatives.

As a conclusion, an exploration of *BEPS* datasets needs DVTs that can be used with heterogeneous data (*R1*), with different correlation levels (*R2*) and a medium database size (*R3*).

B. Tasks required by BEPS tool users

In early design stages, designers do not require accurate simulation results, but rather “*an understanding of the relative effect on performance due to changes in design alternatives*” (Bambardekar and Poerschke, 2009b). The priority for the designer is to get “*a qualitative and overall design direction*”. Such a tool should allow the visual exploration and assessment of the potential solutions’ space and should be able to generate new solutions if required. A key remaining challenge is to focus the attention of the designers on the most important parameters and to integrate simulation feedback into their design process (Ibarra and Reinhart, 2009; Reinhart et al., 2012). According to Huot, numerous studies about the design process highlighted three main activities: exploration, solution generation and evaluation (Huot, 2005a). An appropriate decision-making tool should integrate these tasks, allowing for smooth user-machine interaction.

Exploration
Exploration brings together the prior learning of the designer and the external data that he/she will have to gather and assess on the subject. Exploration allows the designer to better understand the constrained problems – correlations, patterns – by tuning parameters.

A more detailed list of tasks that the designer should be able to execute would be the following:

- Dataset overview (*R4*): being able to get an overview of the whole dataset, with all its dimensions at a glance.
- Impact of parameters (*R5*): identifying the parameters with the highest impacts on the assessment results.
- Similarity task (*R6*): identifying the strength of correlations between input and output, patterns and clusters.
- Frequency task (*R7*): identifying the most represented parameter values.

Solution generation
Generating a solution is here defined as filtering the database to keep one or a family of design alternative that complies with a set of constraints. As previously discussed, the designer should be able to make decisions based on feedback from BEPS software, rather than prior experience (Bambardekar and Poerschke, 2009b). These solutions can then be compared and the best one can be selected, according to the designer's own preferences and other criteria such as norms. Then, the filtering task (*R8*) would be: being able to set constraints – e.g. norms, cost, preferences – based on parameter values, in order to filter out the undesired alternatives.

Evaluation
The third step consists of selecting the most convenient solution within the solutions space. It is up to the designer to assess the solutions, giving more importance to some criteria. The evaluation is permanent during the creative process, often raising the need to take the first two steps over again. This task would be covered by the same filtering task (*R8*) previously described.

C. Data visualization techniques specifications for BEPS datasets

Multidimensional *DVT* should allow to compare different solutions while fitting the designer's creative process. Choosing a set of parameters to define a building can be seen as an under-constrained configuration task: no optimal solution exists, and the final choice depends on both qualitative – e.g. aesthetic preference, – and quantitative criteria, e.g. based on performance thresholds. Such tasks thus involve both the human and the machine: the user is actively involved in the decision-making process and needs to choose among a set of acceptable solutions. A constraint is a requirement that has to be fulfilled for the solution to be valid, like a numerical value representing cost or performance for instance.

In summary, based on these dataset characteristics and on the already identified user needs, we can set the following key requirements for visualization techniques applicable to *BEPS* multidimensional dataset: *R1* Dataset size <100k; *R3* Data type; *R4* Overview; *R5* Impact; *R2*, *R6* Similarity/Correlations; *R7* Frequency; *R8* Filtering. These specifications will be used in the next chapter in order to qualify different *DVTs*.

3.1.6.2 Overview and selection of data visualization techniques

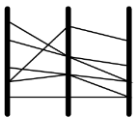
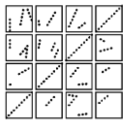
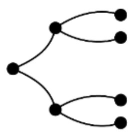
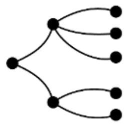
Data visualization is a powerful way to provide the user with insights and useful information about very complex problems (Agrawal et al., 2006). Complementing it with interaction techniques allows the user to actually explore a dataset and ideally solve problems in real-time. A very delicate compromise usually has to be established between the amount of information, simplicity and accuracy, especially in the case of multivariate *DVT* (Chan, 2006). As opposed to fully automated systems, Mixed-Initiative Systems (*MIS*) involve the user in the problem resolution process (Horvitz, 1999), and are therefore useful in optimization problem solving since "*non-expert users [...] prefer an incremental and interactive procedure to build solutions rather than a completely automated approach*." (Cortellessa, 2006). *DVTs* actually play an important role in Mixed-Initiative user interfaces, as they give the user visual cues and information, reducing his cognitive load (Pu and Lalanne, 2002).

A. A first overview

A selection of DVT applicable to multivariate and multidimensional data has been established by means of a literature review of reference datasets pertinent to this study, but typically found in domains other than architecture or building performance. Table 3 summarizes the potential of each technique to fulfil the requirements *R1* to *R8* that have been listed in the previous section.

A usability assessment of all these techniques would have been too time-consuming, that is why we suggest here a first qualitative ranking by rating each DVT according to its potential to fulfil the requirements: “+” is associated with a high potential to meet the requirement and is credited with 2 points, “-” means that the requirement may be hard but is not impossible to meet, and credited with 1 point. “ø” means that the DVT cannot fulfil the requirement, and is credited with -1 point. In the end, each DVT is ranked according to the resulting sum of all individual scores.

Table 3. A comparison of data visualization techniques for Building Performance Simulation dataset. Scoring: +=easy to reach (2pts); -= hard to reach (1pts); ø: impossible to reach (-1pts)

	Parallel Coordinates 	Parallel Sets 	Scatterplot Matrix 	Decision Tree 	Dendrogram 	Force Directed 
Requirements	(Davies, 2017a)	(Davies, 2017b)	(Bostock, 2017a)	(Schumacher, 2017)	(Bostock, 2017b)	(Bostock, 2017c)
R1 Size <100k	+	+	+	+	-	-
R3. Data type	+	ø	-	+	+	+
R4 Overview	+	+	-	-	-	-
R5 Impact	-	-	-	+	-	-
R2-6 Similarity	-	-	+	-	-	-
R7 Frequency	+	+	-	-	-	-
R8 Filtering	+	+	+	-	-	-
Score (points)	12	9	10	10	8	8

With a few visual enhancements such as alpha blending (i.e. playing with the transparency of the data), jittering (i.e. adding random noise to data), or frequency encoding (for categorical data), the first four *DVTs* can handle 100,000 design alternatives. Parallel Coordinates and Parallel Sets allow the assessment of the correlation between adjacent dimensions, i.e. they require the user to reorder the dimensions if non-adjacent. While both of these visualization methods are the most effective at assessing the frequency of a given parameter value amongst the ones selected in Table 3, there is a significant drawback with Parallel Sets due to their inability to handle continuous parameters, ultimately making them useless for a *BEPS* dataset. In contrast, the Scatterplot Matrix is designed for continuous values, and represents categorical results in heavy over-plotting. In this case, jittering and alpha blending can improve the visualization to some extent. However, the number of dimensions should stay under 10 to remain readable.

The Decision Tree is, on the other hand, the most suitable to show the impact of parameters. Dendrogram and Force-directed do not scale well with the dataset size, as they need to represent each design alternative as a node, and thus require a lot of space in order to display all the data. Decision Tree, Dendrogram and Force-directed are not appropriate for comparisons across dimensions but are a good way to find clusters of design alternatives. However, they do not implement a filtering interaction, and thus require the use of link and brush interactions with an external filtering method.

Harrison et al. recently expanded on previous work by studying the perception of correlations in Parallel Coordinates compared with eight other visualization techniques: scatterplots, stacked areas, stacked lines, stacked bars, donuts, radar charts, line plots, and ordered line plots (Harrison et al., 2014). 1,687 participants took part in the test, using a crowdsourcing platform. The task was to judge the strengths of different correlations. Their results are consistent with the work from Li et al. (Li et al., 2008), in which scatterplots depict correlations better than Parallel Coordinates.

In the end, considering this first qualitative approach, Parallel Coordinates seems to best suit the requirements of a *BEPS* dataset visualization. Second comes the Decision Tree, as it can handle more than 10 mixed categorical and continuous dimensions quite well. The next sections give a more qualitative analysis regarding the tasks that these two techniques should support, as they emerged as the most promising based on the scoring of Table 3.

B. Parallel Coordinates

The most popular visualization method to represent multivariate multidimensional data is in the form of Parallel Coordinates (Inselberg and Dimsdale, 1990). They have been successfully applied to a large range of multidimensional problems (Rodriguez and Nancy, 2016) in many different fields, from life sciences to engineering or finance (Heinrich and Weiskopf, 2013). In practice, such datasets contain up to some 10-15 dimensions (Kosara et al., 2006). Moustafa (Moustafa, 2011) states that Parallel Coordinates are becoming an "*essential tool for visualizing hyper-dimensional numerical data from almost all real-life applications* [...]".

They rely on a parallel layout in terms of axes: the horizontal spatial position is used to separate axes, the vertical spatial position is used to express the value along each aligned axis, and each data item is depicted as a polyline intersecting all the axes. Parallel Coordinates allow the user to set constraints: filtering the dataset is done by selecting a range of values for each parameter (an action called brushing). Parallel Coordinates can be used to select a set of parameter values that define a building design and to assess whether the solution is valid i.e. whether the output values from the output axis are below a given threshold (e.g. price, comfort, or energy consumption).

Parallel Coordinates can be displayed in other layouts: vertical, and star layouts. The star layout is better when there are inliers in the data: "*homogenous records [...] appear as distinct star shape*" (Moustafa, 2011). A connecting line between two entities shows the relationship between two axes in an explicit way:

this is especially pertinent to spot trends (Munzner and Maguire, 2015) and can be used to identify an individual data item.

Parallel Coordinates are well suited for the type of tasks that we mentioned in the previous section. Without the use of any enhancement method, the number of items is limited to a few hundred. 100,000 items can be represented by adding clutter-reduction methods such as jittering or alpha blending to the polylines. Parallel Coordinates can assist in the identification of highly discriminant dimensions (Moustafa, 2011), and make the assessment of correlations strength easier. The connecting lines indeed enable to identify correlated dimensions: a high positive correlation will be characterized by a set of parallel segments, while a negative correlation will correspond to set of segments crossing over at a single point. However, this only allows a pairwise comparison between neighboring axes, and visible patterns ultimately depend on the ordering of axes. This requires the user to test all possible configurations of axes, which becomes time-consuming as the number of dimension increases.

Parallel Coordinates are thus helpful in data mining tasks such as the identification of clusters and the exploration of class properties. They allow the user to identify the most represented parameter values. For the larger datasets, jittering and alpha blending can be used to restore the frequency information.

C. Decision tree

Decision trees are a very common decision support tool. Although they cannot be considered true exploratory tools, they make it possible to *"[...] break down a complex decision-making process into a collection of simpler decisions, thus providing a solution which is often easier to interpret*." (Safavian and Landgrebe, 1990). The first step in the construction of a decision tree is a learning phase. It is initiated taking a set of vectors as input, each belonging to a known class: several machine-learning algorithms will then help to determine which attributes best divide the data between the classes, based on impurity measures.

As an example, the C4.5 algorithm is an Information Gain algorithm. It selects the parameters that best split the target class into the purest possible children nodes. In other words, the parameters with the highest scores are the ones that best divide the samples between the two classes. It places the most important parameters closer to the root of the tree. By adding collapsible nodes to the decision tree, only the most important parameters are initially shown to the user. In order to get a full set of parameter values, the user has to click on the children nodes until a leaf is reached.

Tree nodes can be visually enhanced with two types of visual cues: a color coding (e.g. green vs. red) can, for example, show the ratio of each class included in the leaves represented by the node. The size of a node can indicate the number of design alternatives included in the subset.

The decision tree is not highly scalable in terms of dimensionality. As stated by (van den Elzen and van Wijk, 2011), "*For a decision tree to be understandable, its complexity should be low, which can be measured by the following metrics: (1) the total number of nodes; (2) total number of leaves; (3) tree depth; (4) number of attributes used*". Small trees containing fewer attributes are therefore preferred. This method imposes a ranking of parameters and is thus optimal for assessing the impact of parameters on performance. Each node represents a parameter value, and the depth in the tree depends on the impact, allowing the user to quickly detect the most important parameters. The decision tree only shows the strength of the relationship between the class and the parameters. There is no relationship between the rate of correlation of two attributes and their position in the tree.

3.1.7 Synthesis

Methods to extract knowledge about energy or environmental performance of buildings at early design stages have been reviewed. *LCA* is widely used to have a comprehensive assessment of the building environmental impacts. However, this methodology is time-consuming (*L1*). In addition, *LCA* is hardly usable at an early design stage, because of the mismatch between the project resolution detail and the *LCA* detail needs (*L2*). Finally, *LCA* results are specific to a case study, but also to the scope of study that differs from one project to another. This makes the results non-generalizable (*L3*).

On the other hand, the design process is iterative as it involves multiple quantitative and qualitative criteria. The parametric analysis allows to accelerate the generation of design alternatives as references that will feed the process, but so far have been commonly used only to optimize a project rather than providing design alternatives, as put forward in the reviewed exploration methods.

Through a new approach, the benefits of the parametric assessment could become the exploration of the design alternative database that it generates and not the optimization process. However, suitable exploration techniques that fit the LCA specificities still have to be developed to extract knowledge from a database (*L4*). Another limitation of the parametric assessment when it comes to *LCA* is the high number of design parameters needed to describe all the building components, which substantially influences the performance (*L6*). Very little research has already coupled parametric assessment and *LCA*, and results have been limited by the simplification of the description of the building model. A new trend we observed in the literature consists of coupling techniques, such as parametric assessment and visualization techniques seem promising to support the exploration process.

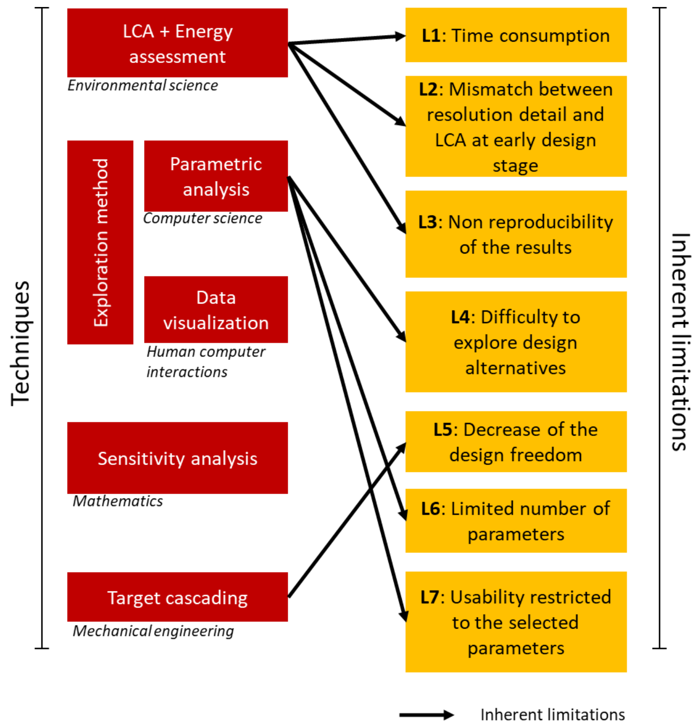


Figure 35: Promising techniques for increasing LCA usability at early design stages and their identified inherent limitations.

More specifically, combining data-visualization techniques such as parallel coordinate plots with decision-trees offers a lot of potentials when it comes to exploring BEPS datasets. However, the usability of such methods is currently limited by the way buildings are divided into parameters, and by the way these parameters are qualified (*L7*): as an example, the possibility to reach a target with aluminium-framed windows cannot be explored if aluminium or window are not included as individual parameters inside the database. Also, exploration methods have never been applied to *LCA* so far. Finally, target cascading may offer interesting guidance for designers by fixing sub-targets and then decreasing design iterations and its time consumption. However, the decrease in design freedom is seen as an important risk (*L5*).

Figure 35 summarizes the various techniques that have been identified in this chapter as promising to increase LCA usability at early design stages, and summarizes their most problematic limitations in this context. The following chapter will introduce a new LCA-based method, that managed to couple these techniques and to address their seven main limitations.

3.2 A new LCA-based data-driven method

3.2.1 Towards a system of references

References are crucial to include in an iterative design process, as previously discussed in section 1.3.2. As far as the nature of these references goes, the ethical/aesthetic pairing can be interesting to highlight (Younès and Paquot, 2000). Hence, we can identify two types of references that could facilitate an iterative design process between formulation and problem-solving (cf. section 1.3.2). First, there is the architectural corpus as a reference to aesthetics. The richness and diversity of formats (photos, sketches, drawings, etc.) allow this dimension to be easily and frequently integrated into the design process. Then there is the problem and its context as a reference to ethics, including the issue of climate change. Here, it is necessary to note the poverty of the deposit. One way of providing such references would be to create a catalogue of low carbon buildings as a system of references usable by designers. However, there is not any database of low carbon buildings so far that would be large and detailed enough to serve as a knowledge-database, probably because of the following reasons:

- The recent awareness of climate change limits the number of low carbon buildings that can be considered as references. For instance, only 350 Net Zero Energy Buildings have been referenced worldwide by the IEA in the Solar Heating and Cooling Programme ("IEA SHC || Task 40," n.d.), and they could not be considered as low-carbon buildings as they did not follow a life cycle approach,
- The expected and constant reduction of the *GHG* emission thresholds during the next century (SIA, 2017a), which will make the few available references quickly obsolete,
- The lack of uniformity in the technical description of buildings which do not use the same format to store the collected data, and do not use the same method for the performance assessment that would enable to compare the performance of one building to another (L3 in section 3.1.7).

Therefore, considering the limitations to constitute a catalogue of existing low carbon buildings, we suggest in the next section a parametric workflow to generate a system of references as a knowledge-database to support an exploration process.

3.2.2 Description of the method

3.2.2.1 Parametric analysis as a design alternative provider

The parametric assessment generates thousands of simulations, which makes result interpretation very challenging (*L4*). Data visualization techniques such as *PCP* allow getting knowledge about the data in order to address this issue. An exploration method can be defined as the association of parametric analysis and data visualization.

With current techniques, it would not be possible to investigate all the solutions, as the number of design parameters used in *LCA* is too high for a reasonable computational time (*L6*). In Naboni's research (Naboni et al., 2013), 221,184 alternatives were computed in 71 hours for 8 design parameters, qualified by up to 16 performance levels. However, the scope of this research was limited to the operative energy consumption. In a previous co-authored work (Jusselme et al., 2016), a building has been decomposed into 17 significant design parameters. Without considering a higher computational cost per design alternative for an *LCA* (which is obviously optimistic, as embodied impacts have to be calculated in addition to operating impacts), increasing to 17 design parameters and 4 performance levels each, the parametric analysis that covers the full design space means performing $1{,}7\text{x}10^{10}$ simulations. This is, of course, incompatible with the design process timeline. Even if we consider Moore's law i.e. doubling the computing performance every two years, and considering the computational time from Naboni's research, it would take more than 17 years to develop a cloud-computing infrastructure that would enable to perform this amount of simulations in 71 hours. That is probably why no exploration techniques based on *LCA* have been found in the literature review so far.

3.2.2.2 Sensitivity analysis as a sampling process and design support technique

There are two solutions to reduce the computational time to a reasonable length. First, by removing from the parametric simulation some of the parameters that do not affect *GHG* emissions. Second, by reducing the simulation resolution thanks to a sampling of the parameter combinations. According to the literature review, this would be possible with a sensitivity analysis that provides a sampling of the parameter combinations and a ranking of the parameter sensitivities. Sensitivity analysis proceeds by changing the parameters of a simulation model. It provides a wide range of parameter combinations, shows their effect on results, and can help designers to choose the most suitable path to achieve their goals. In addition, it assesses the robustness of these combinations in relation to the future adaptability of the building, considering parameters that allow the highest amount of combinations to reach an environmental target.

The Sobol method seems to be interesting for that purpose, as this variance-based approach gives quantitative sensitivity results and provides a low discrepancy sampling to evenly screen parameter combinations. Ruiz and co-workers (Ruiz et al., 2012) demonstrated in their case study that only 8 parameters out of 64 were responsible for 80% of the variance regarding the electric consumption of buildings. Therefore, when reducing the computational cost by combining parametric analysis, sensitivity analysis and data-visualization, an *LCA*-based data-driven design method can be envisaged that would solve four of the identified limitations: *L1*, *L2*, *L4* and *L6*.

3.2.2.3 Target cascading to increase the usability of the method

The proposition as it is previously described still has three unresolved consequences previously identified as *L3,* and *L7*. First, *LCA* results will still not be generalizable (*L3*). Second, the usability of the knowledge database will be limited to the design options that were used in the parametric approach. Hence, designers will still not be able to explore the whole design solution domain (*L7*), as the design alternative exploration will be limited by the way the buildings have been decomposed, and by the way parameters have been described.

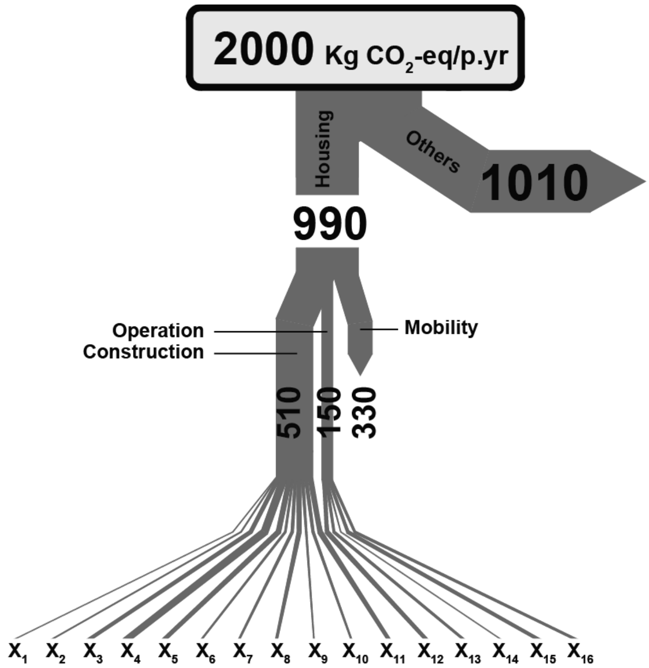


Figure 36: Target cascading with a top-down approach from the 2000W society vision and its 2050 intermediate target of 2 tons of CO_2-eq per people and per year, toward sub-targets: operation, construction and induced mobility of housing. These sub-targets are finally decomposed into GHG emission objectives at the component and system level X_n (Jusselme et al., 2015b)

Section 3.1.4 identified an interesting way to address these problems, namely the target cascading approach, as it would decompose the building into subsystems and building components. However, no research has tried to define targets for components and systems of buildings so far and it has never been used as a decision-making method to guide designers towards building environmental performance. Recently, Jusselme et al. used the target cascading approach to decompose the 2000W society objectives into subsystems (i.e. building function) and component targets (Jusselme et al., 2015b). A Sankey diagram (Schmidt, 2008), was used to identify the *GHG* emission fluxes from the 2000W society top-level targets (2 tons CO_2-eq/p.y in 2050) to the component level targets (Figure 36).

Following this work, Hoxha and co-workers introduced *GHG* emission targets at the building component level as a guideline for designers (Hoxha et al., 2016). A project population was generated by means of a sensitivity analysis. Targets were attributed to each component and system of a case study. These targets, or carbon budgets, allows to better understand the environmental weight of each component in the global system. The parametric analysis provides a knowledge database of design alternatives as a ground material to set up targets at the component level, as proposed in previous co-authored work (Hoxha et al., 2016). Moreover, target cascading combined with exploration methods allow fixing specific targets, integrating the designer's choices. To push further the example of the triple glazing that was suggested in section 3.1.4, if the designer wants to explore a design situation where the building has a triple-glazing, the knowledge-database will be filtered to select a subpopulation with projects that have triple-glazing only. Doing so, the target cascading of this sub-population will automatically integrate the embodied impacts of the triple glazing, and the benefits it has on the heating demand. Therefore, a flexible approach of the target cascading is possible if it is dynamic and specific to the design situation. By coupling exploration and target cascading, it is possible to integrate a building component or system that was not used initially in the parametric approach that generated the knowledge database, into an architectural strategy as long as the user is able to know the carbon emissions of this new component and if it fits the component carbon budget.

In synthesis, the target cascading makes it possible to define carbon budgets that are reproducible from one project to another, tackling the “Non-reproducibility of the results” limitation (*L3)*. Indeed, even if each carbon budgets are specifically calculated to a project, the sum of all budgets will always fit the overall building performance threshold defined by SIA2040, no matter of the project context. Moreover, a target at the component scale allows the user to assess the compliance of a design option that would not have been integrated into the parametric approach, by comparing the carbon emissions of this option with its carbon budget. It allows thus to extend the usability of the knowledge database beyond the design options it includes, facing that way the seventh limitation (L7).

3.2.2.4 Coupling five techniques as an LCA-based data-driven method

In previous research, Østergård et al. proposed a simulation framework coupling parametric simulations, statistical analysis, and visualization techniques “*with the ambition to facilitate proactive, intelligent, and experience-based building simulations*” (Østergård et al., 2016). Their main goal was to develop a knowledge-database that helps integrating energy performance objectives within the design process. Thousands of simulations were run in that study to cover a design space based on a building model. A statistical analysis of these simulations allowed calculating the energy demand sensitivity to the design parameters. Finally, a PCP allowed an exploration of the knowledge-database. We suggest extending and adapting this workflow to the LCA specificities, with the combination of *LCA*, parametric analysis, data visualization, sensitivity analysis, and target cascading to offer a powerful basis from which to develop an *LCA*-based data-driven design method.

All these techniques are involved in the new method illustrated by Figure 37. This figure updates Figure 35 which was only highlighting the inherent limitations of these techniques. The pertinence of their combination lies in their answer to the inherent limitations identified on the right. In synthesis, we understand thanks to this figure that upon three of the LCA limitations, the time consumption of the method (L1) and the resolution detail mismatch (L2) are lowered by coupling LCA and a parametric approach, which lead to generating a knowledge database. However, the database will be difficult to explore (L4) and support the design process, this is why our proposition added visualization techniques as a component of this new method. Coupling parametric analysis and data visualization techniques lead to what we called an exploration method. However, at this point, there are still limitations that have not been tackled yet. Indeed, a parametric approach is limited in terms of number of parameters that can vary for computational issues (L6), and this limited number of parameters will decrease the design options that can be tested in the knowledge database, lowering its usability (L7). Thanks to the target cascading, it is possible to propose a carbon budget at the building component scale where the sum of all this sub budget equals the upper limit of the building carbon emissions. As a result, it allows comparing this carbon budget to any component that would not have been involved within the parametric approach, increasing the usability of the technique. These carbon budgets can easily be reproducible from one project to another, guiding architects and engineers towards compatible solutions with the SIA2040. In a very different building context, using these specific budgets might be challenging, but still usable as their sum equals anyway the SIA2040. Finally, we proposed to add the sensitivity analysis to the method, as it is a powerful way to highlight the parameters that have the lowest influence on the life cycle impacts, enabling thus to remove them from the parametric approach and decrease the computational issue (L6).

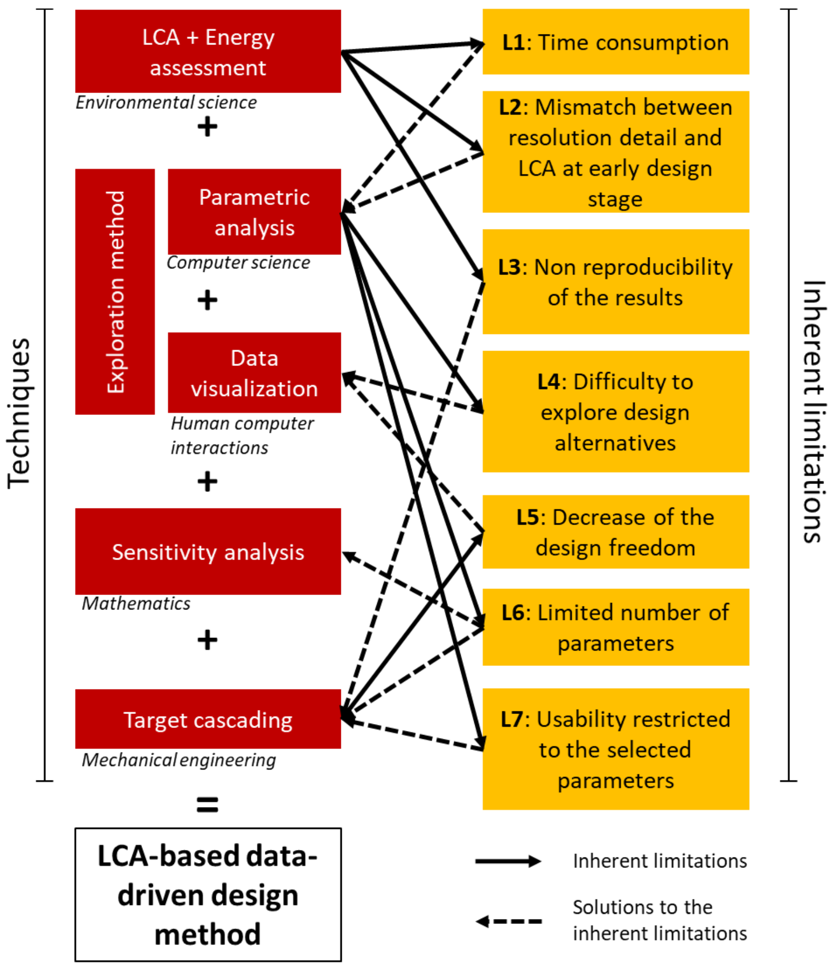


Figure 37: Technique combination towards an LCA-based data-driven design method. Techniques on the left, inherent limitations identified on the right, which can be tackled by other techniques. Text in italic font specifies the original scientific field of each technique.

3.2.3 Description of the *LCA*-based data-driven design method

This section aims to describe the *LCA*-based data-driven design method, as it should be implemented in a computer program. Figure 38 represents the method in five major steps that have to be completed in sequence and can be performed with various software and tools. A technical proposition for its computer-based implementation will be proposed later in Chapter 4. The five steps can be iterated several times within the design process, as long as undefined variables exist in the design space. Each iteration will enable the designer to make choices within a new design space delimited by the design parameters that have been previously defined. It will help to better understand which are the variables that have to be carefully considered, i.e. that have the highest sensitivity indices, and which are the design options that can bring the highest benefits to reach a specific environmental target. Thanks to the different iterations of the method, this can be done progressively according to the level of details of the project, and thus according to the design space that is valuable to explore.

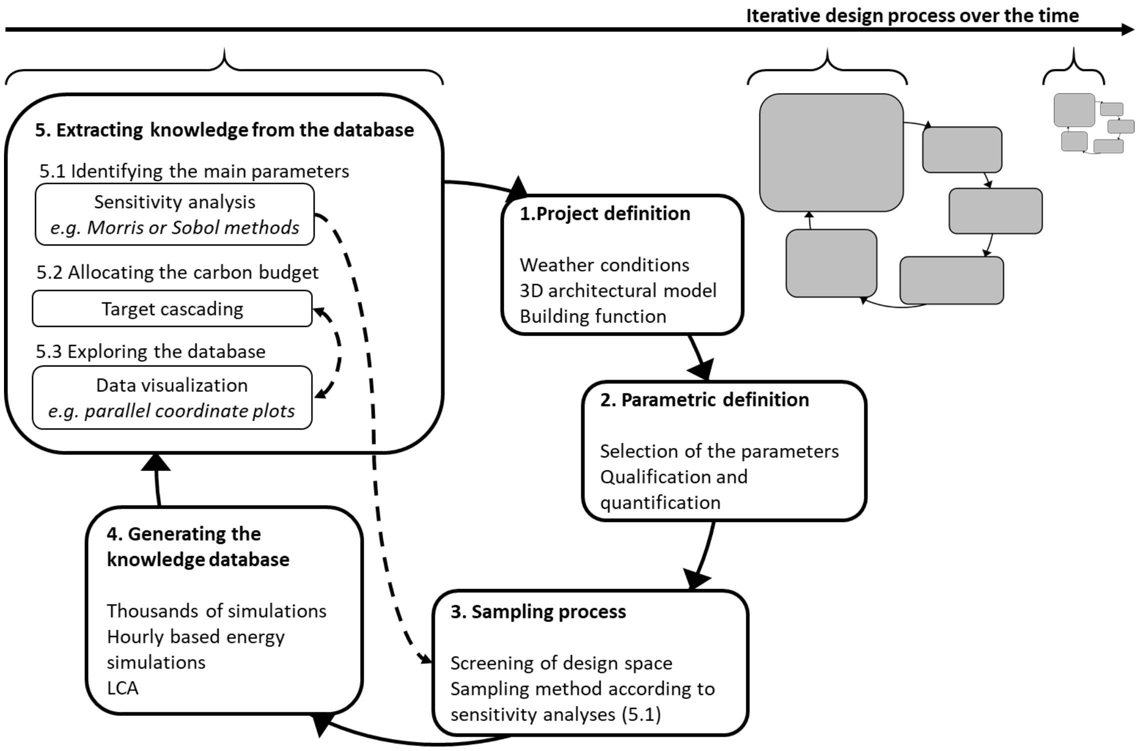


Figure 38: Description of the LCA-based data-driven design method. The five steps of the method can be replicated all over the design process timeline.

Step 1 - Project definition: the project is described and located in a specific context. A weather file corresponding to the project location is selected. The architectural project is described by choosing an archetypal geometry, or by importing a 3D model. Finally, the building function is required to define the building's occupation scenario. The simulation software will further use all this information as the main hypotheses. It will also ensure that the design alternative database is unique and specific to one architectural project.

Step 2 - Parametric definition: the scope of the design space that the method will cover is described. Designers select the design parameters that matter for them according to the level of detail of the design stage they are. Each parameter is qualified or quantified in different values within boundaries that have to be chosen in line with the designer's practice and wishes:

- Example 1: design parameter is thermal resistance of the walls, ranging between 0.1 W/m²K and 0.2 W/m²K in five steps of 0.02 W/m²K,
- Example 2: design parameter is insulation material with 3 options available (wood wool, rock wool and polystyrene).

The iterative nature of the method might lead the designers to adapt the parameter definition according to the knowledge they learned from a first database.

Step 3 - Sampling process: design alternatives are described by combining all the design parameter values. The number of design alternatives, that will be generated by the sampling process to cover the design life cycle space, will depend on the number of design parameters and their values. Current exploration methods focus on the building occupancy phase and limit the number of parameters to five or six in order to have a reasonable computational time. However, in our case, the methodology has to be used at an early design stage for a better efficiency, where the design space is the widest. In addition, the whole life cycle of the building must be analyzed, which increases the number of parameters influencing the results.

In this method, the sampling process of the sensitivity analysis shall be used to generate a database with the highest number of design alternatives according to the available computational power, if covering the full combinations is not technically feasible.

Step 4 - Generating the design alternative database: all the design alternatives, consisting of parameter combinations (Step 3) applied to the building geometry (Step 1), are assessed with an energy simulation tool and a life cycle assessment tool. This step generates the ground data from which all the knowledge will be extracted. Tools have to be chosen according to the metrics that designers want to assess, but also according to their time consumption.

Step 5 - Extracting knowledge from the database thanks to various techniques.

- **5.1:** The sensitivity analysis used as a sampling process in step 3 provides the sensitivity index of all the design parameters. This enables us to reduce the number of parameters while exploring the database, so as to focus only on the most impactful parameters. The entire method could also be used in a two-step process by following the dashed arrow in Figure 38. Based on the results of the sensitivity analysis, Step 2 is redefined according to the most influential parameters (removing the others from the parametric analysis), and steps 3 and 4 generate a knowledge-database with a higher design space resolution on more influential parameters and within the same computational time. By doing so, the sensitivity analysis contributes to face the *L6* issue, which is induced by the high number of parameters required to perform an *LCA*. The sensitivity analysis can be performed on the full database, but also only on the design alternatives within this database that fulfil constraints chosen by the designer while exploring the database. As an example, the *GHG* sensitivity of the insulation quantity of a subpopulation of design alternatives, which have a wood boiler as a heating system, will be far lower than the subpopulation that uses a gas boiler. By linking exploration techniques and sensitivity analysis, the designer is guided to explore the most influential parameters according to his/her previous choices, and not according to the full database.
- **5.2:** At this stage, the method still has to face three issues identified in sections 3.1, 3.1.4 and 3.1.5. First, target cascading approach enables us to address *L3* and *L7*, i.e. the non-generalizability of the results, and the usability limited to the selected parameters. Linking the target cascading to the exploration of the database allowed to automatically calculating targets at the component level, specific to a design situation, giving independent and specific objectives to the designers (the carbon budget for windows considering a concrete structure). Second, it also consequently addresses *L5*, namely the risk of decreasing a holistic design, as targets become specific to a design situation. As an example, it is possible to define a specific carbon budget for the windows according to a building with a concrete structure. Thus, the remaining carbon budget of the windows will be automatically updated according to the carbon that will be emitted for the concrete structure. It becomes possible for designers to compare any windows they want to use to this carbon budget, and then to validate its adequacy with a specific design strategy (the concrete structure in our example), and with a specific building performance threshold, even if this window is not in the database as a design parameter. In addition, these targets can be further used as guidelines in other projects to start the design process, thus allowing a generalization of the results.
- **5.3:** Finally, data visualization allows us to explore the set of design alternatives and their respective performance, using *PCP* technique for instance (cf. section 3.1.5). The sensitivity indices could help the user prioritizing the dimensions to be explored. By filtering the data, the target cascading approach could dynamically adjust the carbon budget allocated to building components, so as to be consistent with the selected sub-population of the database.

3.2.4 Synthesis about the LCA-based data-driven method

In section 2.4.1, it was pointed out that the design process is iterative and needs references to support these iterations. However, there is a lack of built references that prevent us to create a knowledge database with existing buildings. Thus, the first objective of the method is to generate a system of references that will be used as the knowledge database in order to support the decision-making process. To do so, we propose to combined five techniques in a single workflow as an *LCA*-based data-driven design method. These five techniques are *LCA*, parametric analysis, data visualization, sensitivity analysis, and target cascading.

Exploration methods already exist and couple parametric assessment with data-visualization in order to provide design alternatives within the iterative process. However, they are currently limited to assessing impacts on operative energy in buildings. Adapting exploration methods to *LCA* means increasing the complexity of the simulation model by adding all the other life cycle stages, e.g. materials and components, as embodied impacts. By doing so, the number of variables increases and a priori prevents designers from investigating the full possible parameter combinations of the design space. A first solution would have been to over-simplify the *LCA* simulation model in order to decrease the number of variables, but this would have led to a lower robustness of the results and a weaker impact of the results on the design.

Instead, this thesis proposes a second solution that might have more potential: exploring the *LCA*'s complexity, rather than simplifying it. Keeping the complexity of the *LCA* simulation model allows identifying more precisely the design parameters that contribute most to the performance of the building. It also gives the possibility to better explore correlations between them. Human-computer interactions, and specifically the information visualization research field, already developed data visualization techniques enabling the exploration of large and high-dimensional datasets. However, *BEPS* datasets have particular characteristics. They embed multivariate and multidimensional data, which have different levels of correlations and have a medium size, generally up to a hundred thousand design alternatives. In addition, the dataset analysis should aim to support the design process through specific tasks that might allow to explore, generate or evaluate solutions based on designer's requirements. By crossing *DVT* and *BEPS* user requirements, a first selection of techniques has been made. Parallel Coordinates, Parallel Sets, Scatterplot Matrix, Decision Tree, Dendrogram and Force Directed techniques have been compared, and a qualitative ranking according to our understanding of the literature review allowed the selection of the two most promising ones, namely the Parallel Coordinates and the Decision Tree.

The computational cost induced by the exploration approach can finally be lowered thanks to a sensitivity analysis, using a sampling technique that limits the dataset to a reasonable computational time and narrowing down the design alternatives diversity to the most influential parameters. Target cascading has been identified as a powerful technique. Coupled with an exploration approach, specific targets can be fixed at the component or system level, and at the same time solve the issue of non-exhaustively exploring alternatives. However, further development on this technique must be carried on, as target-cascading applied to buildings brings part of the added-value of the proposed method but is a new proposition, and will thus be evaluated further within this thesis.

In a nutshell, the method proposes to increase the LCA usability by increasing the knowledge that could be extracted from the method, represented by the grey arrow on the left of Figure 39. At the early design stage, this potential is usually very low and typically follows the dashed grey curve. The proposed method instead allows exploring the whole design space represented by the grey surface in this graph.

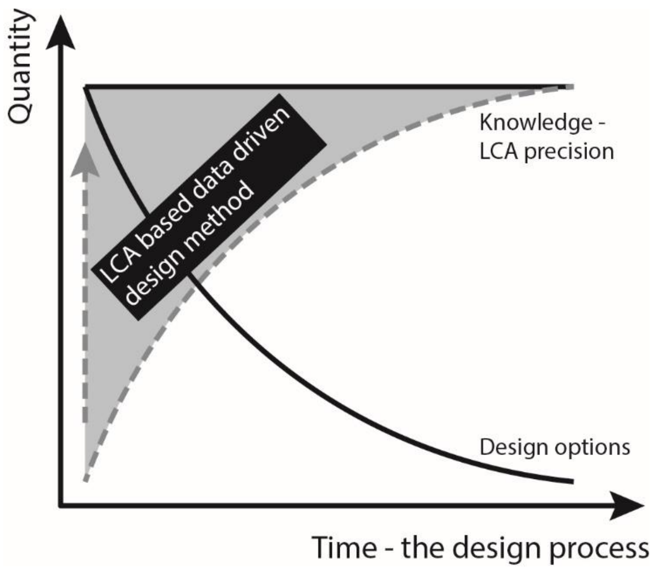


Figure 39: The LCA-based data-driven design method concept. Inspired by (Malmqvist et al., 2011).

The feasibility of this new method will be investigated in the next chapter, using the smart living lab case study. A prototype of the method will be set up to verify its ability to deliver design insights that might be helpful to support the design process.

Chapter 4 Development of a computer-based prototype

Disclaimer: Parts of this chapter are adapted from the following articles – with permissions of all co-authors and journals:

Jusselme, T., Antunes Fernandes, P., Rey, E., Andersen, M., 2019. Design guidance from a Data-Driven LCA-Based Design method and tool prototype. Presented at the IBPSA, Rome, Italy. My contribution: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Validation, Visualization, Co-Writing – review & editing

Jusselme, T., Hoxha, E., Cozza, S., Tuor, R., Zülli, R., Henchoz, N., & Lalanne, D., 2019. A data-driven approach for lifecycle performance. In EXPLORING / Research-driven Building Design. Towards 2050 (Park Books, pp. 207-237. 276). My contribution: Conceptualization, Investigation, Methodology, Supervision, Validation, Visualization, Co-Writing – review & editing

Jusselme, T., Tuor, R., Lalanne, D., Rey, E., Andersen, M., 2017. Visualization techniques for heterogeneous and multidimensional simulated building performance data sets. Proceedings of the International Conference for Sustainable Design of the Built Environment 971–982. My contribution: Conceptualization, Investigation, Methodology, Supervision, Validation, Visualization, Co-Writing – original draft

This chapter described the development of a computer-based prototype that implements the data-driven method for low-carbon buildings at early design stages described in Figure 38. A workflow allowing the performance of the five steps of the method is detailed. In the end, the prototype is ready to be used and applied to a case study.

4.1 Defining the parameters

The design parameter selection aims at defining the scope of the design space that will be explored. In our case, we have to keep in mind that the prototype will be later applied to the smart living lab building which is an office building. Accordingly, the design parameters have to be chosen to fit with the office building specificities, e.g. a large range of window to wall ratio. It is important to choose parameters that might be interesting for the designers according to techniques they are used to implement, or according to the targeted performance. Indeed, to be valuable, the future knowledge-database must have a significant part of its design alternatives within the performance range which is requested in the building specifications, e.g. below 13 kg CO_2-eq/m².y in the case of the SIA2040 and office buildings.

For this prototype, the design parameters have been defined thanks to the following inputs:

- The practitioners' wishes identified in section 2.6.3 and Figure 30,
- The "*catalogue of building elements*" (Kurt, 2002) was used to define building element options commonly found in Swiss construction. Further details about the quantity and quality of materials are available within this catalogue or in its online version "*www.bauteilkatalog.ch*".

- An online catalogue of low-energy buildings certified by the "Minergie" Swiss label (*www.minergie.ch/fr/batiments*) was also used that includes detailed specifications of heating systems commonly found in Swiss construction,
- A literature review of building carbon emission assessment was used to highlight the component or systems that usually has the highest carbon impact and that should be part of the exploration process. (Jusselme et al., 2015b)

From this analysis of catalogues, a list of parameters was selected, provided in Table 4. They will be used to generate the design alternative database and will form the boundaries of the design space that will be possible to explore. The parameter "Transport" included additional transportation of the building materials from manufacture plants to the construction site. It considered transportation distances of trucks with load capacities between 7.5 to 16 tons with an average load factor of 30%. We have to note that the building layout and orientation were identified in section 2.6.3 as design parameters of prior importance for architects and engineers at the early stages. However, the building layout has not been implemented as a parameter since it would have led to increasing the complexity of the prototype development, outside the available timeline to deliver a first prototype to the case study. Further development of the prototype using parametric modelling thanks to software such as Rhinoceros 3D coupled with Grasshopper might solve this issue. To face this limitation, the case study highlighted in Chapter 5 have been used with three different building layouts to demonstrate the influence of the shape on the different environmental performance metrics. Regarding the orientation, we decided to remove this parameter in our specific situation because of the construction rules of our case study (later presented in section 6.1) do not offer the possibility to change the building orientation.

The building components that have not been included in the parametric approach were kept constant, and are detailed in Table 8. Regarding the structure of the building, horizontal and vertical elements are described in Table 5 and Table 6, which highlight the thermal properties and the thickness of each layer of the building components.

Table 4: 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 W/m²K)	Triple glazing (U=0.6 W/m²K)		
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	EPS	PU	Rock wool
	Cellulose fiber	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.*

Table 5: Horizontal elements for the building structure used in the parametric approach.

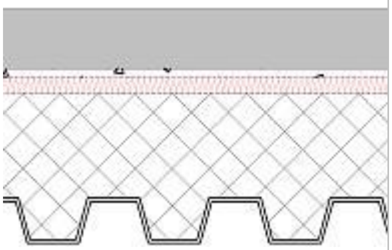
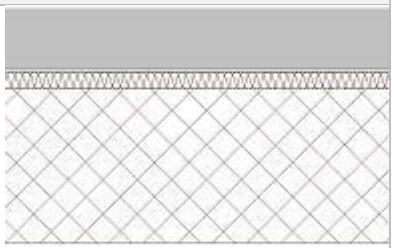
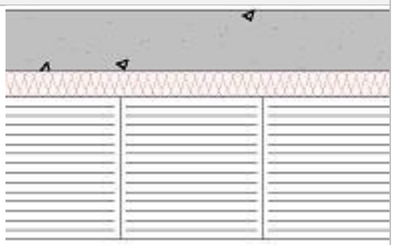
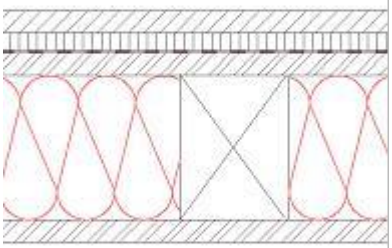
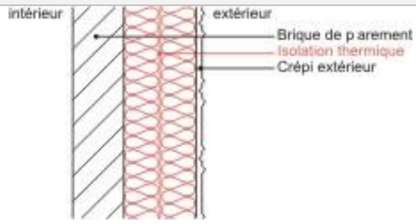
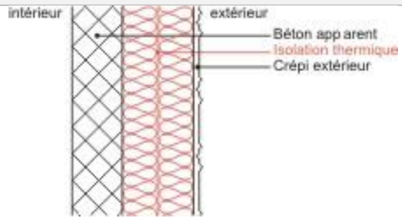
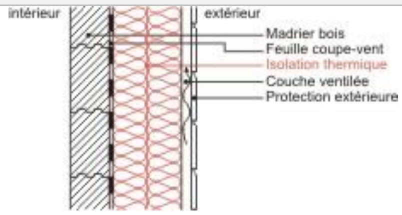
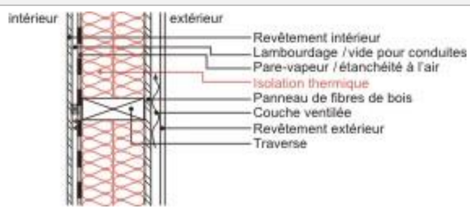
	Thickness (m)	**Thermal conductivity $(W/m^{-1}\cdot K^{-1})$**	**Thermal resistance (m^2K/W)**	**Cross-sections** *(www.bauteilkatalog.ch)*
B301 - Trapezoid plate				
Cement screed	0.07	1.4	0.050	
Steam barrier PE	0.0002	-	-	
Glass wool, ρ 100[kg/m3]	0.02	0.04	0.500	
Polyethene (PE) sheeting	0.0002	-	-	
Concrete slab (Fe 80kg/m3)	0.22	2.3	0.096	
Profiled sheet metal	0.00125	50		
B300 - Reinforced concrete				
Cement screed	0.07	1.4	0.050	
Steam barrier PE	0.0002	-	-	
Glass wool, ρ 100[kg/m3]	0.02	0.04	0.500	
Concrete slab (Fe 80kg/m3)	0.26	2.3	0.113	
B303 - Laminated Wood				
Anhydrite screed	0.05	0.8	0.063	
Steam barrier PE	0.0002	-	-	
Glass wool, ρ 100[kg/m3]	0.02	0.04	0.500	
Solid wood slab (BSH)	0.16	0.13	1.231	
Bi101 - Wood Framed				
Particleboard, UF glue, dry area	0.024	0.14	0.171	
Glass wool, ρ 100[kg/m3]	0.02	0.04	0.500	
Steam barrier PE	0.0002	-	-	
3-layer solid wood panel, PVAc glue	0.025	0.13	0.192	
Wooden beam 12/16cm[m1]	0	0.13	0.000	
Stone Wool, ρ 30[kg/m3]	0.16	0.04	4.000	
3-layer solid wood panel, PVAc glue	0.025	0.13	0.192	

Table 6: Vertical elements for the building structure used in the parametric approach. The insulation and external covering layers drawn on the cross-sections were excluded from the "Vertical elements" parameters as they are part of the "Building U value", "Insulation materials", and "Wall covering" ones.

	Thickness (m)	**Thermal conductivity ($W/m^{-1} \cdot K^{-1}$)**	**Thermal resistance (m^2K/W)**	**Cross-sections** *(www.bauteilkatalog.ch)*
W-W02 - Fired clay block				
Terracotta brick masonry	0.15	0.44	0.341	
Synthetic-based adhesive mortar	0.003	0.8	0.004	
Reinforcing mesh	0.003	0.8	0.004	
W-W04 - Reinforced concrete				
Concrete wall (Fe 60kg/m3)	0.15	2.3	0.065	
Synthetic-based adhesive mortar	0.003	0.8	0.004	
Reinforcing mesh	0.003	0.8	0.004	
W-W47 - Laminated Wood				
3-layer solid wood panel, PVAc glue	0.12	0.13	0.923	
Steam barrier PE	0.0002	-	-	
W-Wi01 - Wood Framed				
Steam barrier PE	0.0002	-	-	
Chipboard type OSB, PF glue	0.027	0.13	0.208	
Wooden beam 12/18cm[m1]	-	0.13	-	
Soft particle board panel	0.027	0.06	0.450	

4.2 The sampling process

The parametric approach involves the 14 parameters of Table 4. The calculation of all parameter combinations would lead to almost a billion life cycle assessments, which is clearly impossible considering that a single dynamic energy simulation takes about a minute. Thus, sampling methods were resorting to, which allowed creating a knowledge-database first without calculating the whole design space.

Its method depends on the sensitivity analysis, as it will be used to calculate also the sensitivity indices.

In this case, the Sobol method (Sobol, 1993), later improved by Saltelli (Saltelli, 2002), was selected. This variance-based method is able to deliver quantitative results, to handle the interactions between the parameters, and to use categorical and discrete values (Duprez et al., 2019; Jusselme et al., 2018b). This method actually requests a high computational effort as the database population needs to include at least 1,000 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. Here, a database of 20,000 design alternatives has been targeted.

Alternative ID	CED [kWh/m² yr]	CEDnr [kWh/m² yr]	GWP [kg CO_2-eq/m² yr]	WWR	GLAZ	FRA	U	PVF	PVR	HEAT	LIGHT	HORS	VERT	INS	COVS	COVW	TRPT
1	114	95	13	1	1	3	3	2	3	1	3	3	1	1	2	1	2
2	112	72	12	1	1	3	3	2	4	2	3	3	1	1	2	1	2
3	96	91	12	1	1	3	3	2	4	1	2	3	1	1	2	1	2
4	98	101	16	1	1	3	3	2	4	1	3	4	1	1	2	1	2
5	101	92	12	1	1	3	3	2	4	1	3	3	3	1	2	1	2
6	97.68	92.72	12.71	1	1	3	3	2	4	1	3	3	1	4	2	1	2
7	97.23	91.87	12.44	1	1	3	3	2	4	1	3	3	1	1	6	1	2
8	98.32	92.79	12.4	1	1	3	3	2	4	1	3	3	1	1	2	1	2
9	103.36	97.73	13.48	1	1	3	3	2	4	1	3	3	1	1	2	1	4
10	121.56	82.98	17.26	1	1	3	2	4	3	2	2	4	3	4	6	1	4
11	110.73	77.61	15.41	3	2	1	1	4	2	2	2	1	3	4	5	4	4
12	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...

Figure 40: Extract of the knowledge database generated by the design option sampling and parametric LCA.

Order	WWR	WIN	FRA	U	PVF	PVR	HVAC	LIGHT	HORS	VERT	INS	COVS	COVW	TRD
S1	0.003	0.004	0.029	0.028	0.006	0.021	0.174	0.002	0.555	0.007	0.097	0.005	0.004	0.059
ST	0.008	0.011	0.031	0.049	0.012	0.024	0.182	0.001	0.530	0.007	0.098	0.008	0.005	0.054

Figure 41: Extract of the sensitivity indices calculated by the Sobol method.

Hence, considering the four steps of a sensitivity analysis described in section 3.1.3, the sampling process is part of the following workflow, illustrated thanks to Figure 40:

1. **Determine** the model inputs (design parameters) and their sample range
   →The design parameters and their ranges are chosen according to section 4.1. Each design option is discretized to correspond to a numerical value as illustrated in Figure 40. As an example, for the WWR design parameter, 1 equal 25%, 2 equal 40%, 3 equal 55%, etc.
2. **Run** the sample function to generate the model inputs
   →The Saltelli sampling technique is used and proposed a database of combinations of this pre-defined design parameters. This sampling is illustrated by a set of numerical value representing the design options previously defined. Each line represents a unique design alternative that has an ID in the first column.
3. **Evaluate** the model using the generated inputs, saving the model outputs
   →A parametric LCA is used to assess the life cycle performance of all design alternatives represented as parameter combinations. LCA are performed according to the method later described in section

4.3. The results are illustrated by the three columns highlighting the CED, CEDnr and the GWP impacts. Here, the first design alternative has a GWP impact of 13 kg CO_2-eq/m².y.

4. **Run** the analyze function on the outputs to compute the sensitivity indices
→The Sobol method is used to calculate the sensitivity indices based on the outputs (i.e. the CED, CEDnr and the GWP impacts) that have been previously calculated. These indices are illustrated by Figure 41. S1 represents the first-order indices, and S2 the second-order, which gives the possibility to understand interactions between parameters (see section 3.1.3).

4.3 GWP, CED and CEDnr calculations

The whole building life cycle impacts (I_{BLC}) in terms of GWP, CED and CEDnr are calculated combining both their operational (I_{OP}) and their embodied (I_{EM}) impacts, according to the SIA 2032 standard (SIA, 2010)and following equation:

$$I_{BLC} = I_{OP} + I_{EM} \qquad \textit{Equation 3}$$

The LCA boundaries are illustrated hereunder thanks to the CEN standard (EN 15978, 2011), which highlights the different life cycle stages of a building: production, construction, use and end of life. In our case, I_{OP} embeds the operational energy use (B6), while I_{EM} embeds the following modules, (Figure 42): Raw material supply (A1), Transport/Product (A2), Manufacturing (A3), Transport/Construction (A4), Replacement (B4), Demolition (C1), Transport (C2), Waste processing (C3) and Disposal (C4).

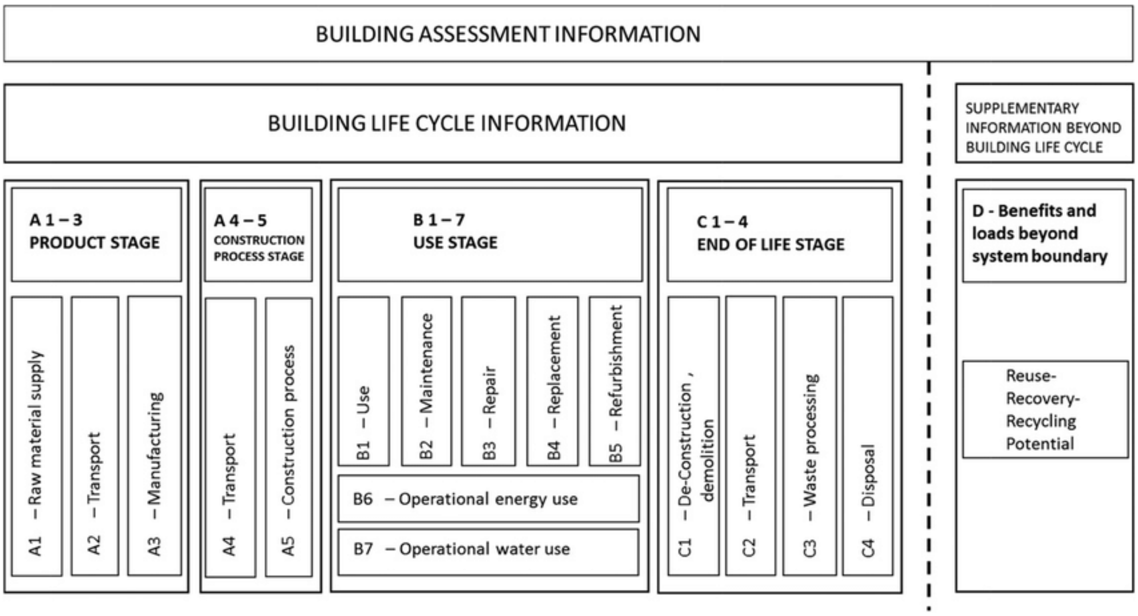


Figure 42: Modular information for the different stages in life cycle assessment (EN 15804, 2012)

4.3.1 Operational impacts (I_{OP})

The operational impacts (B6 in Figure 42) are decomposed into *p* different types of energy sources (e.g. biomass, gas etc.). 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. I_{OP} is derived from (Jusselme et al., 2016) and from the following equation :

$$I_{OP} = \sum_{k=1}^{p} E_k \cdot CF_k \qquad \textit{Equation 4}$$

where 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 7:

Table 7: 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-eq/kWh**
Electricity	3.000	2.520	0.102
Biomass	1.200	0.160	0.027
District heating	0.875	0.549	0.108
Self-consumed PV	-3.000	-2.520	-0.102
Exported PV	-1.400	-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, 2015a) 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. In the end, the calculation of the operational impacts covers the lighting, the appliances, the ventilation, the heating and the Domestic Hot Water (DHW) energy consumptions. Regarding the energy systems, some hypotheses have been formulated:

- The heating systems have the following coefficients of performance (COP): Heat pump = 3; Biomass boiler = 0.85; District heating = 1,
- The thermal losses induced by the heat distribution are considered to be 10% of the heating demand,
- The thermal losses induced by the heat emissions are considered to be 10% of the heating demand,
- The ventilation is running 1470 h per year (SIA, 2015a).

Finally, Meteonorm V.7 generates the weather file used by EnergyPlus. It is specific to the building location in an epw file format.

4.3.2 Embodied impacts (I_{EM})

In order to calculate the embodied impact I_{EM}, the building is decomposed into *n* so-called components (such as the insulation material, or the heating equipment e.g.). Each component *i* is expressed as a mass (kg), a surface (m²) or a quantity (unity) m_i and multiplied by its specific environmental impact conversion factor CF_i. Finally, the ratio between the building lifetime *LB* and the component lifetime *LMi* is calculated and multiplied to obtain the component environmental impact over the whole building lifetime. I_{EM} is derived from (Jusselme et al., 2016) and the following equation:

$$I_{EM} = \sum_{i=1}^{n} m_i \cdot CF_i \cdot \left[\frac{LB}{LM_i}\right] \qquad \textit{Equation 5}$$

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 to consider were based on the SIA 2032 (SIA 2032, 2010), e.g. 60 years for the building. Building components with a shorter lifetime than the 60 years of the building are replaced by new ones. As an example, according to SIA2032, windows have a lifetime of 30 years. Hence, their impacts have been doubled in the prototype to consider their replacement over the 60 years of the building. According to SIA 2032, the service life of the building is a multiple of all life span building component that has been chosen, so that the number of replacements is always an integer.

4.3.3 Bill of quantities

The KBOB database is used to convert material quantities and energy sources into *CED*, *CEDnr* and *GWP* impacts. Thus, the first step of the embodied impact calculation is the calculation of what is called the Bill Of Quantities (BOQ) -i.e. the material quantities- according to the functional unit of the component within the KBOB database. For instance, the bill of insulation quantities has to be calculated in kg. Then, the conversion factor of the KBOB database is 1.13 kg CO_2-eq per kg of insulation.

Starting with a simple 3D volume at early design stages, it is necessary to rely on some hypotheses to convert the surfaces and volumes of the massing schemes into quantities of materials. These hypotheses are listed hereafter:

- The frame-to-window surface ratios are 20% for the Wood and Wood-Alu, 25% for the PVC and 12% for the aluminium frames,
- The thermal insulation thickness assumes the thermal resistance of the walls and slabs as described in Table 5 and Table 6,
- The floor coverings have the following thicknesses: Cast coating = 2mm; Ceramic tile = 9mm; Linoleum = 2.5mm; Parquet = 11mm; PVC = 2mm; Carpet,
- The wall coverings have the following thicknesses: Cement panels = 1cm; Cement plaster = 1cm; wood siding = 2cm; Zinc = 0.1cm; Steel = 0.1cm; Organic coating = 1cm,
- The material densities are defined by the KBOB database,
- The weight of the materials (considered for the transportation impact) includes walls, slabs and windows only. The transport is supposed to be done by a truck of 7.5 to 16 tons capacity.

Table 8: 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, 1m² per SRE
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).

Besides these parameters, other components (Table 8) are simulated to describe an entire building for each design alternative. These elements are kept unchanged as they are, in our case, of no or little interest to the designers at an early design stage, thereby reducing the design space to be simulated and the computational effort. However, in some cases and based to the designer's interest, these components could theoretically be switched as parameters in Table 3 if different materials or techniques have to be explored and used in the parametric approach (Jusselme et al., 2018b).

The low level of detail of some of the building components has been included by increasing their material quantities by 20% (Padey, 2013), adopting the worst-case scenario approach. These components are highlighted in Table 4 and Table 8.

4.4 The computational workflow

A 3D model of the project was first created in the DesignBuilder software (DesignBuilder, 2016). In the methodology, such a model can be as simple as a volume with its different floors, which is what we used. The urban surrounding landscape was included in order to account for its shading effect on the photovoltaic system and on the building's solar heat gains. The 3D model was then directly exported from Design builder as an IDF file. Using a Python library called Eppy (Santoch, 2015), parametric modifications of the IDF file were 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 section 4.1 and delivered a database of IDF files representing design alternatives with all different design properties (e.g. different Heating systems or window types). Figure 43 gives an overview of the general workflow.

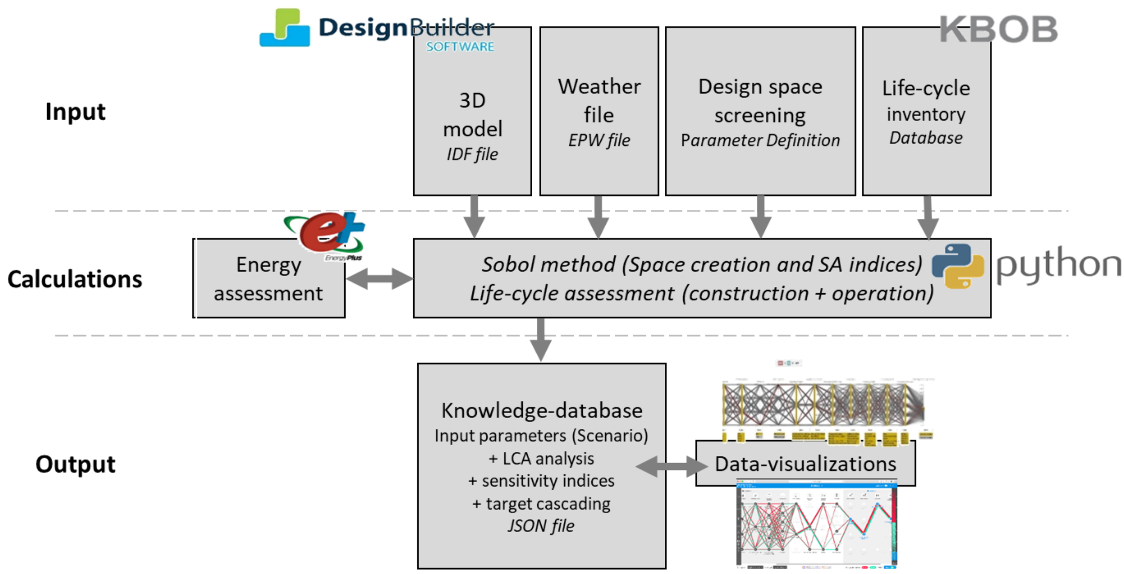


Figure 43: Description of the input, calculations and output that embedded the workflow.

As the design follows an iterative process, designers would be theoretically 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.

An open-source scripting language, GeomEppy, (Bull, 2018) was integrated to allow the geometric and parametric modifications of IDF files 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 bill of quantities and embodied impacts calculation in order to create the knowledge database represented as the output in Figure 43. The embodied impact calculations have been coded with the Python language and integrated into 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 reduced 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 were extracted from the Energy Plus tabular output files in XML format using epXML2CSV.py (Glazer and Analytics, 2016), a script that we adapted to support the proposed methodology. Eventually, the embodied and operational impact calculations were compiled in a .csv file.

The integration of main components of the sensitivity analysis (see section 0) to the parametric workflow was made possible thanks to the SALib library (Herman and Usher, 2017), an open-source library written in Python for performing sensitivity analysis. The SALib library was used for generating the model inputs (i.e. the combination of design options) using the Saltelli sample functions, and for computing the sensitivity indices from the model outputs (i.e. the LCA results in terms of GWP, CED and CEDnr), using the Sobol analyze functions. In the end, a database of 20,992 design alternatives was generated, and each one's related *LCA* was calculated.

4.5 The graphical User Interface

4.5.1 First data-visualizations

Relying on previous research about existing data visualization techniques (Jusselme et al., 2017), section 3.1.6 allowed us to select two Data-Visualization Techniques (*DVT*) that look promising according to our understanding of the literature. Here, the purpose is to apply these *DVT* to a first dataset in order to analyze their advantages and drawbacks, keeping in mind that the objective is to enable a dynamic interaction with a graphical user interface, this is why common and static visualization techniques such as scatter plot, bar charts and others are not discussed in this section.

Two visualization prototypes presented below were implemented using the client-side web technology stack: HTML, CSS, SVG and Javascript. A flexible approach was chosen, to test the visualizations iteratively. This work has been done thanks to a collaboration with the Human-IST research lab from the University of Fribourg, which made its competences in data-visualization techniques and development available to the project.

Here is a summary of the requirements:

- being able to switch between several datasets.
- being able to add visual encodings to a visualization method.
- being able to handle large datasets without compromising the user experience.
- implement several interaction methods such as clicks and brushing.

The D3 Javascript library (Bostock, 2017d) has been used to represent the data, since it is widely used, provides good documentation, and meets all the above requirements.

4.5.1.1 Implementation of the Parallel Coordinates

According to the literature review, a few visual enhancements were added to the D3 library, such as jittering to reduce over-plotting and allow the increase of the visual perception of distribution for each parameter. We also added a color coding: each polyline was colored according to its compliance to the target. In the example, polylines are colored in green if their *GWP* is below 12.6 Kg CO_2-eq/m²·year, red if it is above the target. Brushing interaction makes it possible to filter the dataset by selecting a range of values for a given parameter. The user is able to reorder the axes in order to assess the correlation between specific dimensions.

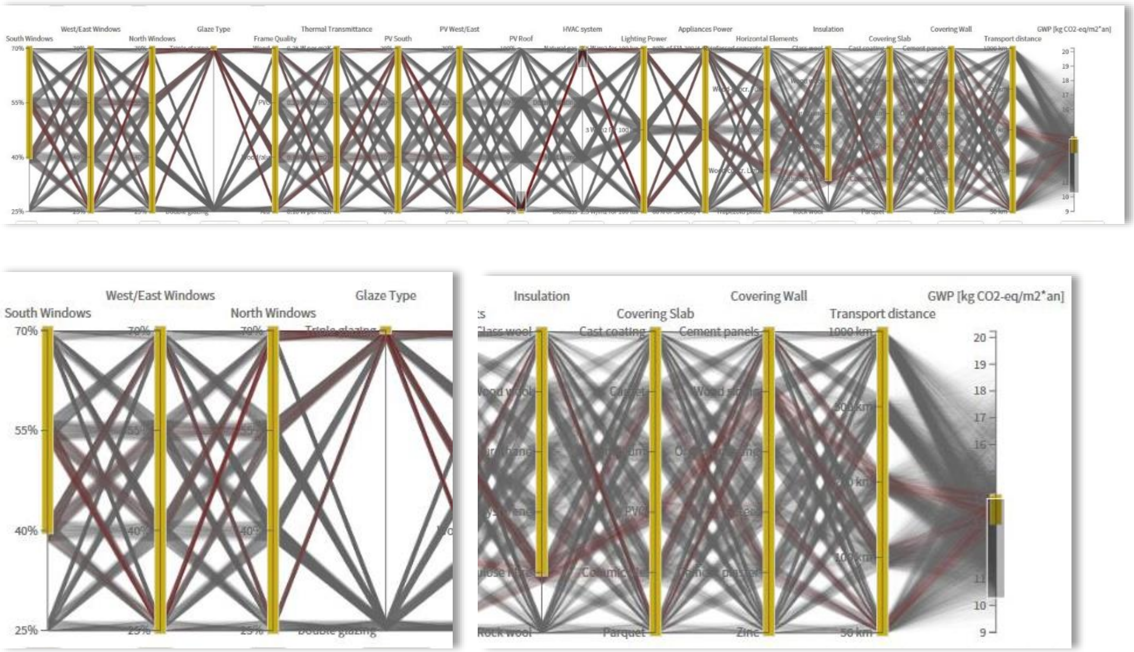


Figure 44. Visualization of the Smart Living Lab's building dataset with Parallel Coordinates (on the top), zoom on input parameters (bottom left) and zoom on output performance indicator: Global Warming Potential (GWP, bottom right).

4.5.1.2 Implementation of the Decision Tree

In order to represent the dataset as a Decision Tree, we first had to compute it with the C4.5 algorithm, using a modified version of LearningJS (Yandong, 2017). The Decision Tree data was stored as a JSON file. The user is able to click on a node in order to reveal its children nodes until it reaches a leaf. A leaf represents a homogenous set of design alternatives: it contains only valid, or non-valid design alternatives. Nodes are scaled according to the number of design alternatives they represent. Each node is colored according to the most represented class inside it: it is green if it contains mostly valid design alternatives, red if it contains mostly non-valid design alternatives. By a user point of view, it means that when you have to make a design choice, the green path is the next best move to do, while the red one will lead you to increase the difficulty to reach the performance threshold.

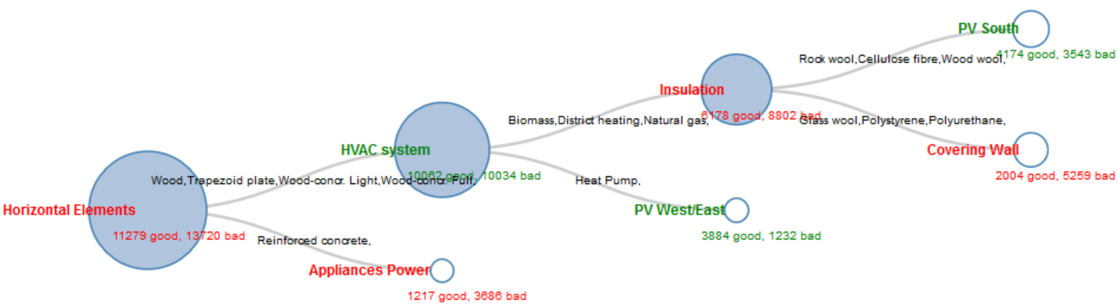


Figure 45. Visualization of the smart living building data set with a Decision Tree. Source: H-IST UNI-FR and (Jusselme et al., 2017)

4.5.1.3 Qualitative comparison

In this section, we perform a non-quantitative comparative analysis of the two *DVTs* most promising for our use case, namely the Parallel Coordinates plot and the Decision Tree. First, both methods can handle a medium-sized dataset. The Decision Tree is more scalable since it only represents aggregates of design alternatives. The Parallel Coordinates plot, on the other hand, requires specific clutter reduction techniques – jittering, alpha blending – to increase its readability.

Both methods can represent mixed categorical and continuous dimensions. The number of dimensions is more limited with the Decision Tree since a large number will inevitably increase the depth of the tree, and thus its complexity. Discrepancies in the user's mental model can appear when the dimensions include several types – categorical, ordinal or continuous – and the cognitive load increases when the amount of parameters becomes too large. In Parallel Coordinates, these problems can be addressed by reducing the number of axes displayed, or by allowing the user to distinguish between the continuous and categorical axes with a specific layout for each type. Unlike the Decision Tree, the Parallel Coordinates plot gives an overview of the whole dataset at a glance.

Regarding the ability to perform the tasks described in Table 1, the Decision Tree is better suited to show the impact of parameters. It first displays the parameters that best divide the data between the two output classes: an identification of clusters, based on one parameter, is a trivial task. Parallel Coordinates can show the same information, but in a less explicit way: parameters axes can be laid out horizontally according to an impact criterion such as the Information Gain (Safavian and Landgrebe, 1990). The C4.5 algorithm (Quinlan, 1992) would be suitable to do that.

Parallel Coordinates allow the identification of similarities between dimensions, while the Decision Tree does not. The effectiveness of Parallel Coordinates for this task is, as mentioned earlier, highly dependent on the order of axes. Interaction techniques should thus be implemented to allow the user to reorder them. The Decision Tree is better suited to identify families of design alternatives sharing a similar output class.

In the Decision Tree, nodes can be scaled according to the number of samples included inside them. With two output categories, each node gives two choices and groups parameter values according to this criterion. Thus, a node can represent one or many categories and does not allow a clear identification of the frequency for each category. Parallel Coordinates show the frequency for each individual category, but the addition of jittering and alpha-blending is needed to resolve the over-plotting problems.

A valid solution can be found at any level of the Decision Tree: filtering stops, when the output class of design alternatives under a given node, is homogenous (only valid, or only non-valid design alternatives). However, this technique is too directive for the user: it forces him/her to follow a predefined sequence of decisions, returned by the algorithm used to generate the tree, and does not give him/her a good overview on the solution space. The user has to click on many nodes before being able to assess the validity of a given solution. Moreover, the output range cannot be visualized individually for each design alternative. For example, it is impossible to show only the references that are really close to the output threshold (Pareto front), or those that are slightly above. The Parallel Coordinates plot offers a broad range of filtering possibilities with the brushing interaction implemented on each axis. However, selecting a range of values makes little sense for categorical parameters, as there is no ranking between them. For categorical parameters, the brushing method should be replaced by a set of checkboxes.

In synthesis, Parallel Coordinates enable the highest flexibility in the dataset exploration and then a better ability to perform tasks useful to support the design process. Decision-tree is easier to use but more limited in terms of data exploration. It is worth noticing that this comparison informs us about the technical possibilities of the different *DVT*, but a usability assessment including an evaluation of their impact on the design process would be useful to confirm their real added value.

4.5.1.4 The Parallel Coordinate plot as the most promising technique

Both *DVTs* have been implemented via the dataset of the Smart Living Lab's future building as a case study. Overall, Parallel Coordinates plots seem best suited since they give a better overview of the database, and are more flexible in terms of the number of dimensions although they do require adding specific visual encodings (jittering, alpha blending) and interaction methods (hiding and moving axes, filtering) in order to be able to perform the tasks described previously. The Decision Tree is less convenient as it cannot represent dimensions without imposing a ranking to the user, does not give a clear overview of the database, is not appropriate to show the details of individual design alternatives, and does not fit the designer's creative process well.

Therefore, the Parallel Coordinate technique was ultimately chosen to be further developed and integrated into the graphical user interface of the prototype. This development will be detailed in the next section.

4.5.2 The Graphical User Interface

The development of the Graphical User Interface (GUI) itself is the result of a joint project with two other institutions. First, the University of Fribourg's Human-IST group already mentioned earlier, which specifically worked on information visualization for this project. Second, the EPFL+ECAL Lab Design Research Center who made its competences in exploring scenarios of use, visual expression and interaction design available to this project. The purpose of this collaborative phase was to develop a Graphical User Interface (GUI) suitable both to architects and engineers, that would provide access to the knowledge-database in a way adapted to the early design stages. We were thus faced with the need to address several challenges:

- Simplification of the complexity. The tool gathers a complex set of data. How to make the interaction more intuitive and provide a clear understanding to non-engineers?
- A tool for inspiration. Common practices assess the energy performance of a designed building. The prototype should work the opposite way by allowing building designers to play with the different parameters from the outset in order to understand which ones are crucial, and account for their relationship when considering the various solutions.
- Freedom, not judgment. Environmental issues are often seen as limiting creativity. The prototype must not be perceived as yet another limitation. On the contrary, it specifies key parameters and relationships, which offers more leeway on many other, less important features.
- Using means effectively. Architectural competitions usually generate stress and costs for offices. The prototype must offer more than just efficiency and impact; it must be exciting and help to fuel the creative process.

Data-visualization often called information visualization, "*is the use of computer-supported, interactive, visual representations of abstract data to amplify cognition*"(Card et al., 1999). In this project, the aforementioned challenges raise the following objectives for designing effective visual representations:

- Reducing visual complexity. With large data sets, data visualization often implies visual cluttering. Techniques such as filtering, jittering, overview/details and sampling are necessary to provide meaningful information to users.
- Highlighting correlations and discriminant dimensions. In the information visualization field, various data visualization techniques exist to highlight patterns (e.g. clusters, trends, correlations). In this project, the visual representation chosen in combination with data mining should highlight correlations as well as discriminant dimensions and choice impacts.

- Data heterogeneity. While most visualization techniques are designed for continuous data, the prototype mainly manipulates categorical data, which involves adapting state-of-the-art techniques or creating new ones.
- Gaining insight versus decision making. The major goal of information visualization is to gain insight, i.e. gain knowledge while exploring the data. The prototype has a somewhat complementary objective: to support decision making in the context of parametric design.

To tackle these multiple challenges, we started with two different approaches, each of which provided specific features in terms of interaction and data visualization for the building designers. The first uses the principle of Parallel Coordinates, which is one way of interacting with the manifold relationships between the parameters. The second is reminiscent of the building-block principle in that it allows users to add one parameter after another. We turned these approaches into prototypes and tested their impacts with users. The results were then used to establish the tool's final design, illustrated thanks to Figure 48 to Figure 54.

4.5.2.1 Parallel Coordinates

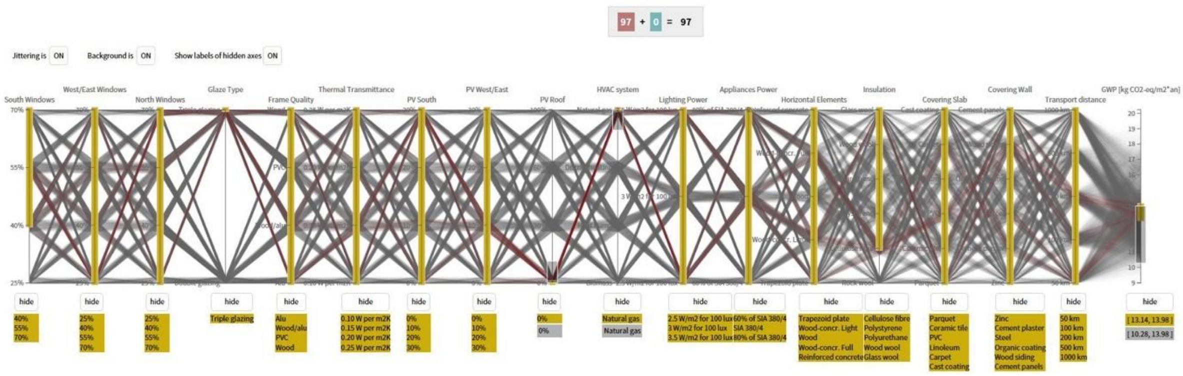


Figure 46: The parallel coordinate plot representing the knowledge database. Source: H-IST UNI-FR and (Jusselme et al., 2017)

This visualization method empowers the designer with data analysis capabilities, which are important in the early stages of building design (Attia et al., 2012a; Huot, 2005b; Østergard et al., 2017). Each graded vertical axis represents one parameter. Each tick represents a value. A design alternative is represented by a polyline that crosses all of the axes at the corresponding parameter values. This method allows users to assess the level of similarity between different design alternatives and between parameters. Color coding is applied to polylines according to their environmental performance, which helps users assess the viability of each design alternative and detect patterns. Brushing interaction allowed us to reduce the number of design alternatives displayed to obtain a clearer overview.

4.5.2.2 Building Blocks

In addition to the work on Parallel Coordinates, the EPFL-ECAL lab spent time in architecture studios exploring the creative process of building design. How could the tool be used to fuel inspiration in the early stages? This led to the creation of a second proposal called "Building Blocks" whereby users could add one parameter after another to see their impact; in other words, not only how each parameter affects building performance, but also how it reduces the number of solutions for all the other choices to come. Using the database, the interface proposes the solution with the most effective impact but always leaves freedom to the building designer. Each pre-calculated solution for each parameter is made visible in order to provide a clear view of the system. When enough parameters have been selected, complete solutions can then be compared in a chart. User experience was designed to make the tool efficient for use on tablets as well, allowing interactions between several people in different situations.

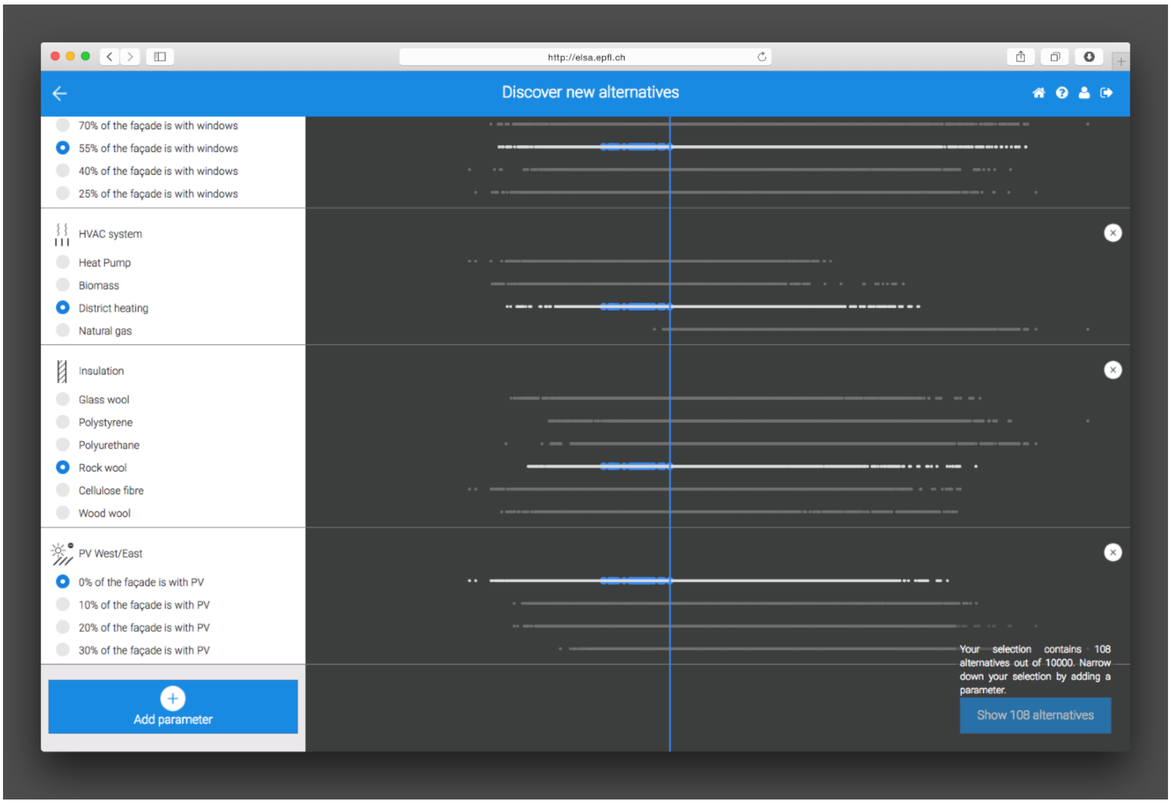


Figure 47: The building block prototype. Source: EPFL ECAL lab, EPFL and H-IST UNI-FR

4.5.2.3 Learnings from the initial prototypes

At the end of the first stage of development in November 2016, we decided to perform User Testing (UT) among the Master's level architecture students from the School of Engineering and Architecture of Fribourg. The 10 students participating to the test did not have any specific knowledge on LCA. The method and the results of this user test have been published in (Cozza et al., 2018) and its objective was to gather information for the following stages based on the initial feedback. We agreed on certain goals for this UT:

1. to determine the GUI usefulness,
2. to see if it helped the architects improve their project performance (e.g. less CO_2-eq emissions),
3. to learn about how it influenced the architects' knowledge and, most importantly, 4) to see how the two visualizations compared.

To evaluate the feedback, we set up specific tests that the students (who were divided into two groups each with a different visualization technique) had to complete.

The UT started with an emotional test, the Self-Assessment Manikin (SAM) (Morris, 1995) to measure emotional response to using the tools. This was followed by a ten-question knowledge test in multiple-choice format (e.g. "*Which of the following parameters can have a greater impact on a design alternative's CO_2 emissions, taking into account both the construction and the usage phase*?") to better estimate the students' knowledge of the subject. The goal of the UT was to perform specific tasks wherein users had to do different practical activities using only the tool. The tasks were classified as:

- Exploration, to reveal patterns and insights from the database;
- Configuration, to introduce and evaluate their own project;

- Frequency, to create a project following specific constraints;
- Improvement, to reduce the total environmental impact of the project.

We then asked them to redo the knowledge test to find out if there were any changes after using the software. We then moved on to a formal evaluation of the GUI with a User Experience (UX) Questionnaire based on the System Usability Scale (SUS) (Brooke, 1996), with questions like: "*How much did you trust the information*?" and "*Would you use it on a regular basis?"* Finally, we concluded with a focus group discussion wherein users were free to express their opinions and evaluate their overall experience.

The user test showed general satisfaction with the two visualization options in terms of usability. The SUS rates were 72.2 for the Building Blocks and 71.6 for the PCP, when a score above 70 is considered acceptable (Bangor et al., 2008). We were also able to observe a decrease in the knowledge test error rate after using the prototypes. The outcomes of the qualitative results from the group discussion were even more beneficial and constructive. Notably, it strengthened our perception of the actual use of such a tool based on early users' comments, such as:

- "We would use it because, even without any detail about the building's performance, we are able to make some smart choices"
- "It's really useful to be able to see the impact of the different parameters in a simple overview and to easily understand the consequences of a selection".

Moreover, we were able to use specific suggestions to improve our prototype. For example, for the question "*What do you think of the interface design? What could be improved?"* they answered: "*It's easy to see the track from left to right (each polyline),*" as well as "It's overwhelming and looks complicated" (for the parallel coordinates). Regarding the building block visualization, the same question received this answer: "*We like it because we can add parameters as we want, progressively, and according to our logic and inspiration*".

Although the small number of users involved in this test, the analyses indicated that the building block approach provided a better understanding of the tool, parameters and process. Feelings seemed to be consistent, though users had more of a black-box feeling and felt the tool was quite time-consuming, especially when it came to adding more parameters. Parallel Coordinates allowed for more interactivity, flexibility and excitement because all of the alternatives were visible and included from the outset. Rather than choosing between two options, the results indicate the need to find a way of combining their unique qualities.

4.5.2.4 ELSA: a new concept and real tool

By combining the key features of both of the initial prototypes, new horizons for data interaction and perception become possible. Of course, obtaining the best of both worlds is easy in theory but more difficult in practice. We decided to name ELSA the final GUI we developed, which stand for Exploration tooL for Sustainable Architecture. Hence, it is under this name that we will call the prototype within the following sections. We based the development of ELSA under three major concepts:

- **Focus on the "*playground*."** Usually, users do not play with all of the parameters simultaneously. Therefore, we divided the full representation of Parallel Coordinates into three areas: One that provides a list of untouched parameters; one dedicated to be the 'playground' (which shows all of the parameters under consideration); and one that gathers all the parameters for which the user has already selected a specific value.
- **Build the solution**. To build their own vision, users have the possibility to move parameters to the playground one at a time. By doing so, the process is the same as that of the building block prototype and allows an understanding of each parameter and its impact.

- **Complex information becomes intuitive**. The method provides a great deal of complementary information. However, we proposed to visualize all information at a glance in a qualitative approach that makes intuitive its understanding and use. Yet, quantitative information is available if requested.

In practice, these concepts were translated into a new GUI that has been designed by EPFL ECAL lab, and encoded by the Human-IST research lab / UNI-FR. Figure 48 highlights the main features of ELSA. On the left (a), one can see the sensitivity indices of the design parameters that are ordered from the highest on the top to the lowest.

The playground (b) is located in the centre of the screen. The design parameters stored on the left can be moved to the playground one at a time. Once moved to the playground, all the options of the parameters become visible, and the user is able to select or deselect them according to the design situations he/she wants to explore. These options are linked one to each other's thanks to polylines once several parameters are moved to the playground. These polylines have the same role than the one in a parallel coordinate chart: they represent the design alternatives of the database. The polylines have different thickness: the larger they are, the higher the number of alternatives sharing the same design options. Also, the polylines have two colors: in green to identify alternatives that are below the impact threshold, in red for the one above. ELSA offers the possibility to change the performance target on the bottom left (c), and let the possibility to visualize the design alternatives according to their CED; CEDnr or GHG impacts. If the user wants to see all of the Parallel Coordinates, it is possible to switch from BUILD (one parameter at a time) to the EXPLORE mode with a simple button on the top right (d). The target cascading results are illustrated by a sunburst diagram (e) that adjust dynamically the carbon budget of the building component according to the design options that are selected.

Figure 49 zooms on this sunburst. In this example, the performance target is set to 13 kg CO_2-eq/m².yr. Depending on the design situation the user is exploring, the carbon budgets of the operational and embodied impacts are respectively 2.6 and 10 kg CO_2-eq/m².yr. Looking deeper into the sunburst allows finding that in this situation; the windows have a carbon budget pf 1.4 kg CO_2-eq/m².yr. On the bottom right (f), it is possible to determine the number of design alternatives that are explored, and to know how many of them are below or above the performance threshold. The distribution of the performance of all the design alternatives is also highlighted by the chart on the right (g). Each alternative is represented by a green or a red dot according to its performance and to the threshold.

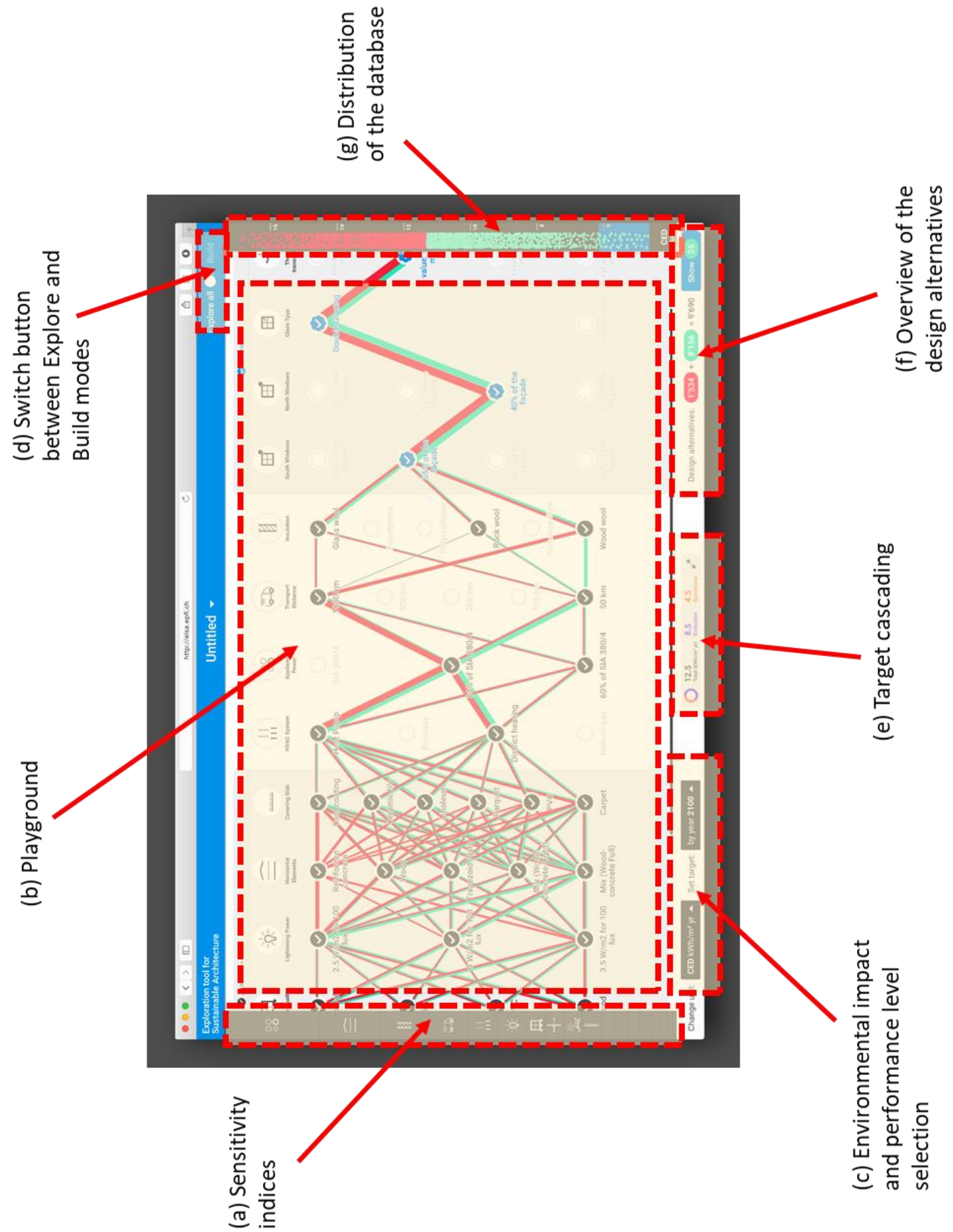


Figure 48: Description of the main features of the graphical user interface of ELSA

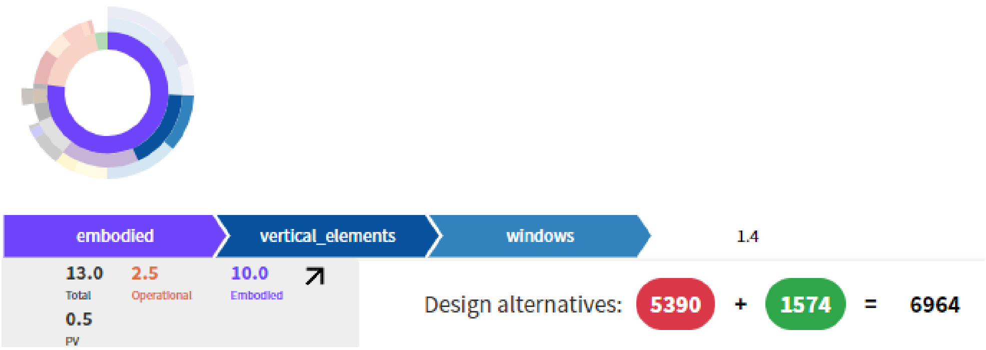


Figure 49: Zoom on the target cascading part of the GUI, represented by a Sunburst diagram.

Figure 50 to Figure 54 show some snapshots of the GUI, that illustrates further the major steps in the exploration process of the knowledge-database, thanks to ELSA.

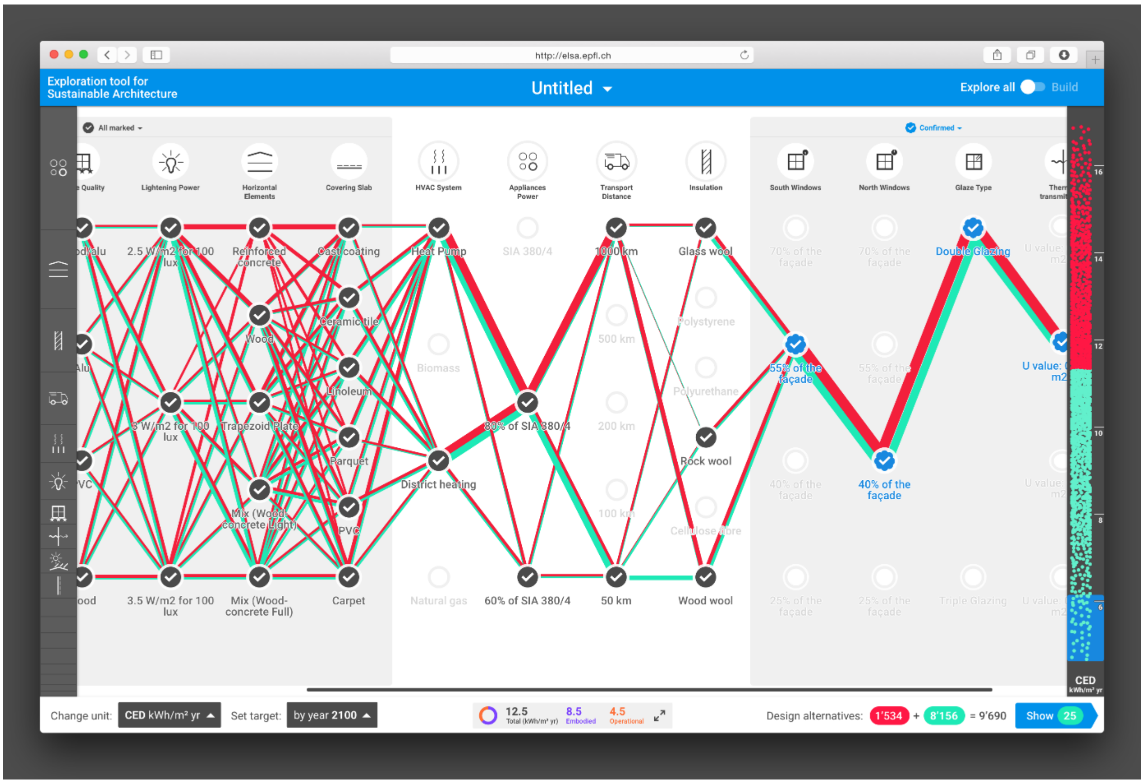


Figure 50: Explore mode: The Parallel Coordinates display all of the parameters. All of the available variables are listed on the left, the central area displays only active values and the user makes a decision on the right: only one path is left. Source: EPFL ECAL lab, EPFL and H-IST UNI-FR

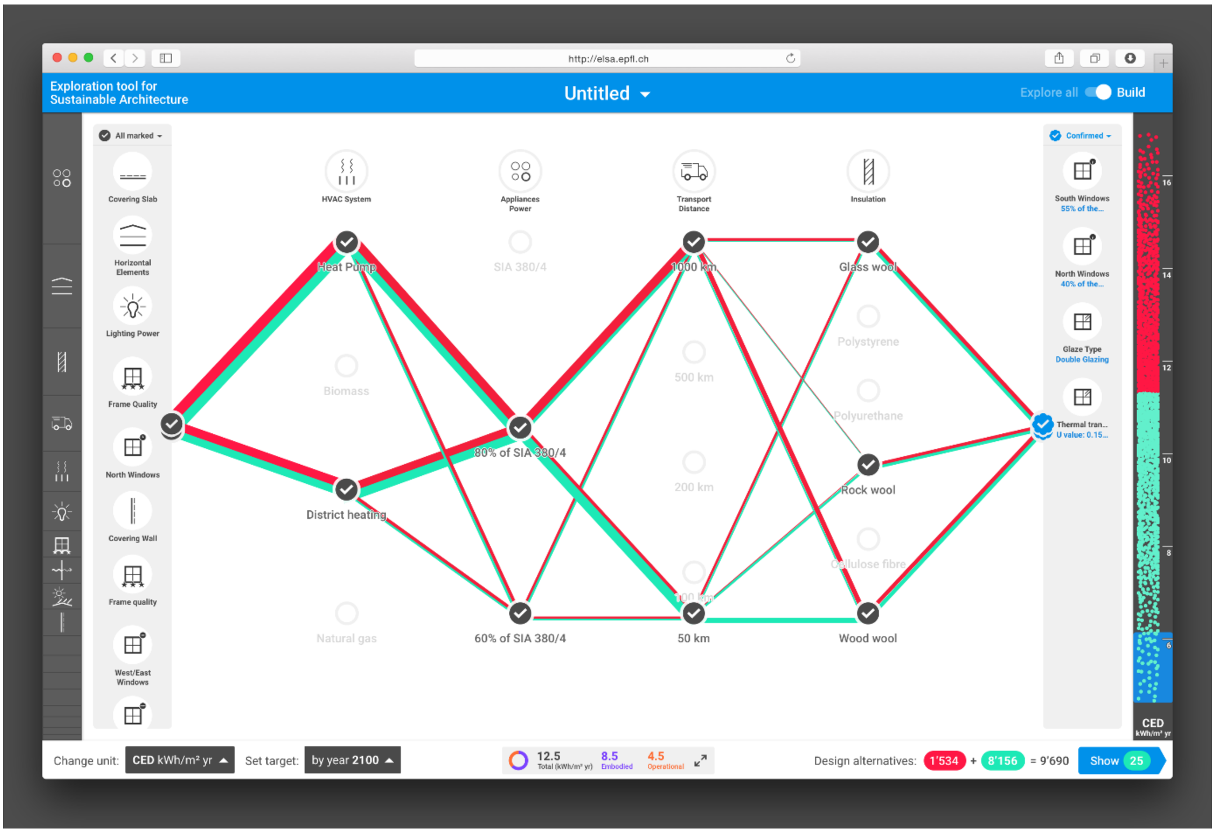


Figure 51: Build mode: The "build" mode shows an identical diagram. However, the unchanged parameters are now listed only in the left column and the defined ones in the right. Users can focus on the parameter(s) of interest in the playground (centre). Source: EPFL ECAL lab, EPFL and H-IST UNI-FR

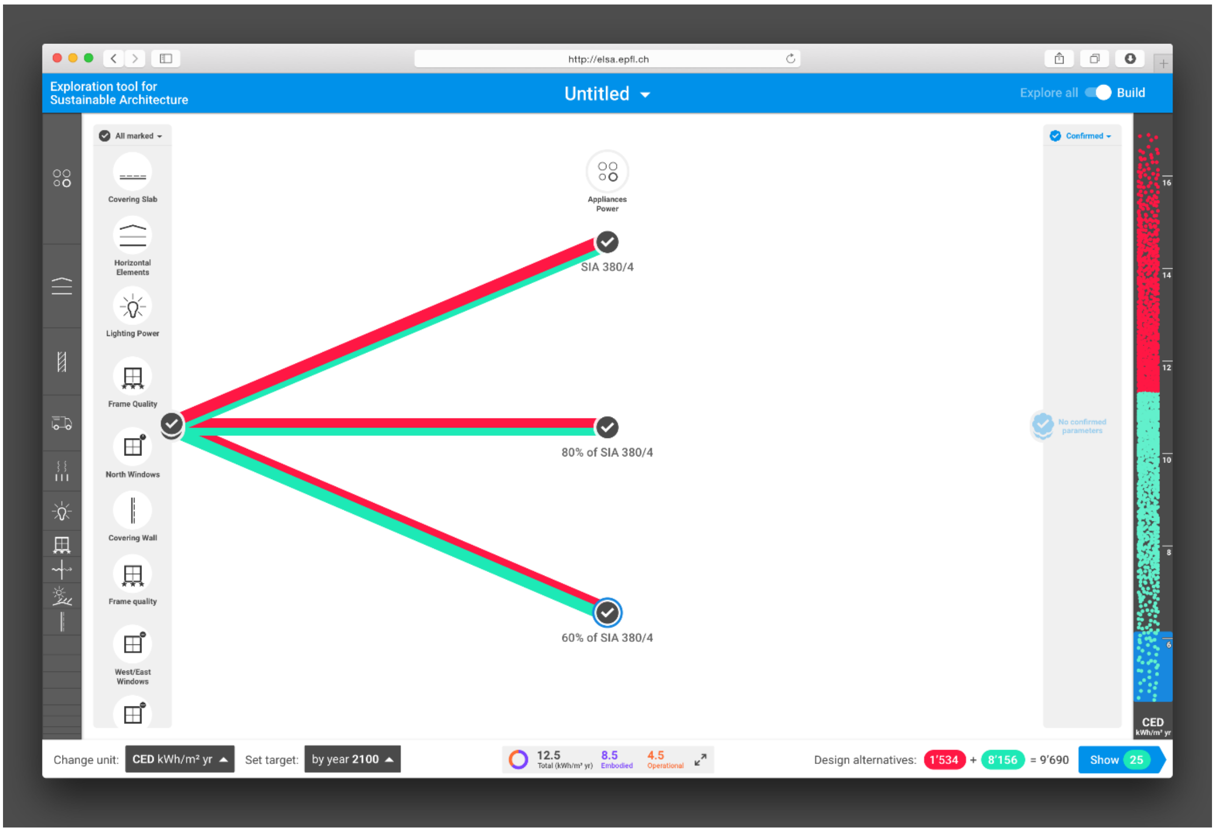


Figure 52: Build mode - First step: Users start by selecting the first parameter of interest and by eliminating some of the solutions proposed by the system. Source: EPFL ECAL lab, EPFL and H-IST UNI-FR

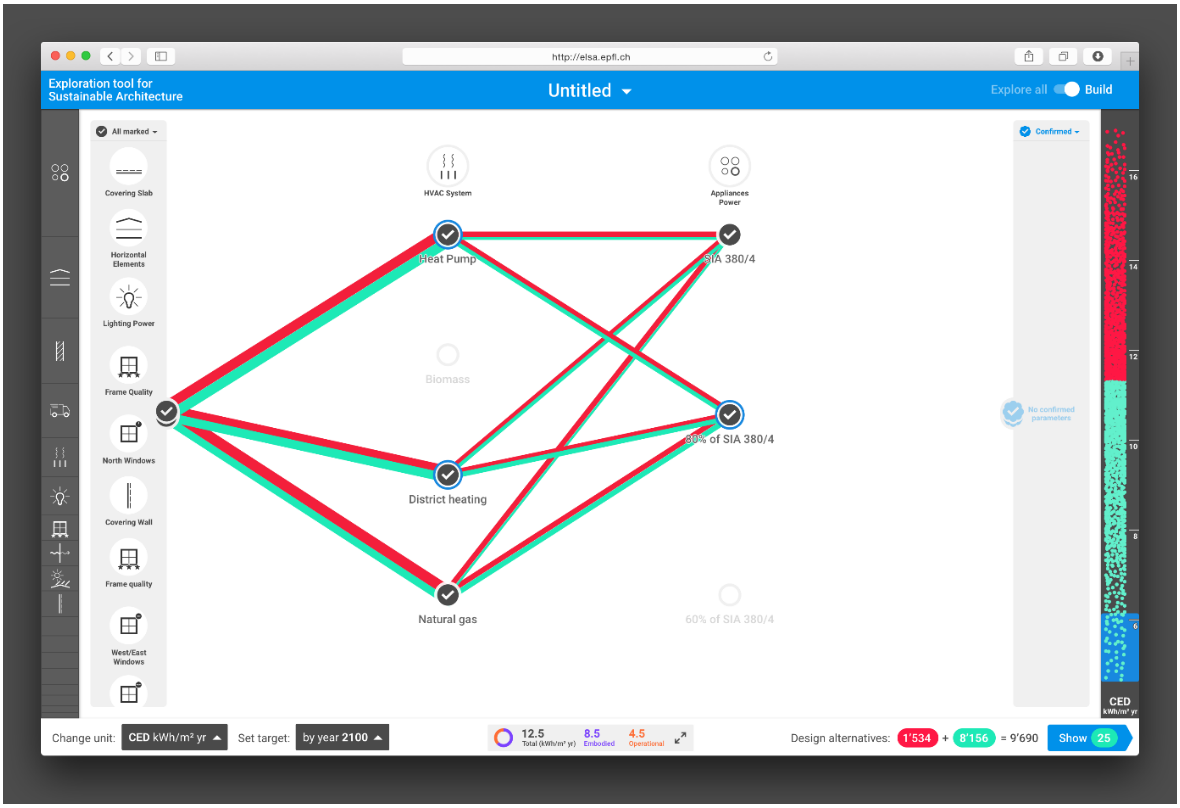


Figure 53: Build mode - second step: Users can add more parameters and observe their interactions by selecting or deselecting specific values. Source: EPFL ECAL lab, EPFL and H-IST UNI-FR

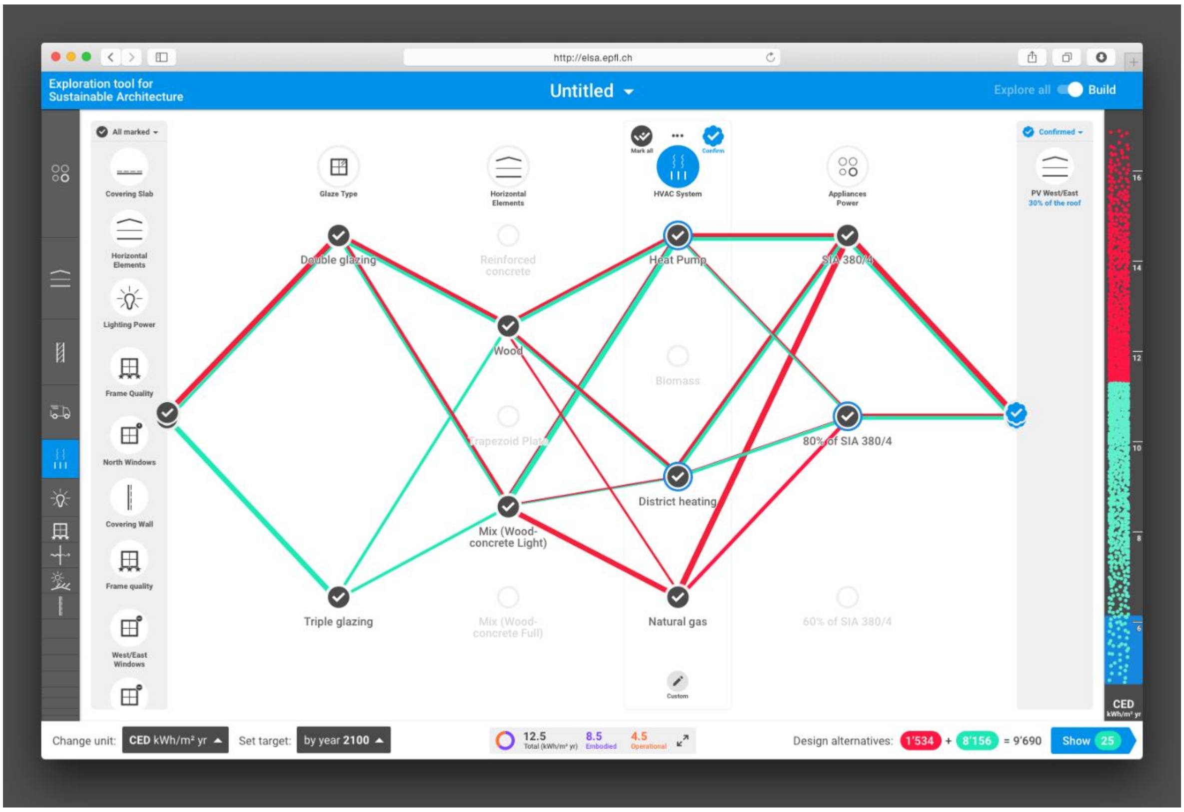


Figure 54: Build mode – third step: Once they have chosen a final value, users can put the parameters in the right column. Source: EPFL ECAL lab, EPFL and H-IST UNI-FR

This new way of interacting with Parallel Coordinates, including a building block approach, brought also new technical and scientific challenges to address with regard to implementation.

4.5.2.5 Key challenges

Information visualisation generally aims to explore data in order to gain insight. The approach and solution proposed open new perspectives for the field of data visualisation as a way of supporting decision making in parametric design. This implies the creation of new, goal-oriented visualisation techniques and interaction paradigms that allow users to alternate between exploration and selection and, at the same time, support their creativity and design choices. This could lead to mixed-initiative solutions involving both computational tools and human intelligence (Pu and Lalanne, 2002).

Our tool had to be usable with a wide range of devices and by a variety of users. We thus opted for web technologies (Javascript, HTML, CSS), which ensure great flexibility in terms of development and maintenance as they do not require software installation.

With a database that can propose thousands of design alternatives in rapid succession, it became clear that the tool needed to be capable of handling a large number of data items simultaneously. ELSA displays aggregates of data items scaled according to their frequency, as opposed to individual polylines (like for Parallel Coordinates). This guarantees good scalability, even with a larger database.

Another challenge of the development of this GUI, was the necessity to have a close collaboration between scientists, designers and developers. This interdisciplinarity has been possible thanks to people with multiple skills, thus able to communicate across disciplines, and thanks to a team that had regular meetings during the two years of the development of the GUI, enabling to develop a common vision about this project.

4.6 A prototype, ready-to-use in a real context

This chapter presented the development path towards the first prototype (ELSA) that enabled to implement the *LCA*-based data-driven design method. In synthesis, the prototype is composed of two parts. First, a workflow that creates the knowledge-database thanks to a parametric approach, LCA, energy and sensitivity indices calculations. Second, a graphical user interface that allows extracting knowledge through an exploration process. The main features of this interface have been presented in this chapter.

ELSA is the result of a user-centered research that started in Chapter 2, with a survey about the LCA-practice context. Based on the context analysis, we were able to identify and combine promising techniques to increase LCA usability at early design stages. They have been integrated into a new methodology that was executed for the first time with ELSA as a result. To close the user-centered research loop according to section 2.7, the methodology still has to demonstrate its usefulness and impact when integrated into a real design process. This confrontation to reality can only be done through actual use by and feedback from practitioners, and is the purpose of the next chapter.

Chapter 5 Assessing the usability of ELSA through the Smart Living Lab case study

Disclaimer: Parts of this chapter are adapted from the following article – with permissions of all co-authors and journals:

Jusselme, T., Antunes Fernandes, P., Rey, E., Andersen, M., 2019. Design guidance from a Data-Driven LCA-Based Design method and tool prototype. Presented at the IBPSA, Rome, Italy. My contribution: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Validation, Visualization, Co-Writing – review & editing

Cozza, S., **Jusselme, T.,** & Andersen, M., 2018. Usability assessment of building performance simulation tools: A pilot study. Presented at the International Conference for Sustainable Design of the Built Environment SDBE 2018, London. My contribution: Conceptualization, Investigation, Methodology, Supervision, Validation, Co-Writing – review & editing

In the previous chapter, a computer-based program implemented the method developed within the frame of this thesis. This prototype, named ELSA, still has to be used by practitioners to assess its usability potential. To that end, we had the opportunity to test ELSA within the frame of the smart living lab competition that aimed at designing a low-carbon building according to the SIA2040. Hence, this chapter describes the conditions in which ELSA was setup, and the procedure we used to assess its usability, with mixed-approaches providing qualitative and quantitative feedback from the practitioners. The presentation of these results allows concluding about the strengths and weaknesses of the prototype and the method.

5.1 ELSA and the Smart Living Lab competition

5.1.1 The smart living lab history

The Cardinal brewery bottled its last beer in 2011 in Fribourg, Switzerland. In order to revitalize this post-industrial urban area, the Canton and the city of Fribourg decided to transform the site into a technology and innovation district, called blueFACTORY[2]. Many technological platforms are currently developed on-site, including the Smart Living Lab, an interdisciplinary, inter-institutional center of excellence on the

[2] *www.bluefactory.ch*

future of the built environment, jointly established by the Ecole Polytechnique Fédérale de Lausanne (EPFL), the School of Engineering and Architecture of Fribourg (HEIA-FR), and the University of Fribourg (UniFR).

The main goal of the Smart Living Lab is to become a research center of national and international reach, specialized in innovative concepts and technologies linked to the built environment. The core research scope of the Smart Living Lab covers construction technologies, well-being and behaviors, interactions and design processes, and energy systems.

As part of the vision of the Smart Living Lab project, the idea was to create, in the heart of the blueFACTORY, a living and working space ahead of its time i.e. to design the physical building that will ultimately host the Smart Living Lab as a landmark infrastructure, able to act as a demonstrator about what is possible in terms of pushing the boundaries of the building sector.

These ambitions necessarily mean that the building has to be at the forefront of current practices and its use require it to be an experimental support facility for the future research teams it will house. According to the institution's website[3]:

"This multidisciplinary living laboratory will serve as a catalyst of progress, providing fertile ground for carrying out work in real conditions. The new building should encourage rigorous investigation and lateral thinking thanks to its range of facilities for different types of research activity. The building will be at the cutting edge of efficient resource use over its complete life cycle. Its construction comes 30 years in advance of Switzerland's 2050 energy targets."

This building will have to support experimentations since it will be a research object for its occupants-researchers, and should express the following values (SIMAP, 2018):

1. catalyze the development and expression of progress,
2. stimulate rigorous investigation and lateral thinking,
3. intensify personal development,
4. encourage collaboration and contributes to the transfer of knowledge,
5. praise the environment and cultural context in which it is established,
6. embody sustainable development in all its dimensions and embraces industrial ecology and the circular economy,
7. be evolutionary and able to redefine itself.

This future building is planned to be completed in 2022. The exceptional nature of the project justified a preliminary research program, which led to numerous publications and has been summarized in a book (Andersen and Rey, 2019).

The primary objectives of the research program were to define the performance targets to apply to the building and to find a way to integrate them into an actual construction project. These methodological and targets requirements have been the subject of detailed building specifications, and included life cycle performance targets that are further described in the next section.

[3] *https://www.smartlivinglab.ch*

5.1.2 The smart living lab Competition

5.1.2.1 Competition process

The competition itself was organized through a particularly innovative format combining competition and collaboration (Radu, 2019). The call for applications was launched in September 2018 and 23 teams submitted a complete candidacy, as illustrated by Figure 55. The competition rules requested the teams to embed interdisciplinary competences with architects and engineers since the beginning of the design, and to include experts in energy efficiency and carbon emissions assessment. At the end of a thorough evaluation and ranking process of the applications based on five explicit criteria that gave emphasis to motivation, references, skills and proposed architectural strategies, four teams were selected in November 2018. The MEP was launched with an introduction and followed by three successive phases of design (Figure 55). At the end of each of these phases, there was a project presentation by all the candidate teams as well as a dialogue between candidates and a jury of experts. The jury was technically assisted by specialists from the smart living lab.

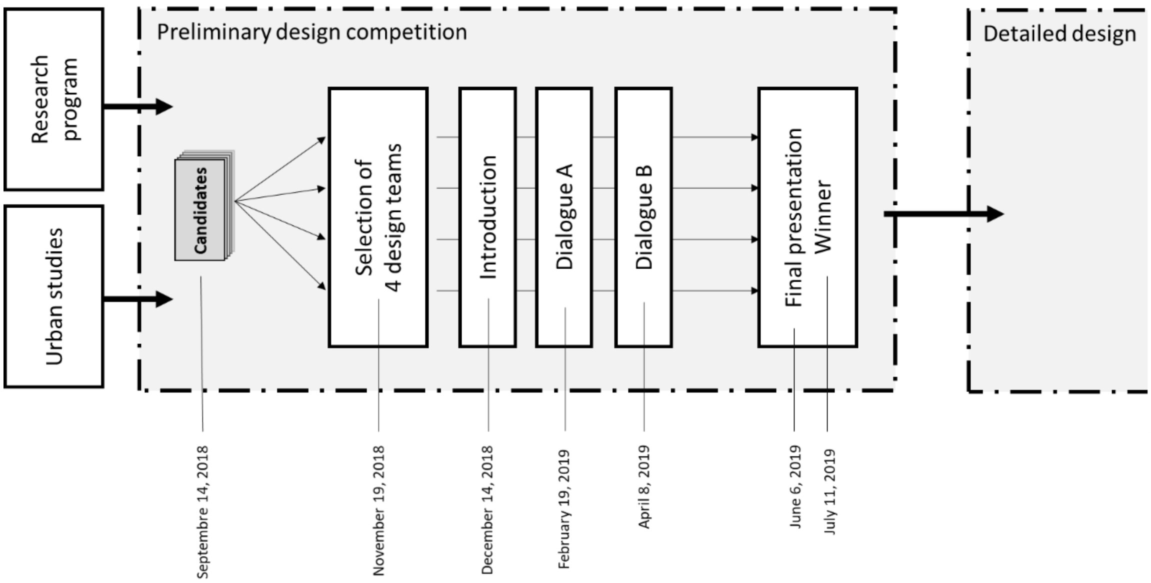


Figure 55: The design competition process and planning

The aim of the dialogues was to interact between candidates, jury and users in order to lead the projects toward innovative and user-centered solutions according to the building specifications. All candidates were present at all presentations and dialogues of the other candidates. Therefore, they agreed to freely share their approaches, ideas and solutions with other candidates, which was a very innovative approach for architectural competitions.

After the final dialogue (B), the jury evaluated the final projects (preliminary designs) and selected one winning team, which was recommended to the owner, blueFACTORY, to detail and build the laureate project. More information about the four competition teams and the winner project are available in Appendix G.

5.1.2.2 Building size and location

The detailed specifications of this building are presented in different documents (SIMAP, 2018) based on which a public architectural competition has been launched. The future building should offer 130 workplaces and various laboratories to its researchers. According to Table 9, its net floor area should reach

5,009 m². Its built volume should be approximately 18,600 m^3 for a maximum construction cost – including engineering fees – of CHF 20,000,000.- incl. VAT.

Table 9: Surface distribution of the future building of the smart living lab.

	Net Floor Area (m²)
Offices	1077
Facility rooms	1356
Laboratories	970
Corridors	1089
Built surfaces	517
Total	5009

The building will be located between two buildings protected by heritage laws as they represent part of the site history. On the South, the "Halle Grise" with a roof at 18m to the ground that might shade the future building. On the West, the "silo" and its 45 meters height.

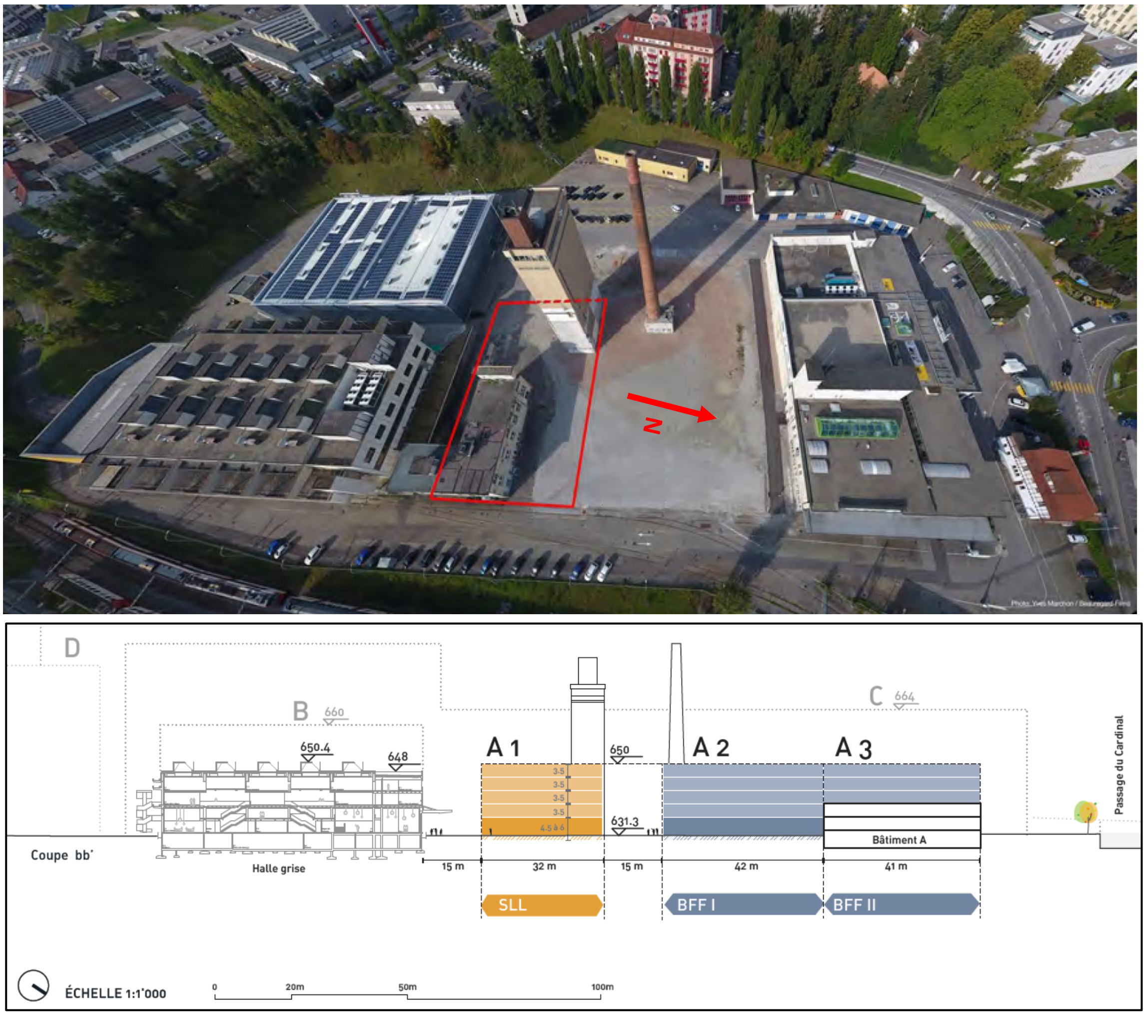


Figure 56: Top: Skyview of Bluefactory and the future location of the smart living lab represented by the red square. Bottom: cross-section of the construction site between the silo and the "Halle Grise". Source: (SIMAP, 2018)

5.1.2.3 The life cycle targets

The ambition of the future building of the Smart Living Lab is to satisfy the 2000-Watts society performance targets at the horizon 2050. Hence, the SIA 2040 targets for offices listed in Table 10 have been chosen as the building objectives for the CEDnr and GWP. The CED target has been defined thanks to Kellenberger (Kellenberger et al., 2012). Only the overall performance targets are mandatory. The indicative sub-targets are given for information purpose only. It is interesting to note that a different proportion of impacts related to "construction" compared to "operation", that is higher regarding the GWP, and lower regarding the CED and CEDnr. These values are based on the ERA surfaces, which sum up all floor surfaces that are included in the thermal envelope of buildings and whose use requires climate conditioning. This area is defined in detail in SIA 380 and 416 (SIA, 2015b, 2007). The original competition rules in French about these life cycle performance targets are extracted in Appendix D.

Table 10: SIA 2040 targets for offices

	Overall performance targets	**Sub-target “operation”**	**Sub-target “construction”**
CED (kWh/m².y)	209	167	42
CEDnr (kWh/m².y)	120	80	40
GWP (kg CO_2-eq/m².y)	13	4	9

In this context, the *LCA*-based data-driven method was used to provide additional support to the architects and engineers involved in the design of this building, a contribution that was made possible thanks to the innovative, collaborative-competitive process that was adopted for the competition (SIMAP, 2018).

5.1.3 Delivering the prototype to the competitors

5.1.3.1 A tool and a reporting frame

The data-driven design method (Chapter 3) was implemented as a tool prototype named ELSA in Chapter 4. As further detailed in the previous chapter, its two main components include, on the one hand, a workflow that automatically generates twenty thousand design alternatives and their respective LCA in eight hours, and, on the other, a GUI that allows to visualize this knowledge-database. The level of development of our prototype was unfortunately not advanced enough at the time of the competition to let the teams implement their own building design seamlessly. It was thus decided instead to generate a database with different massing schemes developed by urban designers as alternatives reasonable to consider as a starting point given the site constraints, with different impacts on life cycle performance.

The three basic massing schemes used to this end were derived from urban studies realized by Urbaplan[4], a Swiss urban design and planning office, with gross floor areas and volumes around 5,300 m² and 20,000 m³ respectively. Figure 57 illustrates the diversity of these schemes, with a U (1), an O (2), and an I (3) typology.

[4] *https://www.urbaplan.ch*

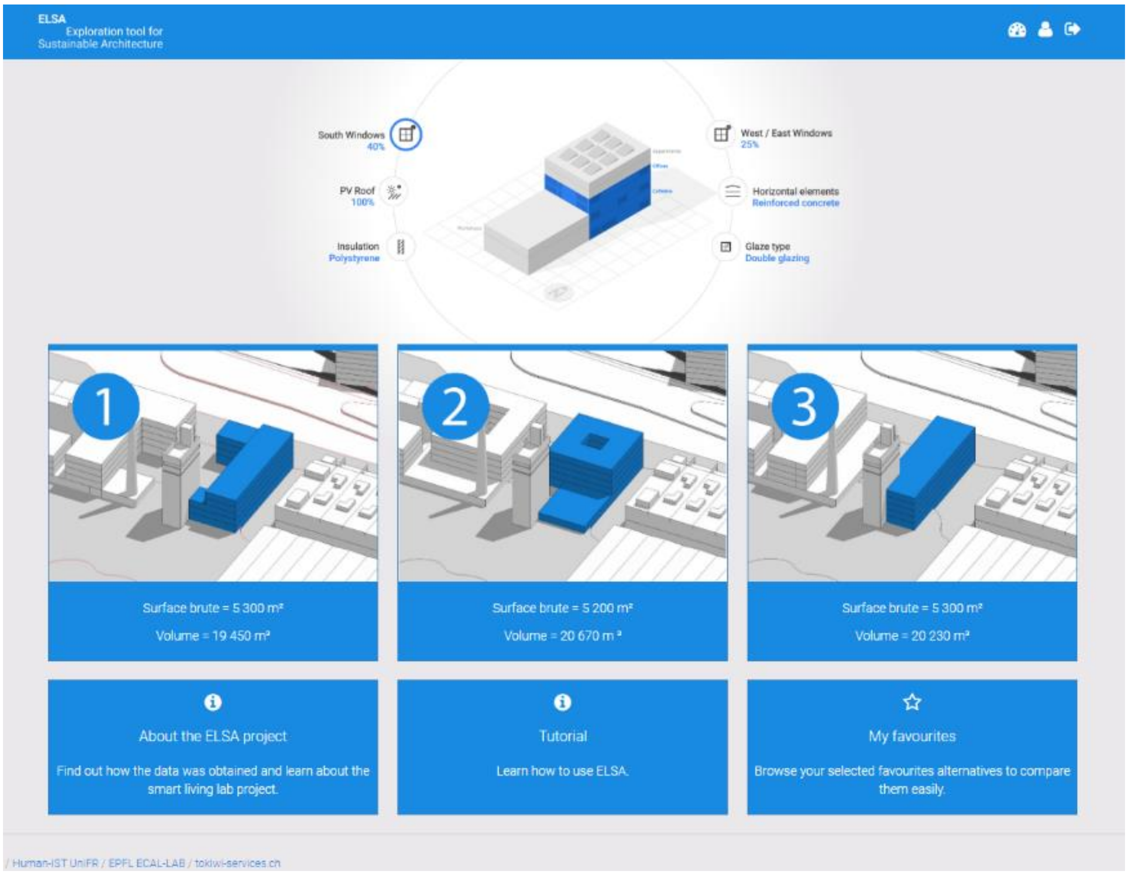


Figure 57: Home page of ELSA: Users choose first one out of three massing schemes that fits the best with their project. Tutorial materials (including the simulation hypothesis) and scientific publications further detailing the methods behind the tool were also made accessible from ELSA's Homepage. Source: EPFL ECAL lab, EPFL and H-IST UNI-FR

Practically, the design teams thus had the possibility to choose the scheme (building typology) closest to their own, and then explore the database by applying parametric changes within a slightly abstracted (as opposed to design-specific) context.

Section 5.1.2 details the building specifications, with the SIA2040 targets when it comes to the CED, CEDnr and GWP impacts. Beyond these targets and ELSA, a tool to justify and report their project performances have been given to the candidates. This tool was an Excel file where each competitor had to report the life cycle performance for each component of the building individually, and for each system too. Indeed, if ELSA is a decision-making tool, it does not allow the designers to justify the performance of their projects. Also, ELSA was used at the for the first dialogue A only. Later, once a higher level of details was achieved, the competitors were asked to assess the impacts of their projects thanks to this Excel tool following the SIA 2032 norm for life cycle assessment. This allowed to get a global and exhaustive overview of the building impacts, but also to be able to compare the competitors' projects to one another.

This Excel-based reporting framework is provided in full in Appendix F. As an example of what data it contains, the comparison between carbon budgets defined by ELSA, and carbon impacts of the competitors' projects is illustrated by Figure 58. This graphic typically allowed the jury to quickly understand which of the systems or components had the highest share of GWP impact, and how far they were from the carbon budgets that were set by ELSA.

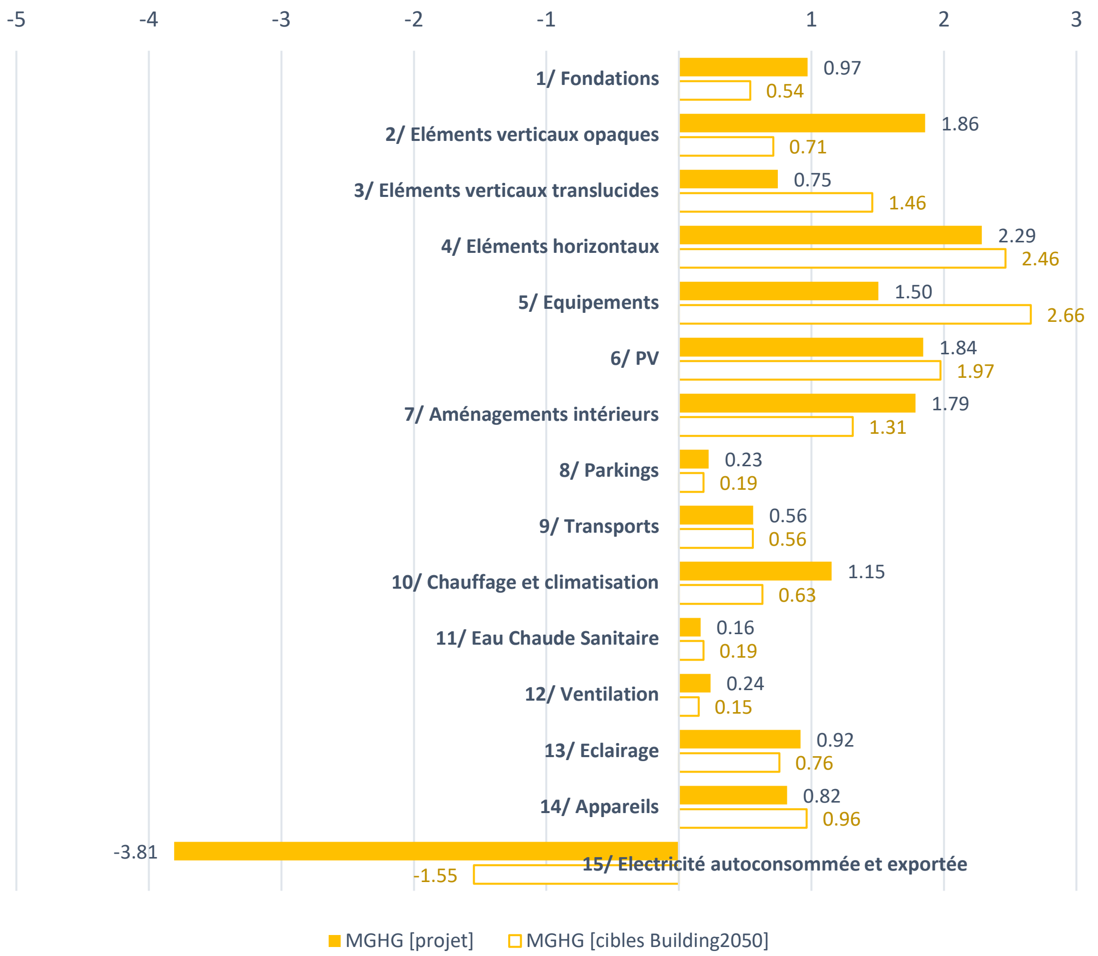


Figure 58: Carbon budgets (yellow bars) defined by ELSA, and carbon impacts (white bars) of the project of one competitor. Source: Building2050 EPFL

ELSA was actually only used to support the design during the first phase of design, until Dialogue A. Later, the SIA 2039 was used to assess the life cycle performance with a conventional LCA, based on a higher level of details.

5.1.3.2 Introducing ELSA

Before making ELSA available to the competitors, its principle and objectives were introduced to them during the kick-off session on December 14, 2018 (cf. Figure 55), where all four teams were present with their architects and engineers. A specific slot of 30 minutes was dedicated to presenting ELSA's purpose, potential and functionalities, followed by a demonstration of the tool, with the help of the slides provided in Appendix E. During this session, the technical details about the online access to ELSA were also explained and questions were answered. Each of the participants was then able to create a personal account on http://elsa3.epfl.ch and to use ELSA without any restriction. In the end, 15 user accounts were created, with three to four users per team on average.

Later, on January 17, 2019, a 1-hour online webinar was offered to discover ELSA in details thanks to a more in-depth demonstration, again followed by a questions and answers session. At least, a member of each four teams participated in this webinar.

As the competition was following public regulations, these two presentations cumulating 1h30 of presentation and training was all that the competitors received in terms of guidance to start using ELSA. For equity reasons, no other contacts between ELSA developers and the competitors were allowed.

5.2 About the knowledge-database of the Smart living Lab project

This section gives an overview of the knowledge content of the database that has been specifically generated for the smart living lab competition. It described the results coming out of step five of the method as it is proposed in section 3.2.3. For clarity's sake, we used Excel-based graphics to illustrate this content. Indeed, if ELSA is very well optimized for an exploration process, with dynamic data visualization techniques, it is not using static graphics that could be incorporated in a report yet.

5.2.1 Step 5.1: Identifying the main parameters

The Sobol method delivers both first-order indices and total-order indices:

- First-order indices: indicates the influence on the output variance by a single model input alone.
- Total-order index: indicates the influence on the output variance caused by a model input, including both its first-order effects and all higher-order interactions.

Considering the high number of parameters, only the total order indices will be discussed.

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 *SI* values for the most sensitive parameters (Archer et al., 1997).

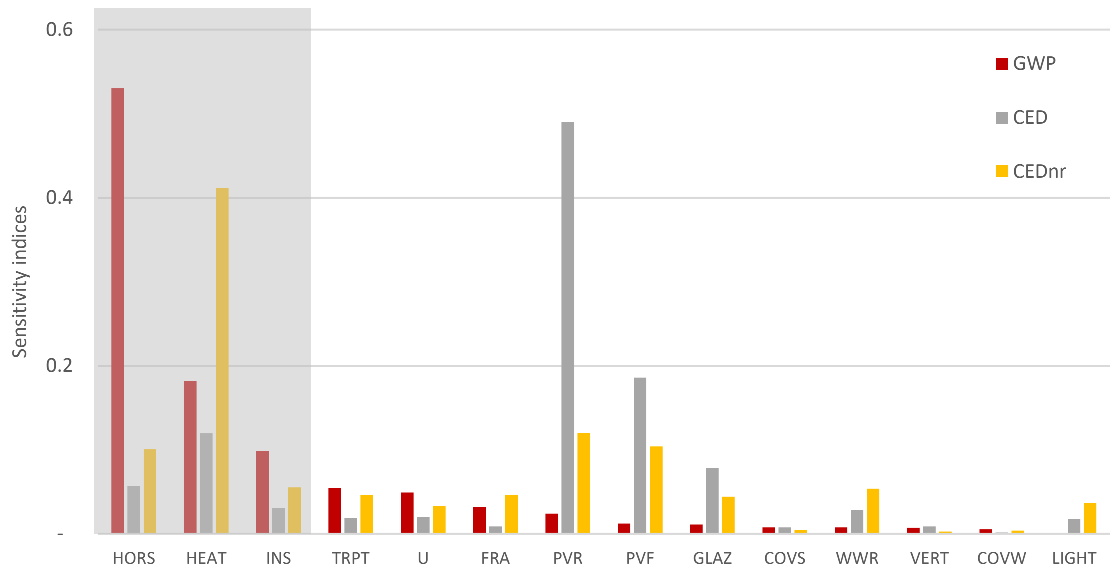


Figure 59: Total order Sobol sensitivity indices for the GWP, CED and CEDnr impacts of the 14 parameters of the design alternative database. The grey zone represents the parameters embedding 80% of the GWP variance. The signification of abbreviations is available in Table 4.

The following description of the results applies specifically to the sensitivity analysis performed on the knowledge-database using massing 1 in Figure 57, but would conceptually be applied likewise for any other scheme or 3D model.

There are important differences in how the *SI* are ranked depending on the impact that is considered: in other words, the parameter with the highest *SI* differs based on the environmental impact that is considered (i.e. CED, CEDnr or GWP). Regarding the *GWP* (Figure 59), the horizontal structure has the highest *SI* with 0.53. In other words, it means that changing the design options of the horizontal structure explains half of the variance of the mathematical model. Indeed, slab, floors and roof represent a large quantity of materials with important surfaces, and there are significant performance differences between these components: the *GWP* impact of the "*wood frame*" structure (44.4 CO_2-eq/m².y) is e.g. four times lower than the one of the "*trapezoid plate*" (186.6 CO_2-eq/m².y). Thus, the parametric approach induces large differences in material quantities, with materials that have very different impacts. As a result, the horizontal structure has the highest SI.

Also, it is interesting to note that PV panels on the roof or on the façade have a low *SI*, due to high embodied carbon emissions and low carbon content of the Swiss grid, which makes their *GWP* mitigation potential not very attractive in Switzerland. On the other hand, PV panels have a 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.

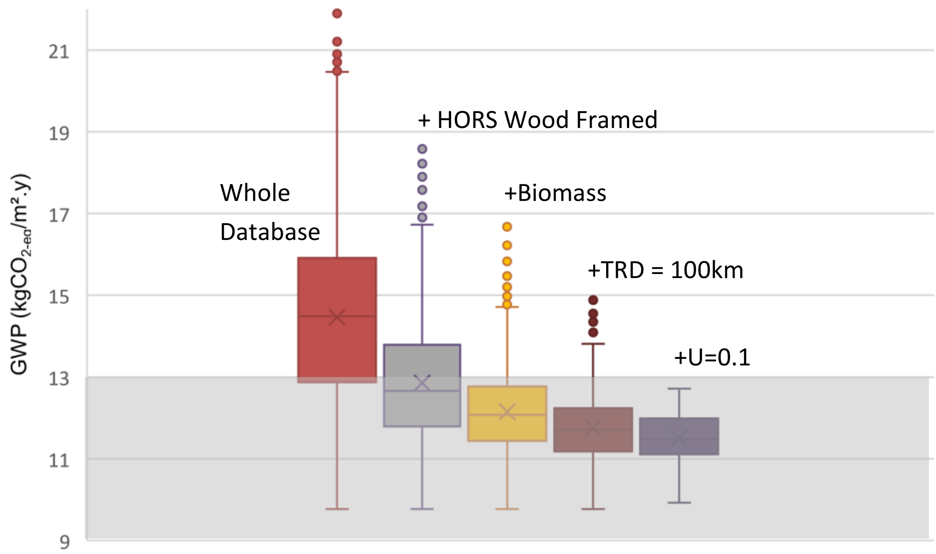


Figure 60: Distribution of the GWP impacts of the full database (left), and other subpopulations with cumulative constraints by the sensitivity indices of the design parameters. The grey zone represents GWP impacts below the SIA2040 objective. GWP axis starts at 9 kg $CO2_{-eq}$/m^2.y.

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 Figure 60 highlighting the decrease of the *GWP* impact 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. On the contrary, filtering the database in the reverse SI order would lead to constraining most of the design parameters before decreasing the dispersion of the resulting database below the GWP threshold.

5.2.2 Step 5.2: Allocating the carbon budget

One of the key techniques of the *LCA*-based data-driven method is target cascading. It is 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. 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 10. 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's target equals the building overall objective. Hence, the carbon budgets are expressed kg $CO_{2\text{-eq}}$/m².y. The target cascading process follows the following equation:

$$T_i = \overline{T_i} \cdot \frac{T_B}{\sum_{i=1}^{n} \overline{T_i}} \qquad \textit{Equation 6}$$

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.

Figure 61 highlight the results of this target cascading process for massing 1 in Figure 57 and its 18 elements and systems, divided into embodied impacts and operational *GWP* impacts. 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).

One can note that PV has high embodied emission impacts, which are not fully counterbalanced on 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. This is due to the lower electricity production if panels are located on facades and orientations that have less favorable solar exposures. While they produce less, they still have the same embodied impacts than the ones on the roof with optimal solar potential.

Horizontal elements have the highest impact target, with a maximum value that can reach 6 kg CO_2-eq/m².y, that is to say almost half of the SIA target. This case corresponds to the trapezoid plate (cf. Table 5 in section 4.1), which will, if chosen, decrease the design options of the other building components by drastically lowering their carbon budget.

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 design. As an example well illustrated in Figure 61, windows might have in average an impact below 1.44 kg CO_2-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 window type to be compared with this carbon budget, demonstrating that the method is usable even with building products that have not been integrated into the parametric approach (L7 in section 3.1.7, Figure 35).

These findings also give an estimation of the performance level that manufacturers should aim at when producing building components. For instance, the ventilation system industry might choose to target systems with embodied impacts lower than 0.91 kg CO_2-eq/m².y.

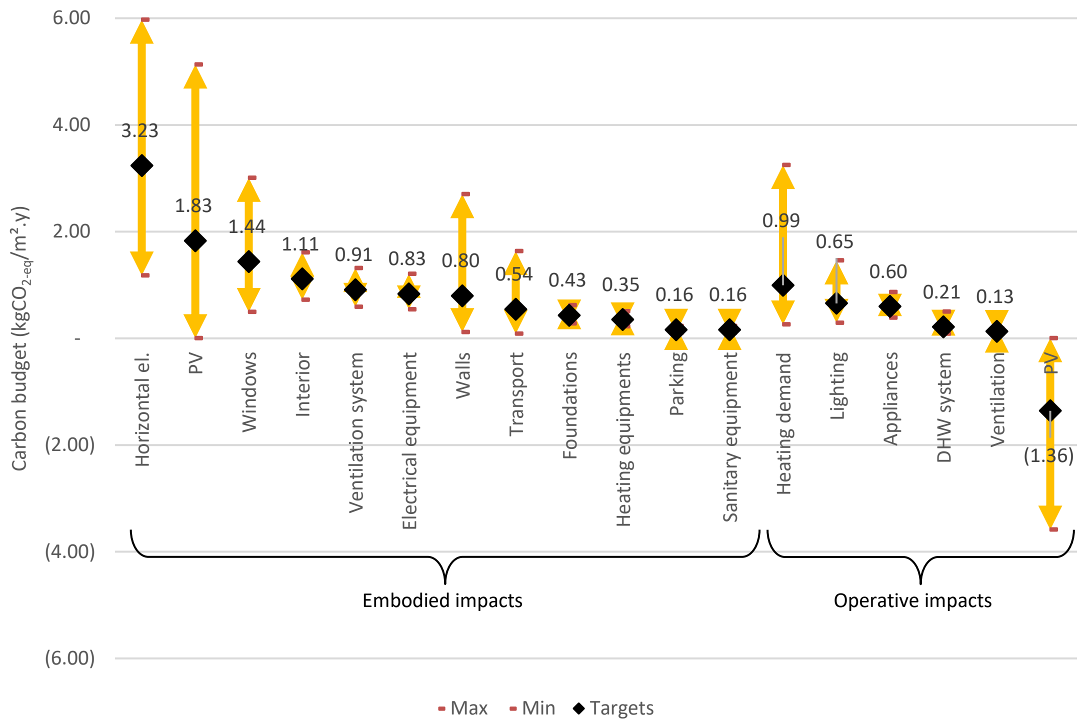


Figure 61: Maximum, minimum and carbon budget values for the different building components of the knowledge-database

It is also interesting to note that the database does not follow the same trend in terms of shares between embodied and operative impacts, compared to the SIA2040. In Table 11, one can note that compared to the smart living lab case study, the SIA 2040 underestimates the share of embodied impacts called "construction" when compared to the operative ones ("operation"). Indeed, the SIA attributes a share of 30% of the overall performance target to the operation sub-target (4 out of 13 kg CO_2-eq/m².y), while the database we generated is between 10 to 20% according to the amount of PV in the project. This analysis thus reveals the necessity to adapt sub-targets to the specificity of the context of the project.

Table 11: Carbon budget for the whole building, its operative impact, and construction impact according to the SIA 2040, and to the knowledge-database

	Overall performance targets	**Sub-target "operation"**	**Sub-target "construction"**
GWP SIA2040 (kg CO_2-eq/m².y)	13	4	9
GWP Shape 3 (kg CO_2-eq/m².y)	13	1.22	11.78
GWP Shape 3 without PV (kg CO_2-eq/m².y)	13	2.64	10.36

This comparison opens an interesting discussion about the opposition between the possibility to generalize carbon budgets, as they are used within the SIA2040 with the same sub-targets for every building in Switzerland, versus the user-specific and context-dependency of these targets which make them less generalizable, but with higher design guidance for a specific project. Indeed, in our case, the method provides project-specific targets as the knowledge database used to perform the target cascading depends on the design options that have been chosen in step 2 of the method by its user (see section

Figure 38, section 3.2.3), and on the meteorological and physical context of the project that will influence the operational impacts. Increasing the generalization potential of this targets at the Swiss scale would be possible by performing a target cascading process on a knowledge database which would be more representative of the design options and meteorological contexts of the Swiss buildings. It would lead to a significant increase of the computational load, but could be later used to any Swiss project. Yet, the design guidance would be lower than if using context-specific targets. Another angle could be to use both – Swiss-representative and context-specific targets – in an iterative process where designers start the design with Swiss targets and refined them later after the calculation of a project-specific knowledge database.

This discussion about the potential generalization of carbon budgets leads also to the current green product certification methods. It is interesting to note that to date, certification schemes have not used the target cascading yet to qualify the building product performances. There are already some quantitative approaches such as the BRE[5] or the EcoBau[6] rating system. However, to rate the performance of the building products, they compare the products within their own family only. For instance, the best window within a family of windows will have the best rate, that could be A+ for instance. The same method will be applied to the flooring products, which will lead to identify the best one and rate it A+. However, even if these two products have the same rate A+, they might have very different impacts in absolute in comparison to the overall building impact. Hence, choosing an A+ product within one product category will certainly not lead to the same benefits as choosing another A+ in a different category. This is why the BRE shares this warning on their website:

"The A+ to E Summary Ratings for some elements span a much broader range of values than for other element groups. Hence, in some cases, e.g. Insulation, the difference between an A+ rated and an E rated specification may be relatively small, whereas for other elements the difference may be substantial.

Similarly, for impact ratings, the intensity of the impact and range can differ significantly. For example, for one impact category, the range may be small and close to zero, for another, small but all with higher impact, and for another, large, starting at zero."

Following this warning, we envision a real potential of using the target cascading approach to extend the current product rating systems to compare the absolute impact of each element to the carbon budget of its category. Doing so, even the best product would have a low rate if its impact is still higher than the carbon budget of its category.

Targets could be also more specifically set according to a design strategy. As an example, if the target cascading process is performed on the sub-population of design alternatives having reinforced concrete for the horizontal elements, the windows target should be decreased from 1.44 to 1.1 kg CO_2-eq/m².y to counter-balance the low performance of these horizontal elements as illustrated by Figure 62.. We have here the demonstration that if the target cascading process is performed according to a specific design situation that is explored, it does not decrease the design freedom. In other words, the target cascading performed on the whole database gives a carbon budget of 3.23 kg CO_2-eq/m².y for the horizontal elements which makes it not possible to use a concrete solution, and lead to an impact of 4.25 kg CO_2-eq/m².y for this element. However, if the target cascading considers the exploration process which selected the sub-population of design alternatives that have a concrete slab, the method is able to increase the carbon budget of the horizontal elements to match a concrete solution by decreasing the budget of the other components.

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[5] *https://www.bregroup.com/greenguide/page.jsp?id=2088*
[6] *https://www.eco-bau.ch/index.cfm?Nav=28&ID=63*

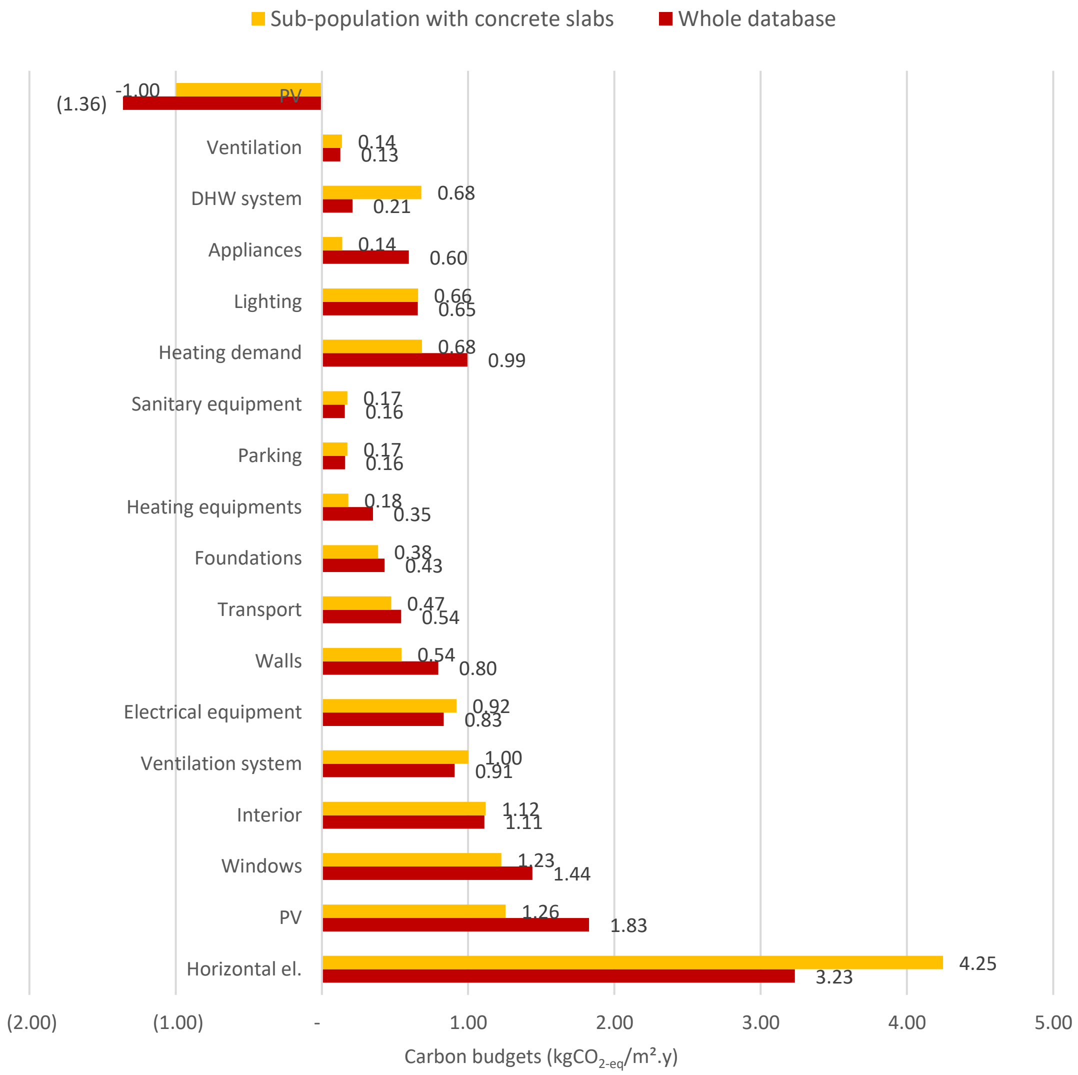

Figure 62: Carbon budgets for the whole knowledge-database, and for its sub-population with concrete slabs.

5.2.3 Step 5.3: Exploring the database

The sensitivity analysis and the target cascading already made it possible to extract valuable design guidance. In addition, this section aims at exploring the database thanks to data visualization techniques, and to extract a complementary knowledge.

5.2.3.1 A comparison of three performance indicators

According to the literature, GWP targets are the most difficult ones to reach. Indeed, one can observe in Figure 63 that all the design alternatives generated have a satisfactory *CED* impact i.e. emissions that remain below the threshold of a 2000W society. This is also the case for the *CEDnr* indicator. However, regarding the *GWP* impact, only 27% of the whole design alternative database is associated with 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).

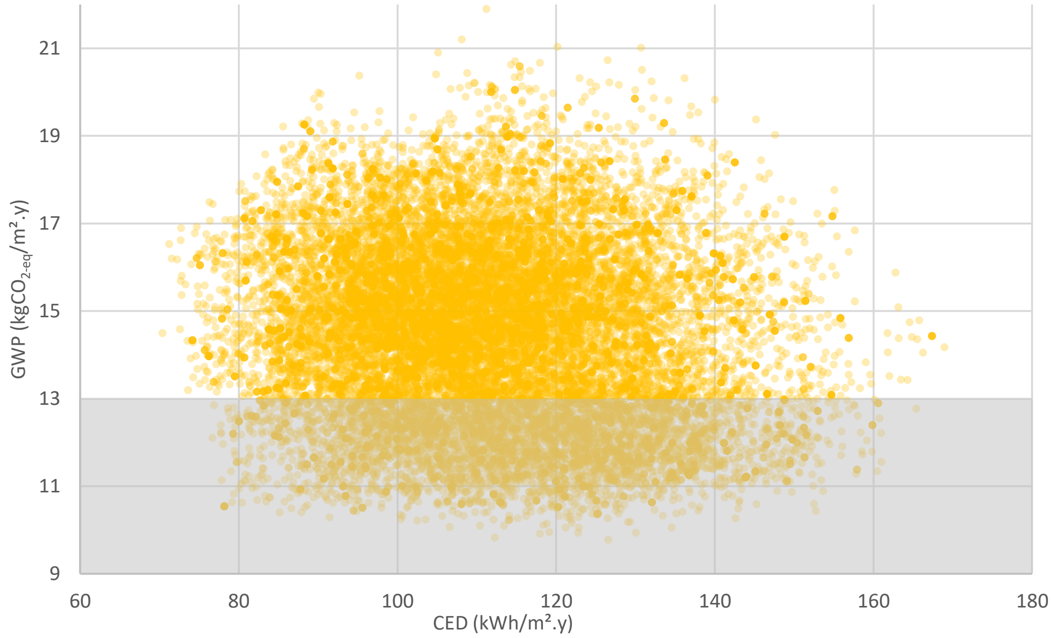

Figure 63: Environmental performance dispersion of the 20'992 design alternatives of the database according to their CED and GWP impacts. The grey zone highlights the 2000-Watts design space.

5.2.3.2 Final energy distribution

Regarding the final energy distribution (Figure 64), the Photovoltaic production has the highest dispersion from 0 to 44 kWh/m².y, which is expected based on the large differences in solar collector surfaces between the various design alternatives (i.e. from 0 to 90% of the roof, and 0 to 30% of the East, South and West facades). Also, the maximum gap between design alternatives for heating consumption is 20 kWh/m².y, which highlights the impact of changing the thermal properties of the model itself. Domestic Hot Water (DHW), Appliances and Ventilation never vary, as they are kept constant within the database.

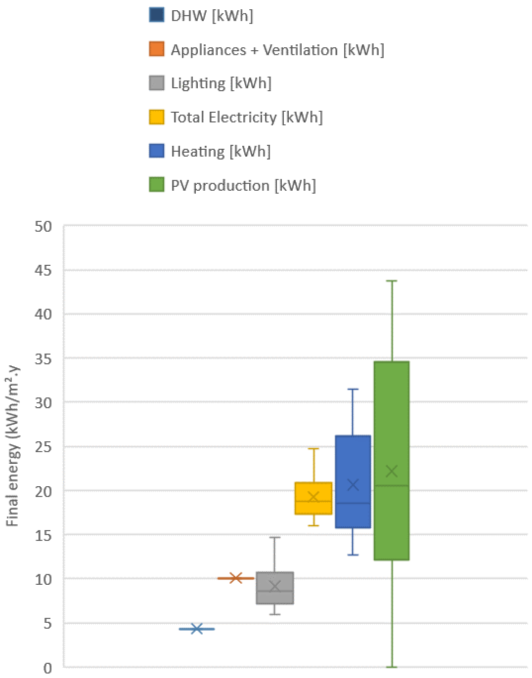

Figure 64: Distribution of the final energy consumption according to different operational energy usages

5.2.3.3 Three models

Three different massing models have been used as a basis to perform the parametric approach and generate the three knowledge-database. Using the same visualization technique as found in Figure 63 but with the three different databases, one more clearly sees differences in their dispersions. From Figure 65, it is clear that the massing scheme itself already influences the boundaries of LCA performance. Massing scheme 3 has the lowest impact, while schemes 1 and 2 are similar. Indeed, their respective average performance is 13.02, 14.47 and 14.38 kg CO_2-eq/m².y. Also, schemes 1 and 2 have 27% and 29% of their design alternatives below the GWP threshold represented in grey in Figure 65, while it increases to 49% for scheme 3.

Figure 65: Environmental performance dispersion of the three databases according to their building shapes, CED and GWP impacts. The grey zone highlights the 2000-Watts design space.

These differences can be explained in the light of Table 12, which details the respective compactness of these three schemes. Compactness is expressed in terms of surface ratios between the building envelope and its energy reference area (ERA). In other words, for one square meter ERA, the scheme that has the lowest envelope surface is also the one that has the highest compactness (e.g. the lowest C-value in Table 12). The compactness could be also expressed as the ratio between the total envelope surface and the heated volume in meters. Thanks to the previous sections, we have already observed that insulation, transportation, U-value, window frame parameters were amongst the parameters with the highest influence. Also, their BOQ per ERA will by definition be affected by the compactness of the scheme. Hence, this case study demonstrates that a massing scheme and specifically its compactness is one of the main strategies to lead buildings towards lower carbon impacts. Scheme 3 with compactness 42% lower than scheme 3 has logically also lower average impact in terms of GWP.

Table 12: Geometrical differences of the three shapes used as a basis for the parametric approach.

Shapes	(A) Energy reference area [m2]	(B) Total envelop [m²]	(C=B/A) Compactness [m²/m²]
1	3700.49	5601.8	1.51
2	3620.46	6325.5	1.75
3	4259.62	4763.9	1.12

5.2.3.4 nZEB vs low-carbon buildings

Exploring the knowledge-database is also very valuable to understand how crucial GWP targets are. So far, EU countries count on their energy regulations (EU - EPBD, 2010), that will force every new construction to reach a net Zero Energy Building (nZEB) performance level to tackle the climate change issue. However, exploring the knowledge-database shows that there is no correlation ($R^2 = 0.03$) between the operative energy performance level and the GWP impact of a building during its entire life cycle. Indeed, Figure 66 presents the design alternatives and their performance in terms of nZEB balance according to the SIA380 calculation, as well as GWP impacts. Among 20992 alternatives, 5360 respect the nZEB definition (i.e. negative primary energy balance in the grey zone of the chart). However, their GWP impacts vary between 10.28 and 21.89 kg CO_2-eq/m².y, meaning that an nZEB building actually does not guarantee a low-carbon performance. Indeed, only 938 cumulate the nZEB and the SIA2040 targets (red square in Figure 66). This is mainly due to the low share of operative impacts within the total GWP impact, and thus to the small influence of the nZEB performance level on GWP.

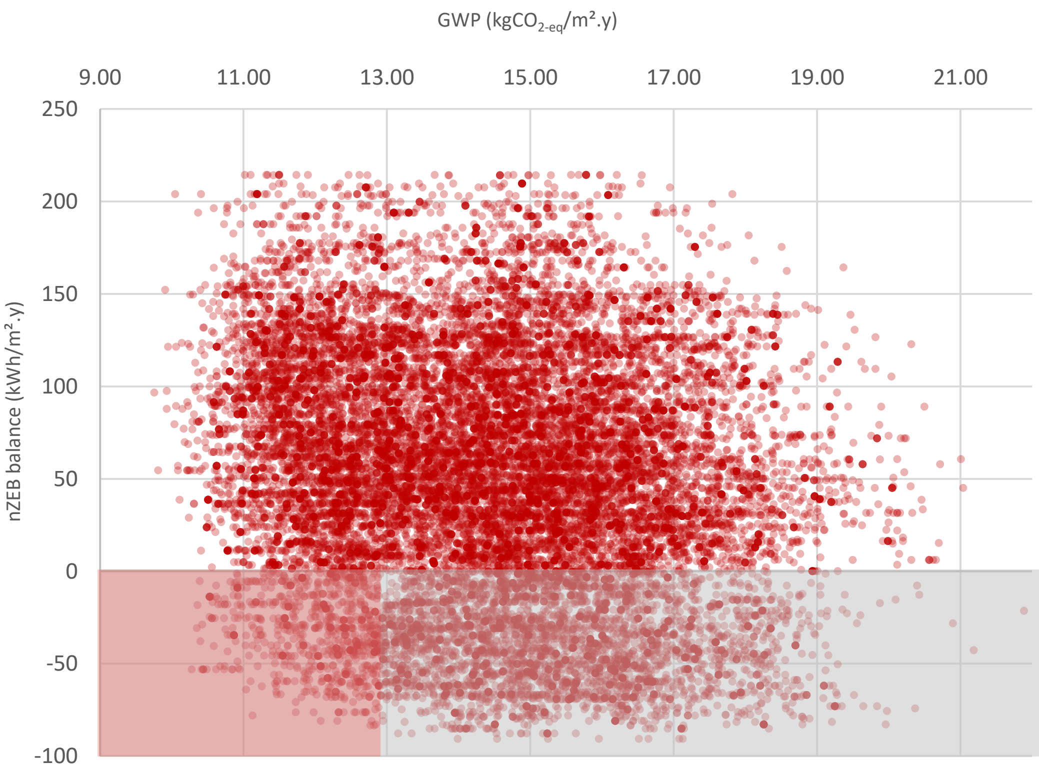

Figure 66: The 20992 design alternatives of shape 1 and their performances in terms of GWP impacts and nZEB balance according to the SIA380.

These data explorations highlight the learning potential of extracting knowledge from the database. 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 such as Excel remain very limited when it comes to handling millions of data. Most of the graphics in this section have been carefully chosen to be compatible with the ability of Excel to support the data embedded in the knowledge-database. Hence, this process is not user-friendly, as the user has to manually plot the data, and choose an appropriate visualization technique. In addition, the charts are not interactive and each modification is time-consuming. This is where the GUI of ELSA comes in, as developed in section 4.5.2, to support the design with a user-friendly environment where graphics are dynamics, and specifically chosen for an exploration process.

5.3 Usability assessment

5.3.1 Assessment procedure

Based on the techniques identified in section 2.3 and coming from the social science research field, we decided to choose complementary assessment methods that would give us exhaustive feedback at different scales: at the individual and collective level, with quantitative and qualitative techniques:

- For the individual level, we sent an online survey to the practitioners that have used ELSA. Within this survey, we were able to collect qualitative answers thanks to open questions, but also quantitative feedback with a Likert-scale, i.e. a scale from 1 to 5 in integer steps, to make answers short and data analysis efficient.
- For the collective level, we followed the literature suggestion by using the focus group method, which involves a group interview with a semi-structured discussion and qualitative outputs.
- We also used the System Usability Scale as it was already used in the BEPS field, strengthening the quantitative feedback, allowing to compare the results with other studies.
- Finally, as ELSA was delivered online to the competitors, we were able to observe their intensity of use, by monitoring their logins.

Each of these usability assessment techniques is further detailed into the following sections. As we collected personal data, an authorized consent form was submitted to the participants for voluntary participation (that they were allowed to decline but none did), detailing the research purpose, the procedure, the nature of the collected data, the confidentiality rules and the legal framework. A sample of the consent form is provided in Appendix C. All the data collected or produced during this usability assessment was anonymized. Hence, the competitors will be named according to their profession as Architect or Engineer, and to their team as team A, B, C and D. The different usability assessment techniques have been conducted independently; they have thus a different number of participants, which are specified in each of the following sections. Regarding the timeline of these assessments:

- The intensity of use has been monitored all along the competition, between December 14, 2018 and February 19, 2019. However, the two first weeks corresponding to the Christmas holidays have not been considered in the data analysis as there were very few logins,
- The focus group was conducted the same day than Dialogue A, on February 19, 2019. According to the design competition process (cf. section 5.1.2), this step corresponded to the end of the schematic design, where the use of ELSA was required,
- After the focus group, the online survey and the SUS test were sent to the practitioners.

5.3.2 Intensity of use

During the competition, the logins to ELSA have been monitored anonymously per design team, and the collected data have been analyzed only after the competition results, to prevent any influence on the jury. Overall, ELSA was used 94 times from the second to the eight weeks of the year 2019. Figure 67 displays this intensity of use throughout this period, by displaying how many times any user from a given team (A, B, C, D) would log in to ELSA each week.

As can be easily observed in Figure 67, there are high discrepancies between teams in terms of frequency of use: team D logged in 45 times, while team C only 11 times. On the other hand, we also observe that there is a general trend with two pics during the third and the seventh weeks, that might represent the first exploration during the first design proposal, and the last performance check before the final rendering of the project. This is actually consistent with the practitioner survey findings presented in section 2.6.2, which pointed at that about three design alternatives were typically produced and compared during the early design phase. In our case, this first design phase in the competition had a length of two months, and we can thus reasonably expect that the design teams may have produced only two design alternatives. This would explain a more intensive use of ELSA happening about twice over that period, and is in observed in Figure 67, as we see peaks for all teams on weeks 3 and 7. It is also interesting to note that team D seems to have followed a more integrated design process, with more continuous use of ELSA over the entire design process.

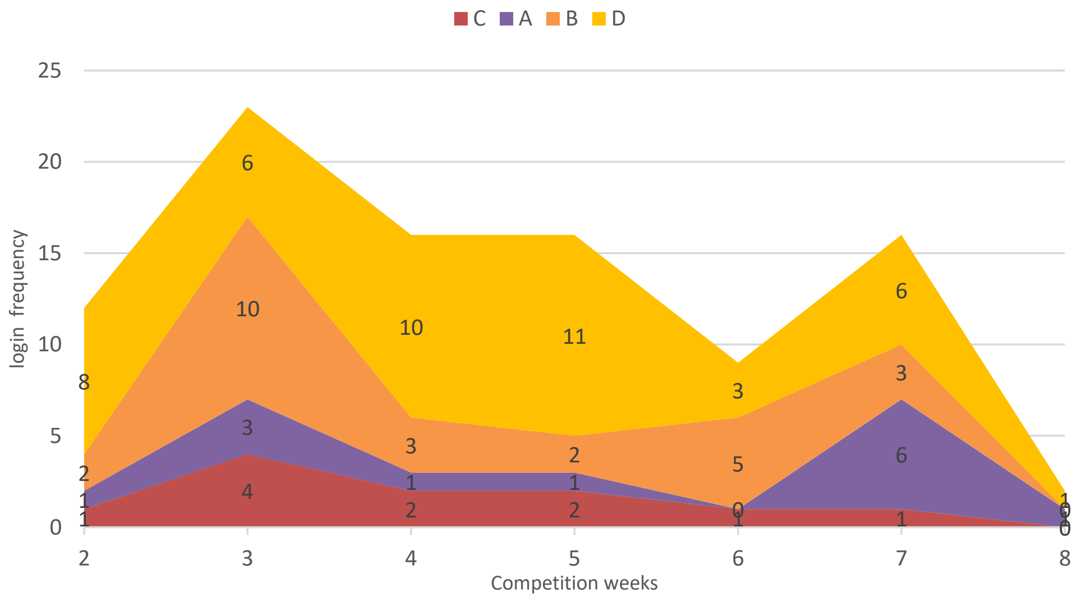

Figure 67: Cumulated use of ELSA per design team and per week, calculated thanks to the login frequency.

5.3.3 Individual feedback

An online survey was set up thanks to the web-based platform provided by Google form. It was distributed via email to all four teams. The questions were inspired by the previously conducted context analysis results detailed in Chapter 2 and all questions and answers of this online questionnaire are compiled in Appendix B.

The survey was ultimately answered by eight participants, which is a too low population for any statistical analysis but allows for some qualitative learnings. More importantly, they reflect the outcomes of a real-life situation, where practitioners used the tool in an actual design context. Their answers can thus give us a very pertinent picture of ELSA's usability, at least in the context of the architectural competition organized for the Smart Living Lab's future building.

Prior to asking questions about ELSA, participants rated their knowledge to achieve the 2050 objectives of the SIA2040. All eight respondents considered their knowledge in this field as more than acceptable. This is in line with the competitor selection process as the teams were also selected according to their skills and low-energy/carbon building references. Regarding ELSA's usefulness, illustrated in Figure 68, answers were very positive: three participants (38%) described it as 'useful' and four (50%) as 'very useful' as design support in achieving the SIA2040 targets. Thus, despite the already high expertise of the participants which included both engineers and architects about LCA questions, they still had a need for design guidance. Regarding satisfaction using ELSA at early design, the outcomes were also positive, with a large majority of answers qualifying it as either 'high' to 'very high'. This can be explained by the answers to the other questions. Amongst the eight participants to the survey:

- 7 qualified ELSA as useful or very useful,
- 5 qualified the effort using ELSA as not very important or not important at all,
- 7 agreed that ELSA had an impact on the design,
- 5 qualified this impact as positive, 3 as neutral,
- 7 stated that they would use ELSA at early design if available.

These results demonstrated the strong and positive impact ELSA has on design. In fact, these answers highlight its high usability within this architectural competition, with high effectiveness, i.e. a low effort for a high impact.

Another insight brought by this survey is that by imposing the same system of references between engineers and architects thanks to the knowledge database, we gave them the possibility to improve their communication, with a positive effect that has been noted in terms of social interactions between the design stakeholders. Indeed, it emerged in our survey about the LCA practice context (cf. Chapter 2), that engineers have difficulties to transfer their knowledge to architects and to the design process. Practitioners who used our tool seemed to consider ELSA as 'useful' or 'very useful' in improving communication between engineers, architects and the project owner during the design process, as can be observed in Figure 69. Moreover, the method's usefulness in integrating actors early on in the design process was explicitly noted by 6 of the participants.

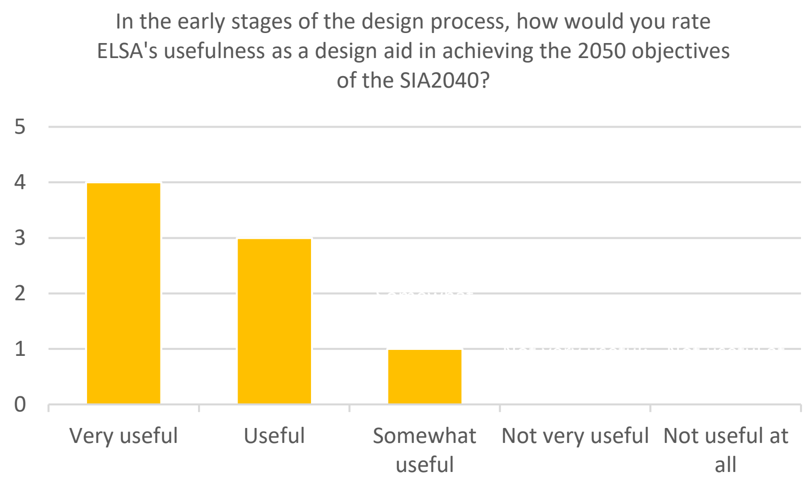

Figure 68: ELSA's usefulness at early design (number of answers per Likert's category).

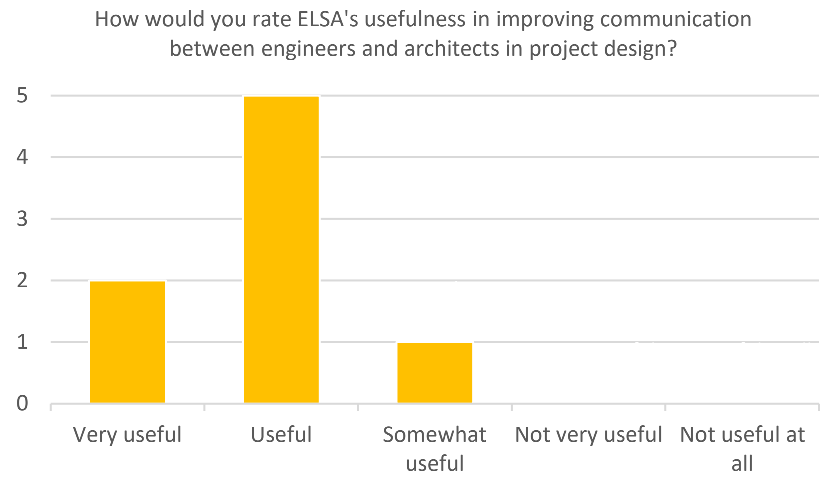

Figure 69: ELSA's usefulness in improving communication (number of answers per Likert's category).

Participants to the survey were then asked to rate ELSA in comparison to other tools they might currently be using, and according to criteria that emerged as most important from our LCA practice context assessment developed in Chapter 2. In Figure 70, the answers we got to these questions, ordered from the least to the most improved criterion, show that ELSA is generally considered in average better for every criterion except for data transparency. It reminds us how important it is to give to the user the ability to have detailed access to all the calculation steps that are performed by the method to increase the trust and the analysis capacity of the user.

The criterion that showed the highest rate is the speed to assess life cycle performance. Indeed, seven out of eight considered its speed as much higher compared to their current tools, and one as higher. This was strong and clear feedback that strengthened our understanding of ELSA's capacity to be time-efficient at early design stages. This result is of great importance, as the high cost of use of LCPA methods was considered to be a major issue in Chapter 2. Seven out of eight practitioners involved in the smart living lab competition also considered the user-friendliness of ELSA as higher than current tools. This rate is probably the result of a better understanding of the user needs. Documentation and tutorials were appreciated with six out of eight users rating this criterion as equivalent or higher. It means that the data transparency issue previously described does not come from a misunderstanding of the prototype, but probably more from the impossibility to have access to the raw data that are visualized in the GUI of ELSA. Finally, the results were considered as more robust averagely, with seven out of eight that rated this criterion as equivalent or higher.

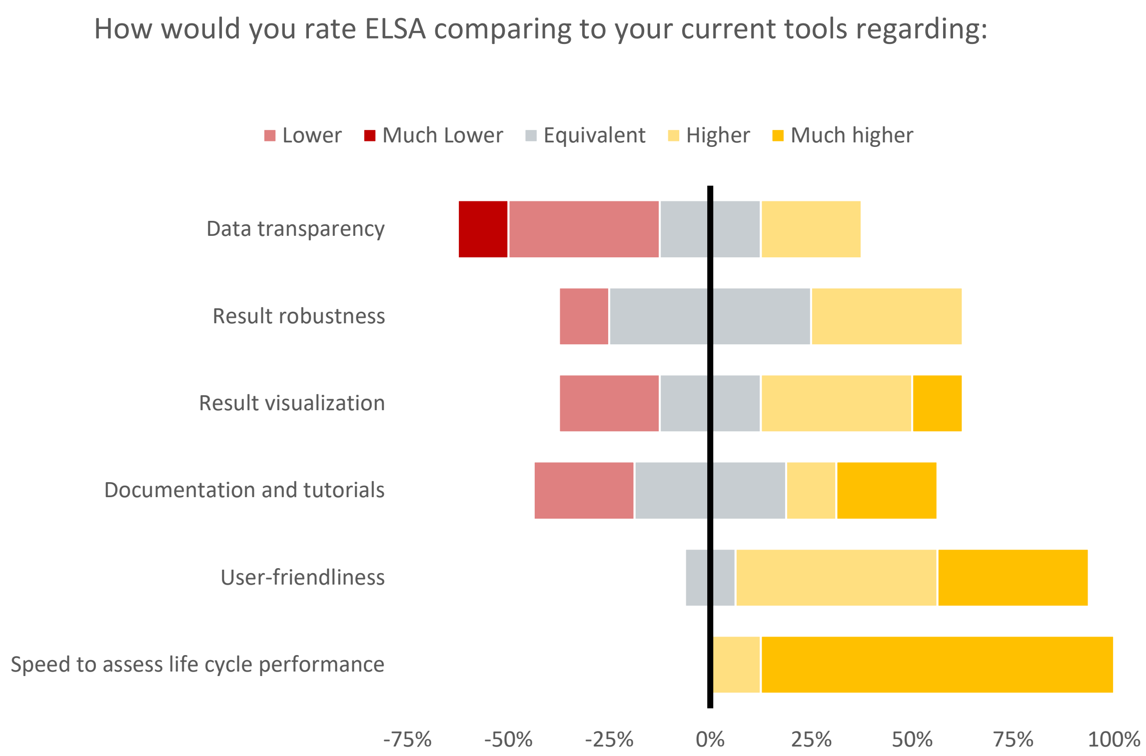

Figure 70: Comparison between ELSA and current tools according to different criteria.

In the end, this individual online survey gives us a first positive assessment from eight practitioners that used ELSA for two months. Three key findings deserve to be highlighted. First, there is unanimity on the time efficiency of the method while the result robustness is considered higher in average than the tools they are currently using. This efficiency has not been offered at the expense of the user-friendliness of the prototype. Finally, there is still room for improvement for the transparency of data that the method use or generate.

5.3.4 The System Usability Scale

The 10 questions of the SUS questionnaire are described in Figure 72. These questions have not been customized as it is a standard questionnaire. Accordingly, what is called “system” has to be understood as ELSA. The five first questions lead to affect negatively the score when the user agreed, while agreements on the five others have a positive effect. The SUS questionnaire has been sent at the same time than the previous survey. Therefore, the number of respondents was the same: eight practitioners replied to this questionnaire.

Figure 71 highlights the distribution of the results of each respondent thanks to a box-plot representation. In this chart, we can observe the scores ranging from 48 to 93. Among the eight participants, seven rated ELSA above 73, and two above 86, which represent the thresholds for “good” and “excellent” usability according to Bangor (Bangor et al., 2008). In the end, the median and the mean (76) SUS scores demonstrated good usability of ELSA, as they both are above Bangor’s threshold of 73.

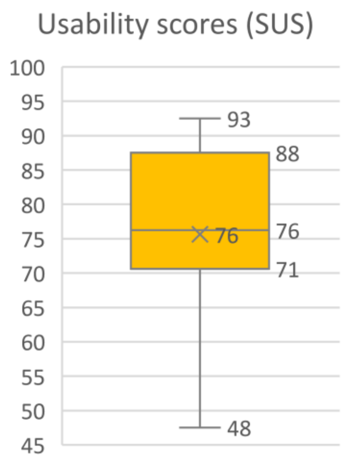

Figure 71: Usability score thanks to the System Usability Scale

Previous research already used the SUS score to rate the usability of BEPS tools. Benchmarking this prior works allowed us to interpret later ELSA's results. Attia et al. developed two successive energy simulation prototypes with scores ranging from 66 to 71 for the first and 70 to 78 for the second, observing an improvement between the two development stages (Attia et al., 2012c). Nault et al. proposed a decision-support prototype for early-stage neighborhood design, and had scores between 70 et 90, and between 45 and 62.5 amongst three users that declared themselves out of the target audience (Nault et al., 2018b). Previously in our research, we already used the SUS score to rate the two first prototypes (i.e. Building Blocks and PCP in section 4.5.2) that lead us to develop ELSA. As a reminder, we obtained a score of around 72 for both.

Looking in detail to the SUS questions in Figure 72, there was a disagreement for the five first questions and an agreement for the last ones, which is very positive according to the SUS score calculation. We also observed concordances with the main findings of the previous individual survey. Indeed, the only question that received a bit less agreement than the others is the one about the user confidence (question 6). We supposed that this was a consequence of the data transparency issue previously described. Also, questions about easiness to use (9), easiness to learn (7), simplicity of the system (5), and to the low need of knowledge or support to use ELSA (1; 4) contribute to qualify the data-driven method behind ELSA as very time-efficient. The different features of ELSA were also acknowledged as well integrated thanks to question eight, rewarding probably the different innovative data visualization techniques that were combined in a unique GUI. Finally, question 10 further defined the application potential of the method. We learned previously that almost all practitioners would use ELSA at early design if available. Here, five participants specified that they would use it frequently.

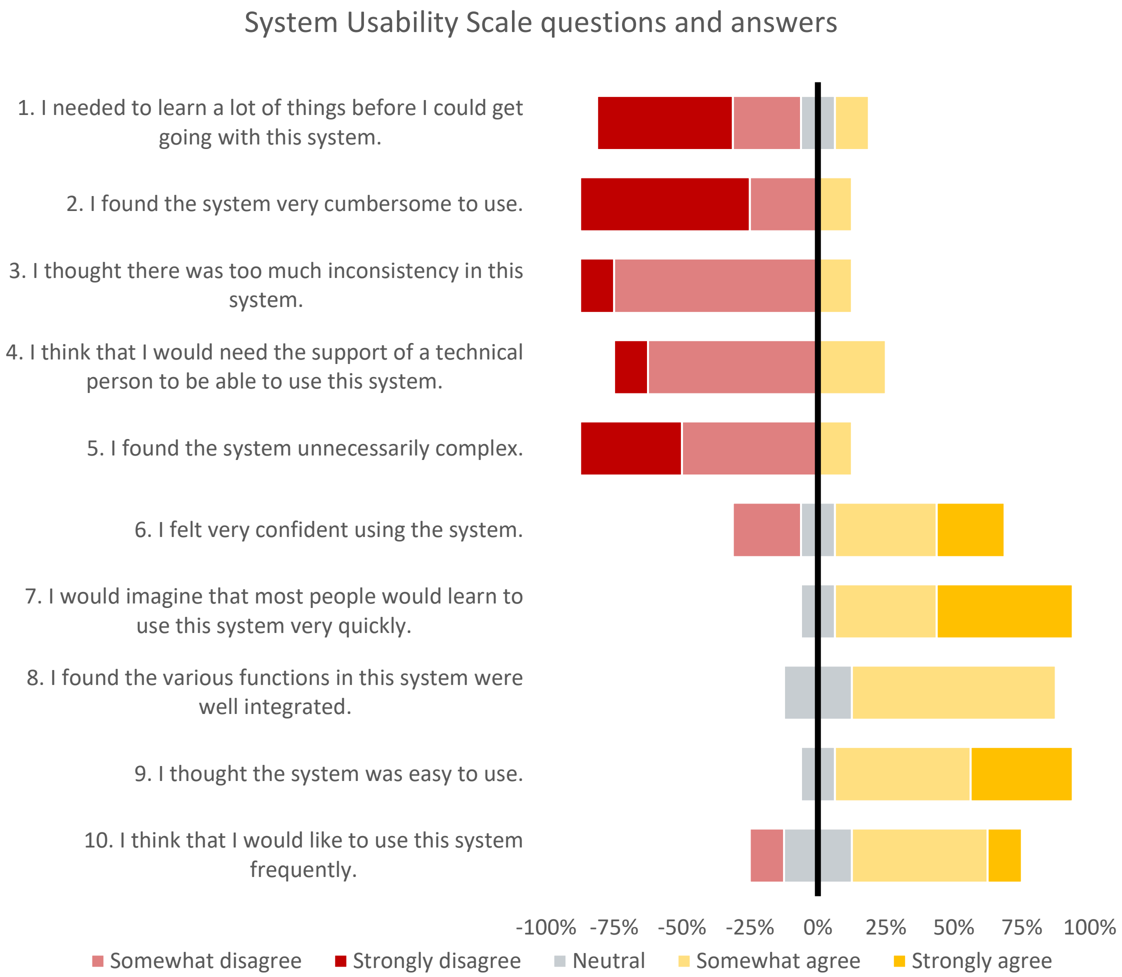

Figure 72: The 10 questions of the System Usability Scale evaluating ELSA and their respective answers.

5.3.5 The focus group session

On February 19, 2020, the first phase of the competition was over. Participants had to present a first schematic design, and justifications about its life cycle performance. The same day, a focus group was conducted with at least an engineer and an architect of each of the four teams. Nine practitioners participated in the focus group discussion: four engineers, five architects, one facilitator (the PhD candidate) and one observer (a scientific collaborator). All of them were direct users of ELSA, and representatives of the four design teams involved in the Smart Living Lab competition. Most of the participants also answered the individual online survey highlighted in section 5.3.3, which was sent to them after the focus point. Basic and anonymized information about all participants can be found in Table 13.

Table 13: Anonymized information about the nine participants to the focus group, the moderato and the script.

Profession	Team	ID	Age	Professional experience (years)	LCA expertise (1: Novice; 5: Expert)
Moderator	-	M	38	15	5
Script	-	S	33	7	3
Engineer	A	A1	29	6	4
Architect	A	A2	52	25	4
Engineer	A	A3	44	15	3
Engineer	B	B1	36	10	2
Architect	B	B2	35	11	2
Engineer	C	C1	38	12	1
Architect	C	C2	34	10	1
Architect	D	D1	34	9	2
Architect	D	D2	49	23	2

The focus group lasted one hour and twenty minutes. The participants were evenly distributed around tables in a square shape. The discussion was audio-recorded in full after having obtained the consent of the participants, then deleted after one year.

The moderator introduced the focus group with the followings:

- The length of the meeting: 1h30,
- The objective of the meeting: to get feedback from the practitioners about the usability of ELSA within the context of the smart living lab competition,
- The fact that the meeting is audio-recorded,
- The confidentiality of the meeting and the presentation of the consent form,
- The structure of the meeting: a first part with a free and open discussion, and a second part driven by specific questions of the moderator,
- The presentation of the script as an observer.

The moderator paid attention to let every participant the time to contribute to the focus point. After the focus group, the analysis started with the audio-record transcription in writing, where the positive and negative comments of the participants were highlighted. Then, these comments have been classified into nine topics that came out of this process. This first work can be found in Appendix B. Based on these quotes and topics, the next nine following sections have been written and constitute the focus group results.

5.3.5.1 Early Design stage

During the focus group session, ELSA's added value at the beginning of the design project was raised several times with adjectives such as *"very interesting"; "very useful", "good to integrate".* An engineer specifically insists on the benefits of the method at early design stages: *"It is a planning tool, very useful at the competition level when decisions have to be made quickly, because a complete life cycle assessment takes time, energy and significant resources."*

An architect claimed that thanks to ELSA, it was possible to introduce a quantitative approach for the carbon emissions assessment earlier, almost before having a project. This was a feature considered highly interesting by the engineers also, as they usually are only asked to provide qualitative feedback to architects at this design stage.

A user mentioned that using ELSA would require him to change his habits; he was not used to perform a quantitative assessment so early. As he still recognized its positive effect in supporting choices in terms of materials, it encouraged him to have a carbon calculation already at the beginning of its future projects. Another user – a civil engineer - pointed out that using this method allowed him to realize very quickly how critical greenhouse gases are at this stage of the project, and how much it can influence the building structure.

5.3.5.2 Efficiency

Efficiency was well evaluated based on the feedback received. On the one hand, practitioners underlined the ease of use of ELSA: "*It's so easy and intuitive*", demonstrating the low time-consumption of the tool. On the other hand, the effectiveness to reach a result was also acknowledged "*in a few clicks we have a result that is quite amazing I must say*". Compared to current tools practitioners are using, ELSA was identified to be "*the most effective"*, in particular when it comes to understandability for customers. Adjectives like "*extremely effective*", "*really impressive*", "*very, very easy to use*", "*very intuitive*", were used by the different practitioners to qualify ELSA's efficiency, even for those not very experienced in life cycle assessment.

5.3.5.3 Decision-making support

ELSA aims at supporting decision-making regarding life cycle performance early on in the design process. The feedback received from practitioners about this goal can be summarized into four points. First, by switching from a qualitative assessment to a quantitative one, ELSA seems to lead to a greater understanding of the architectural and technical consequences of life cycle targets on the building design: "*It really guided us in our choices*". Second, ELSA was particularly appreciated by practitioners who were not familiar with the local context (e.g. non-Swiss firms), both in terms of physical context (climate, local embodied energy, etc.) and performance objectives (SIA2040). Thanks to ELSA and its knowledge database, they were able "*to understand immediately what the influence of the [*design*] parameters was*" in a new context. Third, it has been pinpointed that ELSA might be very useful in a pedagogical context to sensitize students or professionals to the impact of climate change on their profession. And fourth, regarding the negative reaction reported by an architect about parametric technologies: "*it scares me a little bit because it does not invite us to think about what we are doing*". This emphasizes the necessity to include the user of the method within its step 2 (see section 3.2.3, Figure 38) and the definition of the design options that will be used during the parametric approach to shape the design space in which the user will be able to explore the design alternatives. In the smart living lab case study, this step has been pre-defined by the researchers, excluding the future users to be able to compute and provide the knowledge database since day one of the competition. This negative feedback might be a consequence of this exclusion, leading some user in an uncomfortable position where undesired design options were suggested by the method.

In synthesis, it appears that ELSA brings a high level of guidance thanks to its quantitative approach, especially when the user is not familiar with the building context, or the performance objectives. It might also have high application potential for educational training. On the other hand, we should keep in mind that the parametric approach and its automated calculations could also have negative effects on the users if they are not actively part of the design parameter definition.

5.3.5.4 References

As discussed previously (see sections 1.3 and 2.4), the use of references is of major importance to the design process. Thus, references have been discussed twice during the focus group session. It was first generally recognized that the carbon emissions was typically based on using references and their own experience only: "*it is rather the experience that makes it possible today to anticipate certain things*".

Later in the discussion, a proposition was made by an architect to link these design alternatives with visual references, constructive details, plans or building cross-sections that would illustrate the design parameters ELSA is suggesting to meet a carbon target. ELSA could, for instance, be linked with a database of architectural references, and when a user selects, say, a high window-to-wall ratio in ELSA, visual references would include highly glazed facades. Another architect thought that linking ELSA to images might induce additional information to the simulation results, and then mislead to a qualitative interpretation of the image that could be in contradiction with the quantitative output of the data-driven method.

5.3.5.5 Trust and transparency

Regarding the calculation method, the focus group session revealed the necessity for the user to self-manipulate first the raw data before being confident with ELSA. As an example, an engineer compared the results with its Excel-based calculation to highlight any differences in the results. Hence, before being processed by the GUI, the results should be available to increase the transparency of the calculations. It underlines the necessity of transparency and customization possibilities regarding the simulation workflow to gain the user's trust.

Regarding the GUI, an engineer found it very easy to understand, which make it possible to have the project owner on board when it comes to discussing low-carbon strategies: "*We can immediately show what it means to make a building that has reached such a target value"*. However, an architect was afraid about the level of transparency it gives to the owner that can start choosing design parameters, and then influence the design process. These comments illustrate that the method changes the practice by allowing non-expert stakeholders to be part of the decision process earlier, shaking up conventional practices.

5.3.5.6 Interdisciplinarity

During the focus group session, several discussions indicate a potential benefit in using ELSA to facilitate interactions between design stakeholders. While asking if participants would use ELSA in their practice if it would be available, an engineer replied: "From my point of view, as an engineer in an architectural firm, I would say yes, yes and yes, to send a clear message on the main sustainability strategies to colleagues, to building owners". It was also acknowledged that ELSA has the potential to support communication tasks because it makes LCA very easy to understand.

It seems also that the outputs of the method encourage the early integration of engineers in the design process. Indeed, the method is able to specify how the design parameters influenced the carbon emissions, thanks to the sensitivity analysis, and to give carbon budget for the building components. It appeared that the slabs were both highly influential, and having a high carbon budget. As a result, a civil engineer explained that he was thus in charge of a new responsibility because of ELSA. He had an ambivalent reaction: on the one hand, he rather complained to have an overload of work as he had to learn new tools and skills. On the other hand, this new position early in the design process gave him a stronger impact on the project.

5.3.5.7 Creativity / Design flexibility

The focus group reveals that practitioners felt through ELSA how restrictive ambitious carbon objectives are. Hence, two major insights came out. First, architects worried about a decrease in creativity induced by the life cycle performance objectives. For instance, an architect found extremely challenging the use of reinforced concrete as a structural material and was disappointed to be obliged to change his habits. He realized that using concrete was still possible, but would oblige him to narrow the scope of the other design options to the best performing one only, and then decreasing the design flexibility of the project for later development stages. In contrast to this first analysis, the exploration process is acknowledged by an architect to give a higher diversity of solutions, reaching a specific objective, than what he would be able to find without ELSA.

In the end, it is interesting to note that these two feedbacks summarized the two main goals of ELSA: to increase the overview of the design options while illustrating the consequences of ambitious carbon emissions objectives.

5.3.5.8 Target cascading

Regarding the carbon budgets, an engineer recognized that they were facilitating the integration of solutions that were outside the scope of pre-defined design options embodied within the knowledge database. As an example, a design team has been able to justify the compliance of a mixed concrete-wood slab that was not into the database of pre-defined design options of ELSA. They compared its carbon emissions with the carbon budget that was proposed for this component. By calculating the carbon emissions of this slab with another conventional LCA software, they were thus able to compare it with a carbon budget of ELSA coming out of a specific design situation as illustrated by section 5.2.2. On the other hand, a civil engineer noted the additional workload this carbon budget gives to him: "*So we had a lot of work to do because of this target value*".

An architect underlined also the value of this target-cascading by demonstrating its complementarity to the sensitivity indices. For instance, it was very useful for him to understand the carbon share of each building component in order to focus his efforts towards the highest one. As the ventilation system is a parameter that does not vary in ELSA for the smart living lab competition, its Sobol sensitivity index has not been calculated. However, he discovered thanks to the target cascading that the carbon budget of the ventilation system was significant and thus start thinking about ways of mitigations.

In synthesis, the focus group session highlighted examples of practitioners able to integrate products outside the knowledge database boundaries in early design phases, thanks to the target-cascading, and showcased its complementarity with the sensitivity analysis. This might change their habits with a workload earlier in the design process.

5.4 Strengths and Weaknesses of the prototype ELSA

Thanks to the previous survey and focus point, quantitative and qualitative feedback have been collected from engineers and architects using ELSA in the frame of the Smart Living Lab competition. Following this assessment, some relevant strengths and weaknesses of the prototype can be highlighted.

5.4.1 Strengths

First, it is clear that across all the usability assessment techniques that have been used, the satisfaction of practitioners using ELSA at an early design stage was very good. In summary:

- The perceived usability of the tool was considered to be good based on the SUS user test.
- The online survey revealed that seven users out of eight described ELSA as 'useful' or 'very useful' at supporting the design in achieving the SIA2040 targets,
- The focus group confirmed a high level of guidance especially when the user was inexperienced about the building context, or the performance objectives.

Beyond the usability issue, the core objectives of this thesis were to increase the time efficiency of the method, while keeping high design guidance. It was several times acknowledged that ELSA was a new and efficient possibility to introduce at early design a quantitative approach for integrating carbon targets within the design process. This efficiency was justified by the low level of effort required to use ELSA compared to the strong and positive impact it has on the technical and architectural design. When asking about the ease of use of ELSA in the System Usability Scale questionnaire, there was a very strong agreement about its ease of use, with seven positive and one neutral answer.

The method seems to have a positive impact on interactions between the three key stakeholders (i.e. architect, engineer and real estate developer). This was identified to be an issue thanks to the survey conducted about the LCA context of use, but the usability assessment of ELSA suggested that using its GUI supported engineer ability to illustrate the architectural consequences of the carbon emissions objective. The target cascading, in particular, has been revealed as innovative, empowering the civil engineer with new responsibilities in the case study. Also, the target cascading and the sensitivity indices were appreciated for their complementarity to better identify the design parameters on which special attention has to be paid.

The time efficiency of the method relies mainly on its pre-calculated design alternatives that allow the user to have immediate feedback when interacting with the knowledge database. Decoupling calculation from exploration seems to be one of the major strengths of the method.

Despite the lack so far of supporting materials (tutorial, videos, user manual, etc.), and the limited time dedicated to introduce ELSA, there was not any complain regarding the level of effort required to learn how to use the software. Indeed, the large majority of the users stated that they would not require any additional support, suggesting that the method and its GUI are already easy to use enough, even with this low material support.

In the end, both quantitative and qualitative usability assessment techniques highlighted the time-efficiency of the method, and its design guidance abilities at early design stages.

5.4.2 Weaknesses

The prototype has been developed for a research purpose. Therefore, the participants noted some limitations that should be considered to any further development aiming at delivering the tool as a professional software on the market. Comments targeting the graphical user interface only will thus not be discussed here.

A first weakness of the prototype lies in the lack of adaptation of the workflow to the project specificities and the practitioner's wishes. As an example, ELSA does not allow the user to change the design parameters that are varying thanks to the parametric approach. More flexibility regarding design options will be necessary for a more polished version, as already pointed out by the participants, including with regards to the 3D-volume to start from. The specification of the 3D-volume was not an issue at early stages, but frustrations appear once a first design is proposed by the team with the highest awareness about design options that have to be explored. As the method is an iterative process which has to integrate, as inputs, more and more specific design options, the user should be able to change and create new options he wants to explore accordingly. Similarly, the shape and the orientation of the project should be part of the exploration process, in line with practitioner's wishes specified earlier in our research (cf. Figure 30 in section 2.6.3). Thus, the method would benefit from connections with the Building Information Modeling (BIM) process, that could facilitate data exchanges between 3D-models of architects and ELSA's workflow.

The exploration process was limited by the size of the database. Indeed, if 20'000 design alternatives seem to be massive, it only represents a small percentage of the billions of possibilities when exploring a design space with more than 14 design parameters with 2 to 6 options for each parameter. As a result, participants exhausted the entire database after selecting 6 to 7 parameters, at which point none of the design alternatives corresponded anymore to their selection whishes due to the limited diversity of the database. Hence, for the exploration process, the more alternatives there are the better. However, even if these calculations are decoupled from the user experience, being calculated before the exploration process, the method is also planned to be used iteratively, by generating new databases according to the design evolutions. In the case study, generating and calculating the performance of 20'000 design alternatives with 12 logical processors took 8 hours, which might be too much in an early design context where decisions have to be taken very quickly. Hence, a decrease in the calculation duration might be beneficial for the method.

Another weakness of the method that has been reported was the difficulty practitioners faced when they wanted to share their exploration experience in the competition deliverables. Indeed, the GUI has been developed so far with a particular emphasis to foster the dynamic interactions with the user, but did not propose any data visualization that could be basically exported into a report.

Last, the data transparency was also revealed as another issue of the prototype. So far, the GUI is closed, and there are no possibilities for the user to process and visualize the raw data her/himself. It appeared that this transparency issue affected directly the trust practitioners might have to ELSA. This should be improved in future developments by proposing, for instance, an export of the calculated data to a CSV file to enable to make graphs automatically as we manually did in this chapter.

5.5 Discussion

The smart living lab case study was used to assess the usability of the proposed method, through a first computer-based prototype called ELSA. It allowed us to monitor the usage of ELSA, and later to have feedbacks about its usage in the light of the practitioner professional experiences. The two previous sections summarized the strengths and weaknesses of the prototype, thanks to the eight to nine practitioners that experimented ELSA into a real context. We were able to grasp rich qualitative and quantitative insights. However, the results have to be considered carefully, as they might be influenced by the context of this competition, or the profile of ELSA users. In addition, the small sample of users makes it difficult to generalize the findings.

We also have to acknowledge that the use of ELSA was mandatory during the first phase of the competition. If it represents a unique chance for a research-based prototype to be used in real conditions, our analysis might also be biased by this mandatory usage of the prototype. Also, we choose to have the focus group discussion right after the first dialogue between the competition organizers and the four design teams. As a consequence, the practitioners might also have been influenced by the fact that they were still within the competition during this usability assessment. Another option would have been to wait for the end of the competition. However, doing so would have brought us two other bias that might be even stronger. First, the end of the competition was five months later, which might lead to a decrease in the feedback precision. Second, competition results might also influence practitioner judgments. In the end, the usability assessment of BEPS and LCA tools remains a challenge where the researcher has to choose an approach somewhere between a large survey with quantitative feedback outside the context of a real case study, and a real case study with a limited number of users but an in-depth qualitative analysis.

Another issue that has to be discussed is the innovative nature of the method that probably influenced the practitioners in their judgement. We had sometimes the feeling that the feedbacks were targeting issues beyond the method itself. As an example, some users were frustrated by the method output that highlighted their design preferences as very ineffective to reach the SIA2040 targets. Also, we understood that the abilities of ELSA at supporting the design process could be perceived as uncomfortable for engineers, replacing part of the consultancy they were delivering before, i.e. the qualitative assessment based on their previous experiences. Hence, the consequences of using ELSA on the roles and responsibilities of engineers and architects might be interesting to be further analyzed.

We also have to acknowledge the prescriptive nature of the prototype at different levels. First, the choice of parameters defining which are considered within the knowledge database has to be done by the future user of the method. We already noted that this step of the method is of prior importance to increase the usability of the knowledge database. However, within the smart living lab case study, this has not been possible leading the users to explore pre-defined design options that they did not choose themselves. Second, ELSA used a second database of lifecycle inventory impacts of building elements (KBOB, 2014). This database is far from being able to represent all building material that could be on the market in Switzerland. This lack of environmental product declaration is a common limitation to every LCA software and thus penalizes also ELSA. In the end, the exploration space of the method is limited by the size and the diversity of these two databases, leading the user of ELSA to narrow their design choices.

Regarding the LCA methodology used in ELSA, the current exclusion of some life cycle phases as the maintenance or the repair ones (B2 and B3 according to EN 15804) might affect the results. Including them in further development would be beneficial for improving the accuracy of method. Also, this prototype focuses on the Swiss context where the SIA2040 norm targets only three environmental impacts (GWP CED, CEDnr). However, these are only three out of 30 impact categories listed within EN 15804. As a consequence, a design compliant with the SIA2040 might still increase other impact categories, this is why ELSA would have a better holistic overview of the environmental impacts if it could co-simulate larger categories.

Chapter 6 Conclusions

6.1 Summary of main research findings

The core motivation of this thesis was rooted in the necessity to improve the usability of Life Cycle Assessment in the early design stages in terms of both time-efficiency and design support. This willingness emerged from two key elements. On the one hand, the state of climate emergency due to global warming calls for greenhouse gas mitigation, especially in the construction sector as it is one of the major contributors to the problem. Practitioners will thus increasingly be brought to employ the Life Cycle Assessment (LCA) method, commonly used for the carbon emissions calculation. On the other hand, while the early stage presents a high potential to effectively influence the design process, its constrained timeframe combined with the low level of details available then make the use of complex methods such as LCA difficult. Previous research has focused on increasing time-efficiency through a simplification of the LCA calculation, which typically consists of setting predefined hypotheses about future design details and thus, unfortunately, results in decreasing the design support potential of the method due to the uncertainties it generates. And this is precisely the issue we aimed to solve with this thesis: offering pertinent and reliable design guidance while keeping time efficiency at early design stages. We focused our research approach on the development of what we called a data-driven LCA-based method. It addressed the constraints of early-stage design by enabling to explore the architectural and technical consequences on the carbon emissions of varying design hypotheses, by providing a clearer understanding of the design parameters that have the highest influence on carbon and by setting boundaries on carbon budget all the way to the building component level.

By questioning how the usability of Life Cycle Assessment can be improved at the early design stage, both in terms of time-efficiency and design support, we were specifically interested in the three adjacent research topics below, introduced in section 1.4.2 and that led us to the adopted data-driven method. The following sections will use them as a redline to present the main achievement of this thesis.

1. *The issues engineers and architects have to face when it comes to assessing the life cycle performance in the early design phase.*

   A better understanding of the User-Centered Design (UCD) theory, from which the usability concept emerged, led us to improve the usability of LCA. According to the literature, the first step of this UCD was to understand and specify the context of use, i.e. the physical, social, economic, etc. conditions in which the LCA-method to be developed would be used. Up to now, there was little research on this topic as most of the previous work has been focused on improving the LCA method itself rather than understanding the purpose, the users and the context of the method. Considering this gap, a literature review and an extensive survey among 500 European architects and engineers were conducted, specifying exhaustively and for the first time the issues LCA practitioners have to face during early design stages (Chapter 2). Thanks to this survey, we were able to identify that there was a real willingness on the part of practitioners to use life cycle assessment performance methods, but that there were four main mismatches between the LCA method and the context in which they are used.

First, the time-consumption issue, which was confirmed by the respondents. Indeed, the survey revealed that there is still a low market demand for carbon emissions performance, which leads to having little to no budget specifically dedicated to LCA engineering fees in a project and, in turn, to having LCA studies relying mainly on best practice and on the practitioners' own initiative. The survey outcomes also highlighted that about three project propositions were produced on average during the inherently iterative early stage of design, which means that carbon assessments would have to be applied multiple times, which strengthens the need for a time-effective method. The literature review conducted in parallel also highlighted an issue regarding the non-reproducibility of *LCA* results, which limits engineers and architects from being able to capitalize results from one project to another. This was shown to be due to the building contexts (e.g. meteorology, geophysics, etc.) and the LCA method, boundaries and life cycle inventory database that vary according to the projects.

Secondly, the literature review revealed a mismatch between the LCA – that requires a high Level Of Detail (LOD) – and the lack of detail typical of early design stages. Previous research (Cavalliere et al., 2019; Kiss et al., 2019; Rezaei et al., 2019) already take advantage from Building Information Modelling (BIM) developments to shorten the data collection phase of LCA thanks to project details embedded in an interoperable data exchange format. BIM is indeed a process involving methods and tools meant to facilitate the management and construction data interchange between design stakeholders. However, while BIM might solve the time-efficiency issue for the data collection of LCA at detailed design phases, it does not solve this mismatch at the early design stage that by nature has a low LOD.

Finally, this survey demonstrated a strong eagerness to have access to decision support tools that go beyond the sole carbon assessment. On the one hand, the majority of the survey participants confirmed an interest in being able to identify which design parameters have the highest influence on the carbon emissions, and wanted complementary approaches that would allow them to explore design alternatives able to fulfil the life cycle objectives. On the other hand, being able to rely on a multi-criteria approach – i.e. including other performance metrics such as lighting and thermal comfort – emerged as an important ability to bring in so as to have a holistic performance assessment. Indeed, life cycle objectives are not the only performance metric they have to monitor, and each design alternative thus needs co-simulation to assess the other metrics.

2. *The techniques that seem most promising to address these issues, given the iterative nature of the design process and its reliance on references.*

   We conducted a literature review in Chapter 3 to identify promising techniques that address the four issues previously described. The parametric assessment came out as a promising solution to support the iterative process of the design. Because of this iterative nature, LCA tools are used to assess one by one the design propositions and guide designers through an optimization process. However, these iterations are limited by the time-consumption of the LCA. This is where the parametric assessment catalyzes an optimization process with the possibility to calculate automatically the carbon performance of hundreds or thousands of design alternatives. The resulting predefined database is generally used to find an optimal solution. However, this optimum happens to be rarely compliant with other performance metrics, which lead to the need to co-simulate each alternative according to the other objectives the building project has to fulfil. The problem is that it is not possible so far to co-simulate every performance objective, some of them being quantitative but still difficult to simulate (e.g. costs), others being qualitative and influenced by preference or intent (e.g. aesthetical aspects). As a result, the design guidance of finding a carbon emission optimum is limited. In the literature, we identified a recent use of parametric assessment coupled with data visualization techniques (Miyamoto et al., 2015; Østergard et al., 2017; Ritter et al., 2015) that could offer a way to generate a design alternative database, and to get knowledge from it. This technique is meant to be explored by a designer to learn about the impact of a performance threshold on other alternatives. Data visualization techniques can then be resorted to facilitate the exploration process and allow the designer to interact with the database by filtering alternatives according to his/her constraints, or performance objectives. The literature review also revealed that these exploration methods were actually not used with LCA calculations yet. Adapting exploration methods to LCA was thus identified as promising, but challenging considering that LCA requires a full description of the building components, unlike energy simulations which involve only the design parameters that affect the building energy consumption. Thus, including all the design parameters and their variants influencing LCA results would also lead to dramatically increase the number of calculations and their time-consumption. However, as is later discussed (cf. next research topic), coupling parametric assessment and sensitivity analysis allowed us to solve this issue.

An exploration method based on LCA brings also the data visualization problem of heterogeneous and multidimensional simulated building performance data sets. Indeed, LCA inputs are discrete values composed by ordinal and categorical data, and outputs are either continuous, discrete or categorical data and required a technique able to manage this diversity. We defined for the first time the specifications that data visualization techniques comply with to explore an LCA-based dataset. It allowed us to highlight Parallel Coordinate Plots (PCP) and decision tree as promising considering these requirements.

Concerning the wish of designers of being able to identify which design parameters influence most the LCA results, the Sobol sensitivity analysis was revealed to be the most appropriate amongst various methods when using LCA calculations. The review demonstrated its accuracy and its ability to manage heterogeneous and discrete values as inputs, which are required in case of an LCA-based parametric approach. Yet, the Sobol method is considered to be computing-intensive, as it requires in term of simulation intensity, about a thousand times the number of parameters whose sensitivity indices the user wants to quantify. The increasing power computation accessible thanks to cloud computing might solve this issue.

Finally, our literature review pinpointed the target cascading technique, which comes from the mechanical engineering field, as a powerful approach to simplify a problem by decomposing the performance target of a system into sub-targets for its sub-systems. Defining sub-targets indeed allows allocating part of building impact on the different design stakeholders working on the same project, according to their skills and responsibilities. It decreases the scope of analysis to a sub-system, minimizing thus the detail resolution issue between assessment tools that need high LOD and early design stages that have low LOD. Indeed, defining hypothetical details for a smaller sub-system reduces the time-consumption of the definition of these details. Also, sub-targets are reproducible and can be used from one project to another. However, the method defines project-specific carbon budgets, and their usability from one project to another still have to be verified. A drawback of the method was also identified with the risk of decreasing iterations between designers by allocating their performance targets to the sub-system and thus preventing to have a global vision of the design problem, as a local optimum might not always lead to a global optimum.

3. *The limited-time available and the low-resolution details at early design stages to support a decision-making process with LCA calculations.*

   Based on the above promising techniques, their benefits and limitations, Chapter 3 proposed a LCA-based data-driven method. By using a parametric approach on a simple massing scheme, the method took advantage of the low LOD of the design at early stages to decrease the time spent to describe the project. Instead of suffering from the undetailed building parameters that limit the LCA applicability, we chose to generate design alternatives thanks to the parametric application and combination of pre-determined design options to the massing scheme. The resulting design alternative database aimed at supporting design decisions thanks to the knowledge it embedded. Hence, our objective was (a) to generate a database with the highest level of knowledge for its future users, in a reasonable computational time, and (b) to couple the method with techniques extracting the knowledge from this database.

   Regarding (a), it is not likely to calculate all the design combinations of the pre-determined options as it would lead to a time issue with a billion possibilities. Hence, we extend the method by integrating a sensitivity analysis that was used for two reasons. First, the sampling method of sensitivity analysis combines user-defined design options. Applying these options to a project-specific massing scheme generates a smaller and non-exhaustive database. Second, the sensitivity indices calculated by the sensitivity analysis increases the design support potential of the database by ranking the parameters according to their influence on the carbon emissions.

   Concerning (b), three techniques were integrated into the method. The ranking of the parameters according to their sensitivity indices decreased the complexity of the design problem, thus letting the possibility to the designer focusing on the parameters that matter. We were able to demonstrate that the sensitivity analysis was relevant, but not sufficient. Indeed, varying building components having the same impact may lead to low influence on the result, but these components might still have a high environmental impact. Hence, we integrated the target cascading technique to the method, to split the carbon budget objective of the building project to the building component level in sub budget. By doing so, it was possible to highlight the carbon share of all the components, independently of their sensitivity indices, but also to compare the carbon budget of one component to any product on the market, without performing a simulation at the whole building scale. Also, by linking the target cascading and the exploration process, we reduced the risk of adding up local optima that would not lead to a global optimum. Finally, we integrated data visualization techniques to the method, to facilitate the transfer of knowledge from the database to the user.

   In the end, we proposed an innovative method that combined complementary techniques, solving their respective limitations when used individually, to generate a knowledge database of design alternatives. A dynamic exploration of the latter offers insights to engineers and architects about the parameters they have to consider in priority when designing low-carbon buildings, how they should set them, and which budget they have for each component.

   Based on this approach, we developed a first computer-based prototype in Chapter 4. We integrated each technique thanks to a python script that used an IDF file generated thanks to the Design-Builder software based on the low LOD massing scheme of a building project. A parametric modification of this IDF file was performed thanks to the Saltelli sampling techniques that combined pre-determined building components coming from Swiss building detail catalogues. The prototype thus used the Energy Plus simulation engine, and the KBOB life cycle inventory database to assess the carbon emissions on the resulting design alternatives. Then a Graphical User Interface (GUI) was developed to integrate data visualization techniques such as PCP and sunburst. Through the prototype, we demonstrated the adaptation possibility of exploration techniques to the LCA specificities.

Later, after the theoretical development of the method and its technical implementation, we had the chance to deliver a fully functional prototype called ELSA (which stand for Exploration tooL for Sustainable Architecture) to the competitors of an innovative collaborative-competitive process for the design of the future building of the Smart Living Lab in Fribourg, Switzerland. This framework offered us a unique chance to close the user-centered design approach of this research project, by assessing the usability of ELSA in Chapter 5 thanks to the monitoring of its intensity of use, a group discussion and an online survey with the users.

Thanks to this usability assessment, we demonstrated the time efficiency and the high design support of the method. We also had very positive feedback about ELSA's usefulness in improving communication between engineers and architects. Thanks to the feedback from these practitioners, we identified a high application potential as discussed in the next section

6.2 Application potential

The Smart Living Lab case study offered a framework for ELSA to be used by 16 architects and engineers. An extensive usability assessment of these experiences allowed us to demonstrate the potential of the proposed LCA-based data-driven method. The case study revealed the time-efficiency of the method, and validated the design support potential of the design alternative exploration. Moreover, when justifying their design, practitioners used all the different techniques combined within ELSA (exploration, sensitivity analysis, and target cascading). This contributed to the demonstration of their complementarity and application potential, beyond the single carbon emissions assessment that is commonly used at the early design stage.

However, its application potential is still highly dependent on the market demand that fixes the carbon ambitions of each building, which was revealed as still low during the context of use survey, in contradiction with the climate emergency discussed in the media. Still, this market demand might strongly increase in the near future. Indeed, we can already observe a global trend that strengthens fiscal policies about carbon emissions. This will raise the real estate developer willingness to pay engineering fees to decrease the life cycle emissions of their building project. One can also note that leading countries such as France, Belgium, Finland, Norway, Sweden, the US, etc. are about to set mandatory limits for life cycle impacts of buildings within the next few years. It is even already the case in the Netherlands.

In France for instance, the next regulation will make LCA mandatory for every new office and residential buildings starting from 2020[7]. Based on a patent filed in the frame of this thesis (Jusselme, 2018, 2016), Combo Solutions, an EPFL spinoff and French start-up, developed a new software called Vizcab[8], which has already been used to support the design of 90 different low-carbon buildings, demonstrating practitioner interests. The start-up estimates that the data-driven method participated in the savings of 18’000 tons CO_2-eq in terms of greenhouse gases mitigation.

Looking at other applications, the data-driven method has already been applied to an urban scale thanks to a research project called SETUP for Specific Environmentally-conscious Targets for Urban Planning. Similarly to this thesis, this project highlighted the mismatch between current tools for urban carbon emissions assessment, and their context of use. Therefore, SETUP aimed at supporting the urban planning

[7] *https://www.cohesion-territoires.gouv.fr/experimenter-la-construction-du-batiment-performant-de-demain#e2*
[8] *www.vizcab.io*

process by changing the scale of the parametric approach from buildings to the neighborhoods. Thanks to this method, it was possible to split a neighborhood-level target into sub-targets at the building level considering their heterogeneous contexts i.e. solar exposure, density, etc. Doing so, an increase by 30% of the number of design alternatives that reached the SIA2040 performance was possible by varying up to 10% only the target per building (Nault et al., 2019, 2018a; Slavkovic et al., 2019).

Another application potential lies in the building stock refurbishment. The energy and carbon transition will not happen without facing this issue. Conceptually, we do not identify any limitation in terms of application to this field. After describing the existing building, ideally thanks to a BIM model, the parametric approach could be performed on the design parameters concerned by the refurbishment project, delivering a knowledge-database with the same approach as the method proposed in this thesis.

A potential application of the method for building material and system manufacturers was envisioned. Indeed, the method can fix carbon budgets at the material and system level, compatible with the SIA2040. Therefore, it is possible for a window manufacturer, for instance, to benchmark its products compared to the target value coming from the method. The challenge here would be to propose target values that would be representative enough of a building typology and a country, and not of a single and specific building. This can probably be developed by integrating a diversity of massing schemes and climate contexts as the initial input of the data-driven method. Pushing further this idea would lead to improve current green certification systems of building elements by comparing a building element not only with its family of products but also with its carbon budget (see discussion in section 5.2.2).

Finally, we strongly believe in the application potential of the method within an educational context. It could fit the academic constraints of architecture studios where projects have to be developed at the same time as students learn the use of simulation software. As a result, if they want to assess the performance of their projects, they have little time available to be trained on new software, which probably represents a strong barrier for architects to use BPS tools. ELSA demonstrated that practitioners were able not only to understand the tool, but also use it properly only after 2 hours of presentation (introduction + webinar). Also, students' projects are most of the time-limited to early design phases with low LOD, which is specifically where the method delivers the highest benefits.

6.3 Methodological discussion

This research proposed a new method to increase the usability of LCA at early design stages by combining techniques coming from different research fields. During its implementation, many fundamental choices have been done, each one bringing both strengths and weaknesses to the method. Some of the main limitations have been mentioned in earlier sections and it seems natural to go back to them in this last chapter so as to discuss them more holistically in the following sections.

6.3.1 Limitation of the life cycle assessments

LCA calculations have been performed according to the SIA 2032 standard. This choice was consistent with the case study's location in Fribourg, Switzerland, where the future Smart Living Lab building will be built was, therefore, targeting the SIA 2040 objectives and the CEDnr and GWP thresholds. Beyond the different life cycle phases that were covered with the developed method, several modules of the EN 15978 have been excluded, notably in the use stage, such as Maintenance (B2), Repair (B3), Refurbishment (B5) and Operational water use (B7) (see section 4.3). As a consequence, all LCA results discussed within this thesis should be carefully reconsidered when one of these missing phases is likely to represent a significant contribution. For an increased robustness in the results, it would actually be necessary to develop an implementation of the method with all modules of the EN 15978 norm.

Another limitation of our LCA lies in the KBOB environmental impact database we used for the embodied impacts calculation (see section 4.3.2). This database is quite limited in terms of diversity, as it includes around 250 building materials only, compared to the 1500 Environmental Product Declaration of the French INIES[9] database for instance. This limited representativity of building materials will inevitably decrease the usability of the knowledge database provided by our method as the user might not be able to choose every design option he/she wants to explore. This limitation is in fact not specific to our proposed method, but is a common limitation to every LCA approach. Thanks to the rising interest in measuring carbon emissions, an increase of the KBOB database size is likely to happen within the next years, which will partly solve this issue. Another option for the missing building components would consist of using the Ecoinvent[10] life cycle inventory database, one of the largest around the world. However, it might require a higher level of expertise from the user to be able to explore, use or even aggregate this raw data.

6.3.2 Usability of the method and its prototype

This thesis chose to follow a user-centered approach and, as a result, placed usability assessment as an essential aspect of this research. It was the core focus of both the LCA practice assessment and of the practitioner feedback sessions conducted at the end. These studies have certain important limitations that would be worth discussing here.

First, by choosing to evaluate the practice via an online survey, multiple biases are almost unavoidable and were indeed revealed during the interpretation of the results. A very low population of engineers actually answered the questionnaire, as we had difficulties reaching them. As opposed to architects who are often organized in associations and publicly available directories, engineers specialized in LCA were harder to identify and thus remain hard to quantify. Previous surveys (Hofstetter and Mettier, 2003) tried to overcome this problem by using a LCA software user list to send their questionnaire. But in our study, the point was actually to enlarge the survey so as to reach out practitioners that not necessarily use LCA software, but may also use other techniques. The idea was to capture the diversity of practices when it comes to assessing life cycle performance. Given the low representation of engineers in our study, it would have been highly beneficial to complement it with a more qualitative approach such as interviews and focus groups where the ability to reach a small population of engineers would have been easier. Hence, we acknowledge that mixing both quantitative and qualitative approaches could help increasing both the comprehensiveness and the robustness of the results, and would thus be an interesting approach to consider in future developments.

Second, the usability assessment of the prototype ELSA was evaluated by taking advantage of the Smart Living Lab architectural competition. If this real-life case study gave a lot of research material to this project, it was also a very specific project. Indeed, the teams were composed of architects and engineers who had been selected for their competences and experience in designing low-carbon buildings. Hence, their skills can be considered as higher than the Swiss average and it would be very interesting to confront the prototype to another context of use which may be more representative of the Swiss construction industry.

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[9] *www.inies.fr*

[10] *www.ecoinvent.org*

6.3.3 The parametric approach

One of the key steps in our method consists of splitting the building into subcomponents for the parametric and target cascading approaches. And defining subcomponents will inevitably specify the perimeters in which design options will be considered to form the knowledge database. This definition is thus of great importance and will affect the exploration process happening later on. In our approach, it is based on user preferences (step 2 in Figure 38, section 3.2.3), without any guidance. However, the use of a normalized approach instead, with a standard definition of these subcomponents, would probably be beneficial for clarity sake. In the Swiss context, a norm (« *Code des frais de construction*[11] ») specifically proposed for the construction costs a standard decomposition of the building into subcomponents, so as to clearly structure a construction project, and be able to compare one subcomponent from a project to another. In a recent work about LCA and uncertainties at early design stages (Tecchio et al., 2019a) for instance, the MasterFormat® structure, defined by the Construction Specifications Institute (CSI), was used as a classification system for the materials dataset in a five-level hierarchical tree with progressive specifications at each level. In this approach, researchers ran a statistical analysis to demonstrate that "*40% to 46% of the bill of materials components represent 75% of the total impact of single-family houses and multifamily buildings*". Therefore, they suggest increasing the level of description for selected subcomponents of the classification system to obtain the highest accuracy possible with little effort (Tecchio et al., 2019b). These new approaches could be integrated into our exploration method to standardize the decomposition process and increase the level of detail on building components that have the highest carbon emissions.

Another limitation of our prototype lies in the exclusion of the building shape and orientation from the parametric approach. This was a result of technical considerations, namely to favor the use of a python script allowing a multiprocessing batch mode and thus reducing simulation time. To integrate a diversity of building shapes, we decided to provide different knowledge databases during the case study, thanks to three 3D models, as a proxy for building massing and orientation choice. However, an actual combination of parametric modelling and batch simulations might be also possible thanks to software such as Rhinoceros 3D coupled with Grasshopper for instance. This would lead to an increase of trust of the user in the calculation results thanks to 3D models that could illustrate each of the design variants. In doing so, it would become possible to explore the knowledge-database through design parameters, performance thresholds, but also 3D models, building upon the Design Explorer project proposed by Thornton Tomasetti (Thornton, 2017) for example.

6.3.4 Reproducibility of the results

In general, the low reproducibility of the LCA results, which also applied to our approach, was identified in the literature review as one of its main limitations. Indeed, the LCA boundaries are chosen for a given study. Also, the context-specific nature of the environmental impacts of any building materials and the building's location will always make the results difficult to reuse from one project to another. The target cascading approach proposed here offers a new perspective, where it is the carbon budgets that are re-usable from one project to another. Indeed, these budgets are calculated thanks to a knowledge database that is context-specific, and that depends on design options that have been chosen during the parametric definition. However, the sum of each component carbon budgets should always meet the SIA2040 objectives and should thus be applicable anywhere in Switzerland. However, we have to acknowledge that the use of these budgets in a very different geographical context might significantly decrease their usability. Indeed, the user might be in a position where no design options can meet these sub-component

[11] *https://www.crb.ch/fr/Normen-Standards/Baukostenplaene/BKP.html*

thresholds, similarly to the SIA2040 which states that its operational and construction sub-targets might be difficult to reach everywhere. To overcome these context-specific target limitations, a larger knowledge database encompassing a diversity of building shapes, uses and climate contexts at the Swiss scale might be of high interest to highlight the discrepancies of the carbon budgets according to these criteria, and determine how reproducible they really are.

6.4 Prospective improvements

6.4.1 Machine Learning techniques for fast calculations

The exploration process of our data-driven method is based on a knowledge database generated thanks to a parametric approach and a sampling technique that allows reducing the design alternative assessments and performing a sensitivity analysis. While the database size was large enough to calculate robust sensitivity indices, it was not deep enough to meet the designer's exploration wishes. Indeed, the exploration is based on a filtering process thanks to the parallel coordinate data visualization technique, and each new constraint leads to much fewer alternatives to explore. As an example, in our case study, filtering the database with four design constraints narrows down the design alternatives from 20,000 to one hundred. The remaining design space was therefore very small, while 10 parameters were still unspecified. Two solutions might tackle this issue. As previously described in the description of the method (section 3.2.3), an iterative process could lead the user towards a second database generation with a lower number of parameters, and then for the same number of alternatives, to deeper exploration possibilities. Indeed, a first database would, in that case, allow validating some parameters according to the design wishes, removing them from the parametric approach, similar to the parameters having low sensitivity indices or target values. A different approach would be to train metamodels on each specific knowledge-database to quickly assess new design alternatives according to the user exploration wishes, as it was proposed by the author in collaboration with Duprez et al. (Duprez et al., 2019). In this work, an Artificial Neural Network (ANN) was trained on the knowledge-database sampled with a quasi-Monte Carlo technique to predict the carbon emissions of new design alternatives. Using the ANN, the carbon assessment of 20,000 new design alternatives was performed in only 0.02 second with one CPU, to be compared with two hours for the original database that used energy simulation engines and cloud computing (32 CPU) for the same number of design alternatives. In terms of accuracy, the ANN was also very promising, with low root mean square error and a coefficient of determination higher than 0.9, keeping in mind that at the early stage an error tolerance of 20% is generally accepted.

6.4.2 Data-mining for material quantity estimation

In our research, we use several catalogues of building elements (section 4.1) to detail the building materials according to different design parameters. These catalogues were very useful to estimate the quantity of materials involved in each design variants, and then calculating their embodied impacts thanks to the KBOB life cycle inventory database. However, these catalogues were not adapted to the specific context of our case study, as it would have required technical studies incompatible with the time available at early stages. Yet, several site-specific constraints might affect the building components' sizing, and change their environmental impacts. This might be specifically true for the components that have the highest influence on carbon emissions, such as the building structure for instance. Theoretically, the number of floors, the wind exposure, the seism risk, the geotechnical conditions, etc. influence the structure of a building, and for instance the thickness of the concrete walls or the density of reinforcing steel bars. We think that a very interesting improvement of the method would be to have access to a large database of detailed building design. Using data mining techniques would allow extracting typical assumptions of material quantities according to construction techniques, and context specificities. Unfortunately, such a database is not available yet, probably because of the lack of standardization that does not make possible to gather a large amount of data with the same format. The rising development and use of Building Information Modelling methods might remove this technological barrier soon. In their work about BIM-based LCA results, Hollberg et al. also underlined the necessity to create such a large database to increase the usability of LCA at early design stages (Hollberg et al., 2020).

6.4.3 Toward a multi-criteria approach

In this thesis, we focused the environmental performance assessment on the carbon emissions, but in fact, the performance of each design alternative has also been co-simulated in terms of Cumulative Energy Demand (CED), and non-renewable CED. Indeed, we demonstrated in Figure 63, section 5.2.3, that there was no correlation between the Global Warming Potential (GWP) and the CED impacts (r^2=0.01). Similarly, there was not found any correlation between the net Zero Energy Building performance, and GWP impacts. We can also suppose that a low carbon building could be uncomfortable, expensive, etc. As suggested by the user context analysis in section 2.6.4, there is a strong interest to perform multi-criteria assessments, to be able to increase the efficiency of the solution exploration process with design alternatives that fit several performance objectives at the same time. Hence, an extension of the method to other performance metrics might increase its efficiency to support the designers in their holistic approaches. It was also suggested by practitioners using ELSA to link design alternatives and their 3D models to have a qualitative assessment of their façades and schemes. This means coupling the method with 3D libraries where one would be able to explore the knowledge-database through design parameters, performance threshold, but also 3D models, following the Design Explorer project proposed by Thornton Tomasetti (Thornton, 2017).

6.4.4 Representation of the prospective improvements

Thanks to the three previous sections, we envision several improvements summarized in Figure 73. In a synthesis:

- Further BIM development might lead to facilitate the project definition phase of the method, thanks to an easy and fast extraction of the construction data that are already specified in CAD tools used to describe the project,
- Data-mining techniques may suggest typical assumptions to quantify the design variables the user wants to explore, thanks to a future large database of building design,
- The knowledge database could be enriched with co-simulated performance indicators such as thermal and daylight comfort or life cycle costs, facilitating a holistic exploration of the design alternatives,
- The knowledge database could be complemented by 3D models for a graphical representation of the design alternatives,
- Machine learning algorithms trained on knowledge database using simulation engines might support the exploration process with the fast generation of any new design alternatives the user wants to explore.

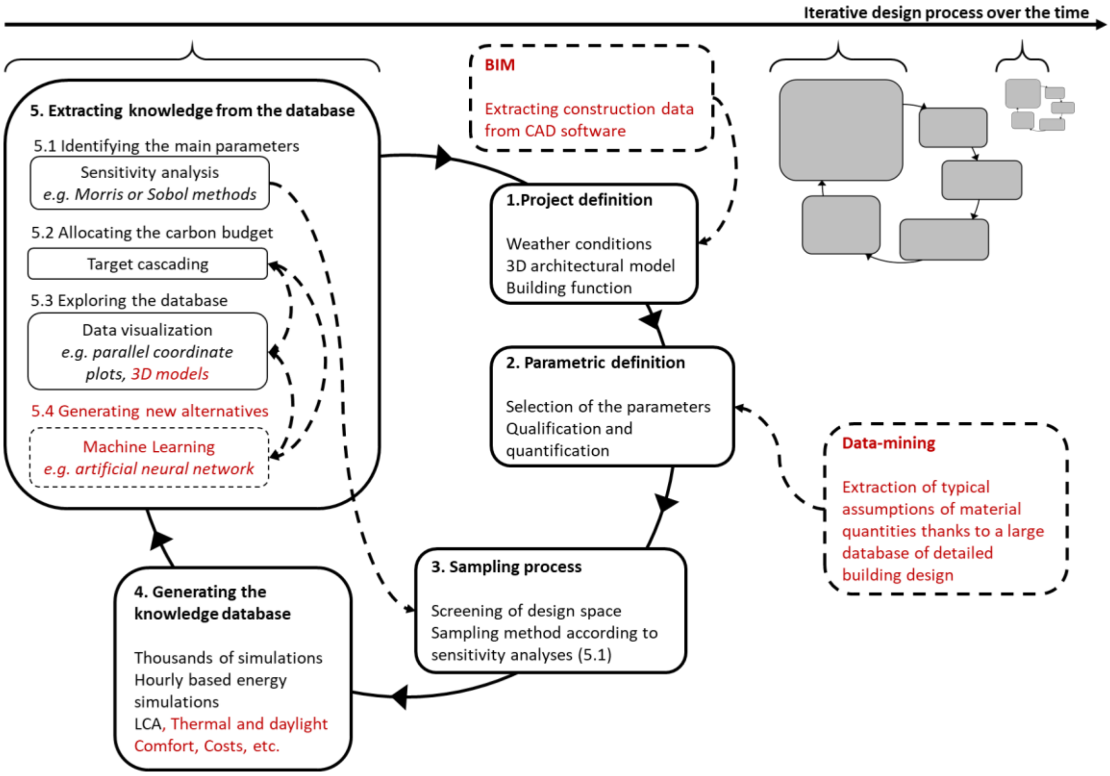


Figure 73: The LCA-based data-driven method and its prospective improvements (in red)

6.5 Outlook

In this thesis, we demonstrated that a high willingness for collaboration between architects and engineers do not lead systematically to an interdisciplinary and integrated design at early design stages. When it comes to integrating low carbon objectives into the design process, we identified that the market demand was still low and does not support designers in their work on this topic. In addition, we also highlighted an important mismatch between the LCA method and the early design context that is due to technical and contextual issues but that decreases the interdisciplinary benefits.

The interdisciplinarity of this thesis would not have been possible without the specific context of the Smart Living Lab in Fribourg. Indeed, interdisciplinarity and user-centered research are at the core of this institution. First, bringing different labs from various fields in the same place had led us to facilitate innovative collaborations. Second, the living lab spirit left room for experimentation thanks to the future building of the smart living lab. It made it possible to apply research in a public architectural competition, which is rare enough to be mentioned. In that way, this thesis could benefit from interactions with researchers ready to go across disciplines, which is encouraged within a research-friendly environment that supports interdisciplinarity and experimentation.

Beyond this framework, our innovative methodological proposition came out with the support of a user-centered research approach. Following the UCD principles, we conducted a research loop with the specifications of the context of use, the development the fundamentals of the method, the proposition of a prototype, its test in the frame of a real case study and the usability assessment of the method thanks to the practitioner's feedback. It led us to identify problems and solutions outside the typical LCA research field, thus bridging disciplines commonly not involved within previous LCA methodological improvements. This interdisciplinary approach involved Human-Computer Interactions, Mechanical Engineering, Environmental Sciences, Statistics, etc. Hence, this work aims to motivate further research towards greater interdisciplinarity, by demonstrating the benefits of such an approach.

The outcomes of this thesis draw the path towards a new generation of LCA-based building assessment tools where a proactive exploration of a knowledge database by the designer is as important as the performance assessment. There was a time when building robust and accurate energy simulation engines was still a research challenge. Nowadays these robust simulation engines are used in a context of high computation capacities (e.g. cloud computing, machine learning) and with a raising ability to capitalize and exchange their simulation results (e.g. BPS dataset, BIM). It leads us to envision a new era where the development of new exploration techniques of BPS dataset will be as much emphasized as the simulation engines that produced these data. This thesis supports this vision by hoping to make LCA relevant, adapted and therefore actually used in early design stages and thus contribute to making low-carbon building design a new reality.

Appendices

A. Online questionnaire about the LCA context of use

The following forty questions represent the online questionnaire sent to architects and engineers to specify the LCA context of use. All results are discussed in section 2.6.

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Life cycle performance at early design stages

Welcome to this survey!

Who may answer the questionnaire?
Practitioners in the field of Architecture, Engineering and/or Real Estate Development. Please be aware that this particular survey is not targeting researchers or educators.

What is this survey about?
Climate change and energy consumption impacts require us to consider the full life cycle of a building but how can we effectively take it into account in a realistic design process?
This survey is part of a PhD project conducted at EPFL and aims to help developing a user-centered method for life cycle assessment at early design stages. That is why we need your contribution!

Why should you answer this questionnaire?
By offering a few minutes of your time, you contribute to a research effort, which could have a very positive influence on the tools you use or could get access to, and will support the integration of more holistic sustainability approaches in practice.
If you are willing to get access to the results of the survey, please leave us your email address at the end of the questionnaire and we will send you a complete analysis report with all results in a few month.
Answering the questionnaire will take only 4 minutes of your time, it has a non-commercial purpose, and all collected data will be treated anonymously.

1

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Life cycle performance at early design stages

About you

1. What is your age?
- ○ 24 or younger
- ○ 25 to 34
- ○ 35 to 44
- ○ 45 to 54
- ○ 55 to 64
- ○ 65 to 74
- ○ 75 or older

2. What is your gender?
- ○ Female
- ○ Male

3. In which country do you work?

4. How would you best describe your profession?
- ○ Practicing Architect / Designer
- ○ Practicing Engineer
- ○ Practicing Real Estate Developer
- ○ Researcher - Educator
- ○ Other (please specify)

2

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Life cycle performance at early design stages

About your company

5. How would you best describe your position?

- Intern
- Non managerial employee
- Project Manager
- Partner/Owner
- Other (please specify)

6. What is the size of your company?

- <5 employees
- 6-10 employees
- 11-30 employees
- 31-100 employees
- >100 employees

7. Is your company involved in research and development activities?

- Yes
- No

3

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Life cycle performance at early design stages

About your experience

8. During building design, do you consider life cycle performance?
(e.g. energy consumption or greenhouse gas emissions for the whole building's life cycle)

Never	Rarely	Sometimes	Often	Very Often
○	○	○	○	○

4

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Life cycle performance at early design stages

About your life cycle performance experience

9. In what kind of projects do you consider life cycle performance objectives?
(multiple choices are possible)

- ☐ Individual housing
- ☐ Collective housing
- ☐ Office
- ☐ Commercial - Retail
- ☐ Hospital - Medical
- ☐ School - Educational
- ☐ Industrial
- ☐ Public - Governmental
- ☐ Other (please specify)

10. Why do you analyze the life cycle performance of your building design?
(multiple choices are possible)

- ☐ Because of the client's requirements.
- ☐ Because it is part of our best practices, and it is what we do in my company.
- ☐ Other (please specify)

5

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Life cycle performance at early design stages

About your LCA software usage

15. Which of the following Life Cycle Assessment (LCA) software do you use?

- ☐ Athena
- ☐ BeCost
- ☐ BEES
- ☐ Boustead Model
- ☐ Eco-BAT
- ☐ EcoEffect
- ☐ Ecosoft
- ☐ EIO-LCA
- ☐ e-licco - Cycleco
- ☐ Elodie CSTB
- ☐ Envest
- ☐ EQUER
- ☐ eTool
- ☐ GaBi
- ☐ LEGEP-LCA
- ☐ One Click LCA
- ☐ OpenLCA
- ☐ SimaPro
- ☐ Tally
- ☐ Tortuga
- ☐ Umberto
- ☐ Other (please specify)

7

16. For each of the following criteria, how satisfied are you with the LCA tools you generally use?

	Not at all satisfied	Not satisfied	Satisfied	Very satisfied	Completely satisfied
Transparency of the data	○	○	○	○	○
Robustness of the results	○	○	○	○	○
Tutorials and documentation	○	○	○	○	○
User friendliness	○	○	○	○	○
Visualization of the results	○	○	○	○	○
Interoperability with CAD tools	○	○	○	○	○
Time spent to conduct a *LCA*	○	○	○	○	○
Cost of the *LCA* software	○	○	○	○	○
Global satisfaction	○	○	○	○	○

Other (please specify)

17. How would you rank the importance of these criteria for you when using LCA tools?

- Transparency of the data
- Robustness of the results
- Tutorials and documentation
- User friendliness
- Visualization of the results
- Interoperability with CAD tools
- Time spent to conduct a *LCA*
- Cost of the *LCA* software

18. Which percentage of your building design projects is evaluated using a*LCA* software?

- ○ 0-20%
- ○ 21-40%
- ○ 41-60%
- ○ 61-80%
- ○ 81-100%

19. Regarding your LCA software, which training method did you use to get trained?
(multiple choices are possible)

- ☐ Self training with video, tutorial or documentation
- ☐ Helped by colleagues
- ☐ Internal/external training courses
- ☐ Other (please specify)

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Life cycle performance at early design stages

You never consider the life cycle performance

20. Please, tell us why you never consider life cycle performance?
(multiple choices are possible)

- ☐ I am not in charge of this task, but another member of my team/company deals with it.
- ☐ It would be too time-consuming.
- ☐ It would be too expensive.
- ☐ It would require skills that I don't master.
- ☐ I don't think it is an interesting or useful analysis to perform.
- ☐ My clients don't request this type of analysis.
- ☐ Other (please specify)

21. Do you think that you may have to consider the life cycle performance of your building design in the future?

- ◯ Yes
- ◯ No

10

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Life cycle performance at early design stages

About your practice

22. Do you see building environmental regulations as an opportunity or as a threat?

- ◯ An opportunity
- ◯ A threat
- ◯ Neither of the two, I consider it as:

23. Which parameters do you take into account during conceptual design stages?
(multiple choices are possible)

- ☐ Glazing surfaces
- ☐ Windows properties
- ☐ Orientation
- ☐ Building shape
- ☐ Photovoltaïc panel surface
- ☐ Thermal panel surface
- ☐ HVAC system
- ☐ Lighting system
- ☐ Insulation thickness
- ☐ Insulation material type
- ☐ Structure type
- ☐ External wall covering
- ☐ Internal wall covering
- ☐ Indoor finishes
- ☐ Other (please specify)

11

24. Did you know that starting from 2020, every new building in the European Union will have to generate more energy than it consumes?
(EU regulation about Net Zero Energy Building)

- Yes
- No

25. How critical is the environmental performance of your building project compared to your other constraints?

Not critical	Slightly critical	Fairly critical	Critical	Very critical
○	○	○	○	○

26. How long does the conceptual design phase of your building project take?
(amount of weeks on average)

1 week — 50 weeks or more

27. The following questions will be specific to your profession. Please select the closest match:

- Architect/Designer
- Engineer
- Real Estate Developper

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Life cycle performance at early design stages

Design process

28. Do you usually integrate Building Environmental Consultants in your project at conceptual design stages?

- Yes
- No

29. How many design alternatives do you produce at conceptual design stages, on average?

30. How would you qualify the valuable input of Building Environmental Consultants to the design decisions?

Very poor	Poor	Acceptable	Good	Very good
○	○	○	○	○

31. How satisfied are you with the environmental consultant's ability to understand your constraints, in general?

Not at all satisfied	Not satisfied	Satisfied	Very satisfied	Completely satisfied
○	○	○	○	○

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Life cycle performance at early design stages

Engineers

32. Do you usually work with architects at conceptual design stages?

- ○ Yes
- ○ No

33. How many design alternatives do you typically analyze at conceptual design stages, on average?

34. How would you qualify the Architects' ability to integrate your valuable input into the design?

Very poor	Poor	Acceptable	Good	Very good
○	○	○	○	○

35. How satisfied are you with the architects' ability to understand your constraints?

Not at all satisfied	Not satisfied	Satisfied	Very satisfied	Completely satisfied
○	○	○	○	○

14

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Life cycle performance at early design stages

About your wishes

Previous questions help us better understand how you work. Now it is time to understand how you would like to work!

36. What do you expect from a life cycle assessment?
(multiple choices are possible)

- ☐ To check the compliance of my project with the client's brief or with regulations.
- ☐ To assess the performance of my project.
- ☐ To evaluate which design parameters are the most impactful on the building performance.
- ☐ To know what would be the technical and architectural optimum in terms of sustainability.
- ☐ To explore which of my design alternatives fulfil the life cycle targets.
- ☐ To compare the performances of different building design alternatives.
- ☐ Other (please specify)

37. At conceptual design stages, where your project usually has a poor resolution of details, what kind of decision support would you prefer to be provided with?
(multiple choices are possible)

- ☐ A simplified and approximated performance assessment of your project.
- ☐ A gallery of possible design options, to explore which fulfill the project needs and allow to reach the life cycle target.
- ☐ I don't know.
- ☐ Other (please specify)

15

38. In your opinion, who should be in charge of integrating life cycle objectives into the design process?

- ◯ Architects
- ◯ Engineers
- ◯ Architects and engineers
- ◯ I don't know
- ◯ Other (please specify)

39. Do you have any other comments about this survey?

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Life cycle performance at early design stages

End of the survey

Thanks!

You have successfully answered all the questions, which will be very helpful for the research project. If you have colleagues who might be interested in answering this questionnaire, feel free to forward them the survey using the following link:
https://fr.surveymonkey.com/r/LCA-survey

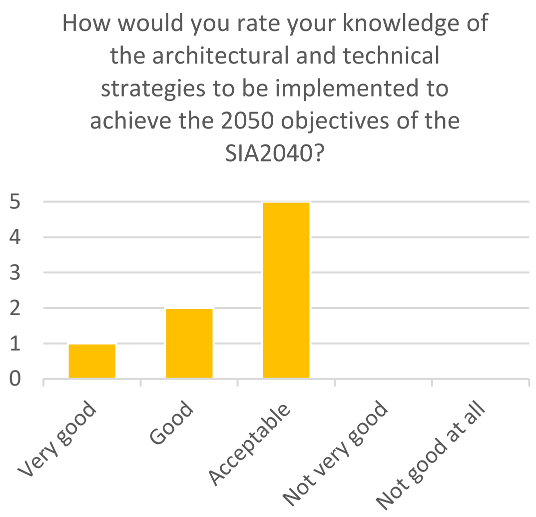
41. Would you like to receive the results of this survey? If yes, please leave your email address here:
(all collected data will be treated anonymously)

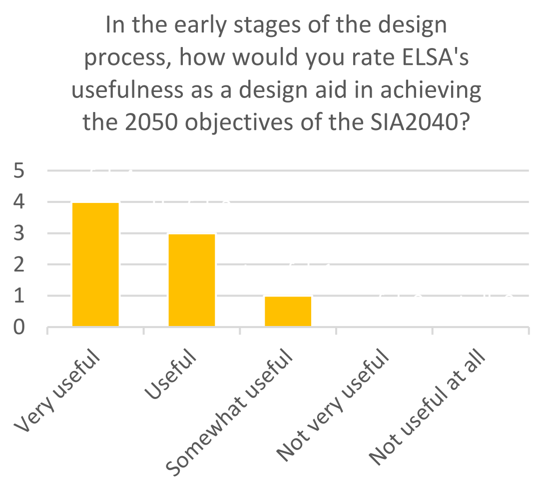
(c) Jon Ashcroft

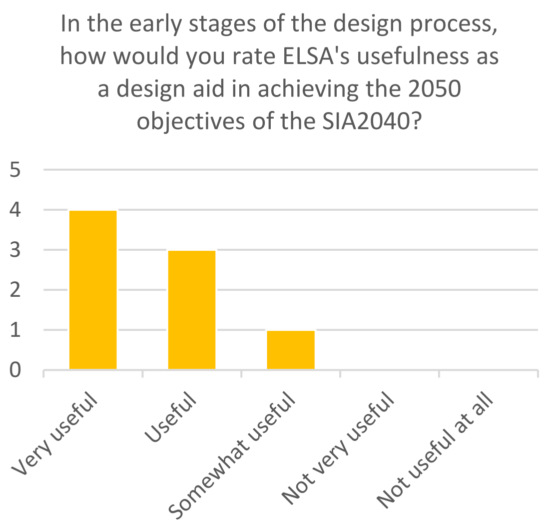
B. Usability assessment results

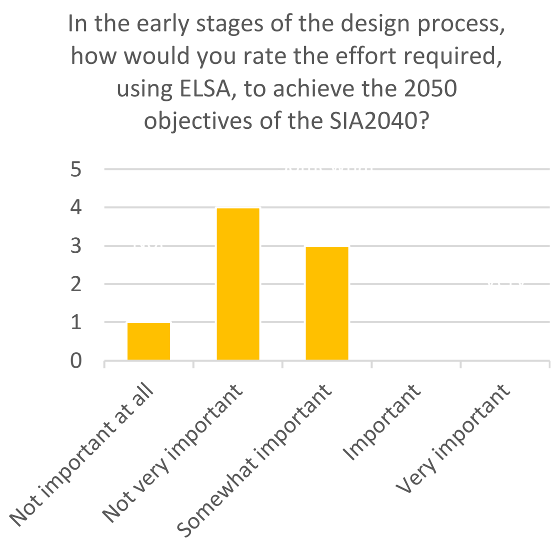
Online survey results

Here the results of the online questionnaire discussed in section 5.3.3.

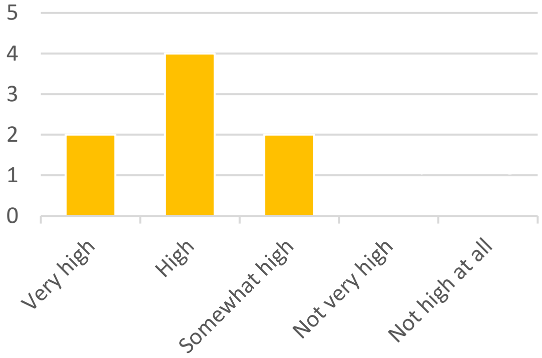




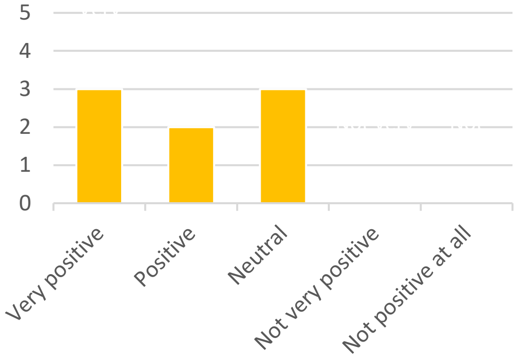




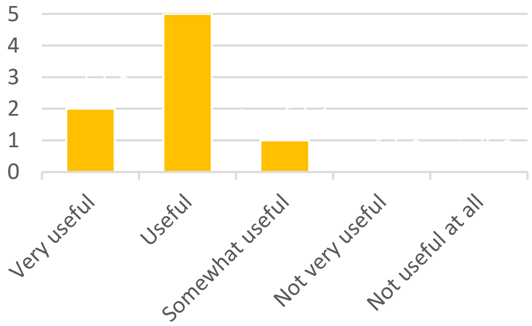
In the early stages of the design process, how would you rate your level of satisfaction with using ELSA?



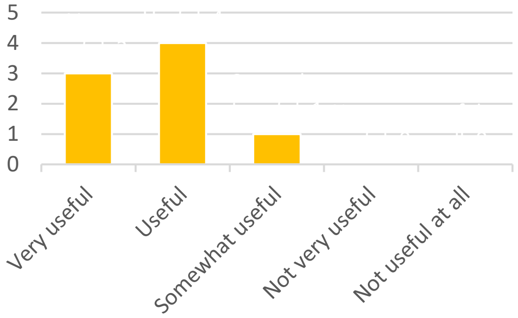
If ELSA has had an impact on your technical and architectural design, how would you describe this impact?



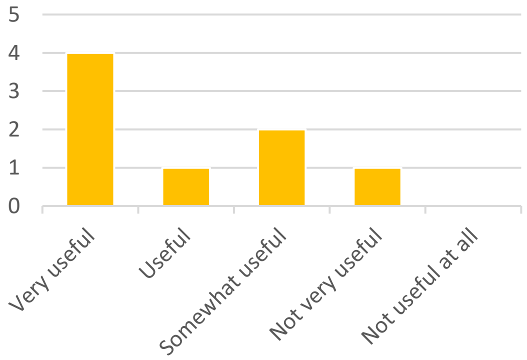
How would you rate ELSA's usefulness in improving communication between engineers and architects in project design?



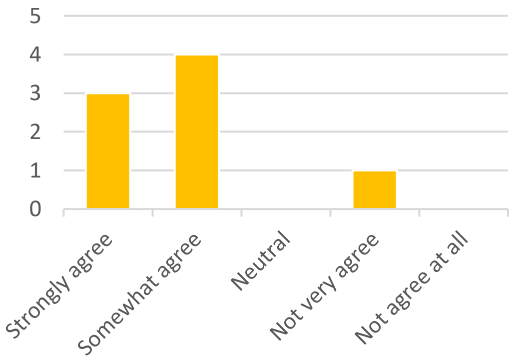
How would you rate ELSA's usefulness in improving communication between designers (engineers and architects) and the project owner in the design of the project?

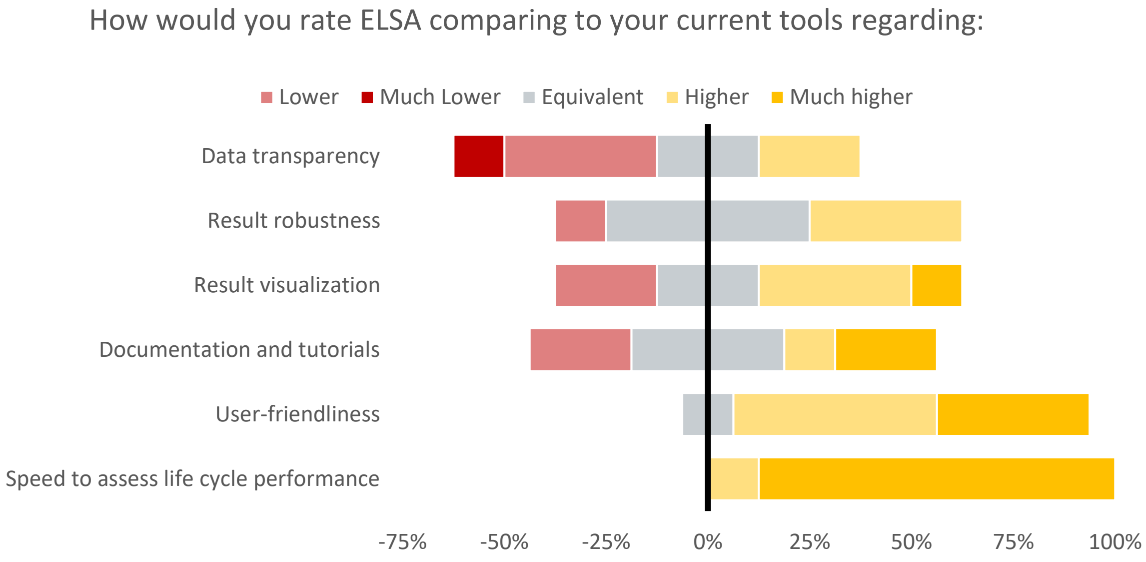


How would you assess ELSA's usefulness in integrating actors who normally intervene in more advanced phases further upstream in the design process?



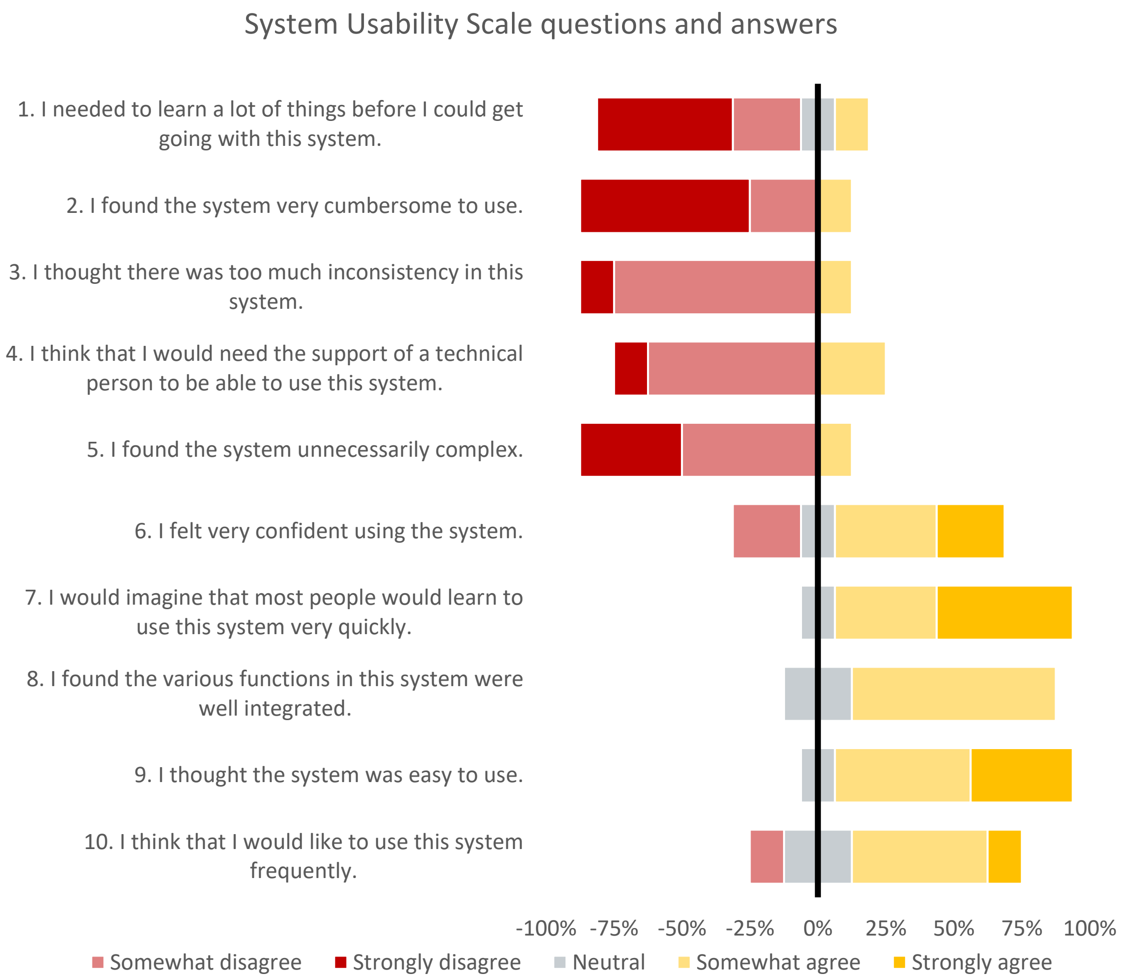
If ELSA were available, you would use it in the early stages of the design process.





The System Usability Scale

Here the results of the online System Usability Scale questionnaire discussed in section 5.3.4.



The focus group discussion

Here the main positive and negative comments extracted from the audio-record transcription of the focus group discussion, further detailed in section 5.3.5.

Early Design stage

Engineer A1: “It was very interesting to have it [ELSA] at the very beginning of the project, it certainly guided our discussions fairly quickly and precisely on low-impact materials, the choice of wood structure, this kind of thing, I think it immediately oriented the discussions, towards directions that we would probably have had much longer discussions about.”

Architect A2: “It is clear that if you work on a project, you first say to the architect: " Well, we have to go in that direction ". And it's only after a certain time that we're going to calculate something, whereas now we're going to get a result almost before we have a project, so it's very interesting.”

Engineer A3: “It is a planning tool, very useful at the competition level when decisions have to be made quickly, because a complete life cycle assessment takes time, energy and significant resources.”

Architect B2: “It may not have been the first step we would take, but it was good to integrate it from the beginning, it helped us to formulate different choices in terms of materials. (…) I think it's positive, it's really something we're going to have in mind for other projects, to have this reflection from the beginning, I think it's great.”

Engineer C1: “I would never have come to see so quickly that greenhouse gases are so critical at this stage of the project, and that it is so important to optimize the structure, so for that reason, it's really useful.”

Efficiency

Engineer A1: “It's so easy and intuitive.”

Engineer A3: “The most effective is Elsa, it is clear because it is the most understandable and for customers it is simple.”

Engineer B1: “Being initially also from the field of research, it is true that it is very complicated to quickly have a result on the life cycle assessment of different parameters. And I found that in this sense it was extremely effective, in a few clicks we have a result that is quite amazing I must say, so frankly it's quite nice to use. (...) In terms of results, I find it really impressive.”

Architect D1: “I found the software very, very easy to use, very intuitive also for me who is not too experienced in all aspects of life cycle assessment.”

Decision-making support

Engineer A3: "I understand the usefulness [of ELSA] of course. Currently, I cannot say so much on primary energy or CO_2 etc. I can only say: "Your building is not good"

Engineer B1 "It really guided us in our choices. (…) It allowed us to prioritize a little bit the choices we were going to make at the structural level, by saying to ourselves: "Well, the horizontal elements, the transport, the insulation choices, these will be elements that will be essential to take into account in our process ".

Architect B2: "We were very impressed by this tool, because we often talk about life cycle assessment, and we try to develop something sustainable, but it's true that to really see what we are designing, in real data, there is still a big difference compared to what we have in mind, at this level it's already very interesting."

Architect C2: "We did this [the competition] with a German group and for us, it was very good to know all this. (...)We were able to understand immediately what the sensitivity of the parameters was, for example, the slabs are important, the façades are less important..."

Architect D1: "Working with all these parametric technologies, personally it scares me a little bit because it does not invite us to think about what we are doing."

Architect D2: "We had a positive experience, to make these issues a little more visible in the project, and as a Professor, I think it is very useful from a pedagogical point of view."

References

Engineer A3: "We work on the basis of our experience, Minergie Eco or SNBS projects, like that, where we know that in the end, if we make a kind of choice at a certain time it is a win. So it is rather the experience that makes it possible today to anticipate certain things."

Architect B2: "I am concerned that linking the results to images would lead to a different interpretation and use of the [ELSA] tool. As architects, we would make some choice again more intuitively, with our own interpretation of the image."

Architect D1: "In fact, as a learning tool, I find it very interesting, especially to discover buildings that comply with carbon objectives. (…) One of the things we missed was having visual references, with constructive details, plans and building cross-sections that meet the parameters I had chosen. (…) If was asked to design a 2000W building, I would have done exactly the opposite process [than ELSA]. I would have look for a building that is good in terms of carbon emissions, and try to understand why the building is good in terms of carbon. Then I would try to incorporate its strategies into my project. [M: And which reference would you have taken for the Smart Living Lab competition?] That's a complicated question."

Trust and transparency

Engineer A3: "What I found very good from Elsa was the transparency that you need to have with the project owner. We can immediately show what it means to make a building that has reached such a target value (...) And if this level of performance becomes the law, we will have to illustrate it to fully understand what it means."

Engineer C1: "When I analysed the results of my Excel calculations, there were a whole series of questions that arose, which made me very suspicious of the calculations behind ELSA. (…) The other thing I would have found interesting is to have a little more data on the hypotheses, the surfaces that were taken, even the impacts of the materials of the "baukatalogue", (...). If you do a calculation by hand, it's like a black box to compare. "

Architect D1: "Do you imagine a customer who uses such an easy software and comes to you as an architect "Here I want a building with these parameters"

Interdisciplinarity

Engineer A1: “[If the tool was available, would you use it in your practice?] From my point of view, as an engineer in an architectural firm, I would say yes, yes and yes, to send a clear message on the main sustainability strategies to colleagues, to building owners."

Engineer A3: “It caused me a lot of problems to calculate the slabs and as a result, as it was sensitive, the civil engineer was the focus of attention. So we had to develop small Excel tools and appropriate our KBOB data and for me, it was the first time.”

Architect C2: “With the engineers, we always have a discussion and it [ELSA] can't replace it. But it can help us to value and verify our choices. With the client, it can help us, because it is very easy to understand.”

Creativity / Design flexibility

Architect A2: "This tool, because it is so simple and optimal solutions can be found, it directs everyone to the same result. There is a risk that creativity will be forgotten.”

Architect A2: “The client who says "wow", you shouldn't experiment too much, you have to comply with standards (...). The scope of action is very limited for an engineer.”

Architect A2: “Where I was a little disappointed is that if you take the three main elements, after all, that you do behind is almost always in the green. Somewhere, it gives you a lot of freedom and you don't have to worry about it [the performance] anymore. “

Architect A2: “You have to give as many choices as possible to meet a goal and then creativity is always there. It is more in this sense that we must use the tool to ensure that creativity is not limited.”

Architect D1: "I believe that unfortunately, efficiency leads us to the idea of general homogenization

Architect D1: “I also found it extremely constraining to use a well-known material such as concrete. I don't know if we should stop using concrete, or if it's a database issue, which may have to incorporate other concrete examples because there are millions of concrete buildings. For example, when we started working with concrete, we found only one reference that was possible."

Target cascading

Engineer A1: “I thought it was important to have the target cascading, which gives threshold values element by element so that we can make our own small calculations in order to respect the budgets that are allocated. For example, for floors or other elements, we use ELSA to have major axes, and then we use our own tools to check that we reach the target.”

Architect A2: “These target values are very interesting, but if I look at the ventilation, for example, we see that grey energy is very important. So if I give a target value to an HVAC engineer I don't know what's going to happen, but it raises his awareness because we know that this is where there's a lot of energy and that we may have to think about how we reduce our technical installation to the minimum.”

Architect A2: "We had chosen another mixed concrete-wood slab for the inertia, and so we calculated the impact of the slab to see if we could hit the target, and for that, it was very good, it's true.

Engineer A3: “In the end, the positive thing is that we see conflicts [between components]. This target value allows us to find solutions to meet a carbon objective. But now civil engineering becomes more interesting.“

Engineer A3: “So we had a lot of work to do because of this target value."

Architect B2: “Before the presentations, it was complicated but after the webinar, I understood the target cascading.”

Architect D1: “The feeling I have is that the customer will ask me to take into account solutions that will not be in the software.”

Limitation of the computer-based prototype

Engineer A1: "It is difficult to go back and forth in the selection of parameters. (…) *We almost want it to go further, to be able to play with more parameters,*"

Engineer A3: “It's not a work tool because I can't configure the volume of the building, the site, all this is quite important because our engineer profile is a consulting profile that plays on the nuances. From our experience, a building is determined to be good or bad within a few kWh/m², or Kg of CO_2.”

Engineer B1: “When you have this result so easily, you say to yourself, it's a pity that there are no more parameters.”

Engineer B1: “Typically we have to click the parameters we don't want to keep (...) it's not very logical.”

Engineer B1: “On small screens, we can't access the "show" button (...), we have to change the resolution of the screen.

Architect B2: “As we took the path of building with adobe, we were a little stuck, it's not that we would have stopped using ELSA, but we can see a little bit of the reality of the program that's still under development."

Engineer C1: I think it's a pity that we can't print the results in detail.

Architect C2: “A maximum of 6 or 7 parameters must be selected to obtain results. Maybe it deserves an explanation from the beginning. Then we understood, (...) evaluated what the important factors were, things like that and it really became interesting.”

Architect D1: “We were also annoyed not being able to select more than six parameters, we wanted to continue to select things.”

C. Consent Form

Here the consent form submitted to the participants for voluntary participation detailing the research purpose, the procedure, the nature of the collected data, the confidentiality rules and the legal framework.

Chercheur principal :

Thomas Jusselme

Passage du Cardinal 13B

Case postale 487

CH-1700 Fribourg

Formulaire de consentement

Dans le cadre du MEP du bâtiment smart living lab, vous devez utiliser l'application ELSA pour justifier votre première proposition architecturale et technique lors du Dialogue A. ELSA est un prototype issu des travaux de recherche de l'EPFL. Ainsi, de manière totalement indépendante du MEP, l'utilisation d'ELSA par les professionnels que vous êtes servira de cas d'étude pour la validation de ces travaux de recherche.

Pour éviter toute confusion, les éléments suivants sont obligatoires dans le cadre du MEP :

- Utilisation d'ELSA en préparation du dialogue A
- Présence à la séance de débriefing de l'utilisation d'ELSA le 19/02/2019.

En revanche, les informations décrites dans le paragraphe « Nature des données collectées » ci-dessous seront données de manière volontaire et nécessitent l'accord et la signature du présent formulaire de consentement de la part des participants au MEP utilisant ELSA.

Objectif du projet de recherche

Comprendre l'impact d'ELSA sur le processus de conception du bâtiment du smart living lab et sur ses acteurs.

Procédure

Au cours de cette étude, vous serez amenés à utiliser ELSA pour la conception du bâtiment du smart living lab. Un retour d'expérience de cette utilisation sera effectué suivant les modalités suivantes.

Nature des données collectées

- Enregistrement du trafic et des actions effectuées sur l'application elsa2.epfl.ch, par compte d'utilisateur,

- Enregistrement audio de la réunion de débriefing sous forme d'entretien collectif entre les utilisateurs d'ELSA et les chercheurs impliqués dans ce projet,
- Réponses à un questionnaire anonyme en ligne de type « Google Forms » à remplir par les participants.

Les données collectées ne seront en aucun cas utilisées pour évaluer la qualité de votre travail dans le cadre du MEP du projet de bâtiment smart living lab.

Confidentialité

Toutes les données collectées seront anonymisées avant publication et sauvegardées de manière sécurisée et anonyme pendant une durée de 1 an conformément à la Loi fédérale sur la protection des données (RS 235.1).

Les données enregistrées dans leur format original seront uniquement accessibles par les chercheurs mentionnés dans la section contact de ce formulaire de consentement.

Une version transformée de ces données sans données personnelles identifiables et respectant les points précédemment mentionnés sera partagée avec la communauté scientifique pour comprendre l'impact d'ELSA sur le processus de conception et sur ses acteurs. Votre identité ne sera en aucun cas dévoilée, les données communiquées se limiteront à une description de votre profil professionnel, de votre utilisation et appréciation d'ELSA.

Risques

A ce jour, il n'y a pas de risque anticipé sur la santé liée à l'utilisation de l'application ELSA.

Planning

L'étude sera portée sur toute la durée du MEP du 14 décembre 2018 au 06 juin 2019.

Participation et annulation

Votre participation à cette étude est complètement volontaire, et vous pouvez vous retirer de cette étude à tout moment sans donner de raisons et sans conséquences négatives. Dans ce cas vous devez communiquer votre décision au chercheur principal (thomas.jusselme@epfl.ch). Egalement, vous êtes en mesure de demander aux chercheurs d'avoir un accès aux données enregistrées vous concernant, ou d'effacer ces données enregistrées à tout moment.

Juridiction applicable

Le droit suisse est applicable et le présent formulaire de consentement est soumis à la juridiction du Canton de Fribourg, en Suisse et de la Loi fédérale sur la protection des données (RS 235.1).

Contact

Pour toutes questions complémentaires concernant cette étude, merci de contacter le chercheur principal Thomas Jusselme (thomas.jusselme@epfl.ch) ou son superviseur Prof. Marilyne Andersen (marilyne.andersen@epfl.ch) du laboratoire LIPID de l'EPFL.

Copie du participant

Consentement

L'objectif et la nature de cette recherche ont été suffisamment expliqués ci-dessus pour que je puisse consentir à participer à cette étude. De plus, je donne ma permission pour enregistrer le trafic que je génère lors de mon utilisation de l'application ELSA, ainsi que les réponses aux questions posées par les chercheurs de cette étude. Je comprends que je suis libre de me retirer à tout moment de cette étude sans conséquences. Enfin, je comprends aussi que si j'ai des questions concernant ce projet, je peux contacter le chercheur principal ci-dessus mentionnés.

Le participant

Nom :

Date :

Email :

Signature :

Le Chercheur principal:

Nom :

Signature :

Copie du chercheur

Le participant

Nom :

Date :

Email :

Signature :

Le Chercheur principal:

Nom :

Signature :

D. ELSA and the smart living lab competition rules

smart living lab

blue FACTORY
Fribourg – Freiburg

BFF SA Étude pour la réalisation d'un
bâtiment pour le smart living lab

Mandat d'études parallèles en procédure sélective

Document A

Règlement et Procédure

Fribourg, le 3 septembre 2018

Haute école d'ingénierie et d'architecture Fribourg
Hochschule für Technik und Architektur Freiburg

UNI FR
UNIVERSITÉ DE FRIBOURG
UNIVERSITÄT FREIBURG

EPFL
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

5. PROJET DE RECHERCHE

5.1 Calendrier

19 février 2019 **A la suite du dialogue A**	Discussion sur l'utilisation de l'outil ELSA

5.2 Retour d'expérience sur l'outil ELSA – hors périmètre du MEP

Dans le cadre de ce présent mandat d'études parallèles, l'outil ELSA (Exploration tooL for Sustainable Architecture) sera mis à disposition des candidats afin de supporter le processus de conception du futur bâtiment du smart living lab. Il permettra aux concepteurs de vérifier les impacts des choix de matériaux et d'équipements sur la performance environnementale de leur projet. Les candidats devront par ailleurs s'appuyer sur ce dernier pour construire une analyse critique des stratégies de conception envisagées lors du dialogue A.

L'outil ELSA, développé dans le cadre d'un programme de recherche spécifique du groupe Building 2050, n'est encore qu'un prototype. Son utilisation dans le cadre de ce présent mandat permettra de valider et de valoriser les travaux de recherche, mais aussi d'être en accord avec l'essence même du futur bâtiment (au service de la recherche) dès sa propre conception.

Dans ce contexte, les candidats devront faire part de leur retour d'expérience concernant l'utilisation de l'outil ELSA. Une séance de discussion de 90 minutes sera organisée sous la forme d'un focus group le jour du dialogue A, à savoir le mardi 19 février 2019, probablement entre 17h00 et 18h30. Le programme exact de la journée sera transmis ultérieurement.

L'ensemble des candidats, sans exception, devra être présent.

Chaque candidat devra être composé à minima d'un architecte et d'un ingénieur spécialiste qui auront utilisé l'outil pour le dialogue A.

Un formulaire de consentement autorisant le groupe de recherche à exploiter les données issues de la séance à des fins de recherche sera transmis à chaque participant pour accord.

La séance sera enregistrée dans son intégralité.

Les discussions qui auront lieu dans le cadre de cette séance visant le développement de la recherche seront totalement indépendantes du MEP. Aucune information, aucun point, concernant le MEP ne seront communiqués, traités avec les candidats lors de cette rencontre.

Document		Dialogue A	Dialogue B	Rendu final	Outils Remarques
07	Simulation thermique dynamique du confort d'été pour 3 locaux de bureaux-types situés en façade Sud, à l'angle des façades Sud et Est et à l'angle des façade Sud et Ouest du dernier étage. Conditions de calculs : norme SIA 2024 pour les hypothèses de présence et d'apports internes. Résultats exprimés norme EN 15251 (nombre d'heures d'inconfort maximal fixée à 5% de la période d'occupation pour les zones non climatisées).		X	**X**	*Onglet descriptif sommaire * 1)* *+* *schéma de principe environnemental du projet*
08	Outil descriptif sommaire		X	**X**	*Onglet descriptif sommaire *1)*
	Qualités environnementales				
09	ELSA + rapport d'utilisation.	X			*ELSA*
10	ACV selon SIA 2032.		X	**X**	*Onglet ACV *1)*
11	Simulation énergétique SIA 380.		X	**X**	
12	Calcul de l'autonomie énergétique.		X	**X**	*PV-opti*
13	Notice sur la prise en compte des certifications environnementales demandées.		X	**X**	
14	Schéma de principe environnemental du projet, avec les stratégies environnementales permettant d'atteindre les valeurs cibles	X	X	**X**	*Schéma de principe environnemental*
15	Exigence Minergie A sur la quantité d'énergie renouvelable.		X	**X**	*Onglet ACV *1)*
16	Productible et empreintes PV simplifiée.	X			*Onglet DA-CdTe /DA-Multi SI *1)*
17	Productible et empreintes PV y c. masques.		X	**X**	*Onglet DB*1)*
18	Productible solaire thermique.		X	**X**	
19	Récapitulatif des aspects environnementaux			**X**	*Onglet synthèse *1)*
20	Notice explicative sur la gestion des eaux			**X**	

2.4.3 Qualités environnementales (c.f. annexe B10)

Le bâtiment du smart living lab héberge des activités de recherche, notamment sur la performance environnementale des bâtiments et se devra donc d'être exemplaire sur ce point, depuis sa mise en service jusqu'à sa désaffectation.

Performance du cycle de vie

L'ambition du bâtiment smart living lab est d'atteindre un niveau de performance compatible avec la vision de la société à 2000 watts à l'horizon 2050. Toutes les mesures nécessaires seront prises pour intégrer cet objectif dès le stade des premières études préliminaires, jusqu'à la construction, puis l'exploitation, et enfin la fin de vie du futur bâtiment. L'utilisation de matériaux de construction écologiques et à faible contenu en énergie grise permettra d'atteindre les objectifs fixés par la société à 2000 watts (énergie grise, énergie d'exploitation, mobilité).

Il est nécessaire de bien préciser le périmètre de l'étude, ainsi que les outils et méthodes qui permettront de valider l'atteinte des objectifs de la société à 2000 watts, notamment dans le cadre spécifique du MEP. En effet, les analyses de cycle de vie sont complexes et peu compatibles avec un stade préliminaire de conception des bâtiments. Pourtant, c'est dans ces phases en amont que les décisions les plus importantes sur la performance du futur bâtiment du smart living lab seront prises le plus facilement.

Les valeurs minimales à atteindre ainsi que la méthodologie de calcul sont décrites dans l'annexe B10.

Des outils comme le logiciel Elsa (Exploration tooL for Sustainable Architecture), dont le groupe de recherche Building 2050 est à l'origine, et différents tableurs seront mis à disposition des candidats pour simplifier les évaluations. Lors de la journée d'information, des explications détaillées seront fournies aux candidats sur ces divers éléments et leur utilisation. Voir Document B10 annexé.

Qualités environnementales

Pour cette partie, se reporter au listing des documents à remettre pour les dialogues et le rendu final (annexe A9).

Le bâtiment du smart living lab hébergera des activités de recherche, notamment sur la performance environnementale des bâtiments, et se devra donc d'être exemplaire sur ce point depuis sa mise en service jusqu'à sa désaffectation.

1) Performance cycle de vie

L'ambition du bâtiment du smart living lab est d'atteindre un niveau de performance compatible avec la vision de la société à 2000 watts à l'horizon 2050. Pour cela, toutes les mesures nécessaires seront prises pour intégrer cet objectif dès le stade des premières études préliminaires, jusqu'à la construction, puis l'exploitation du futur bâtiment.

Pour cela, il est nécessaire de bien préciser le périmètre de l'étude, ainsi que les outils et méthodes qui permettront de valider l'atteinte des objectifs de la société à 2000 watts, notamment dans le cadre spécifique du MEP. En effet, les analyses de cycle de vie sont complexes et peu compatibles avec un stade préliminaire de conception des bâtiments. Pourtant, c'est dans ces phases en amont que les décisions les plus importantes sur la performance du futur bâtiment du smart living lab seront prises le plus facilement.

2) Valeurs cibles

Les exigences de la société à 2000 watts à l'horizon 2050 sont un minima à atteindre pour les trois indicateurs de performance: Energie primaire totale (E_P) ; Energie primaire non renouvelable ($E_{P,nren}$) ; Emissions de gaz à effet de serre (M_{GHG}).

Le bâtiment du smart living lab devra respecter les valeurs cibles suivantes :

	Energie primaire totale E_P (kWh/m².an)	Energie primaire non renouvelable $E_{P,nren}$ (kWh/m².an)	Emissions de gaz à effet de serre M_{GHG} (kg/m².an)
Valeurs indicatives « construction »	42	40	9
Valeurs indicatives « exploitation »	167	80	4
Performances requises	**209**	**120**	**13**

Tableau 1 : Valeurs cibles pour administration issues de la norme SIA 2040/2017 pour EP,nren et MGHG, et de « Kellenberger, D., Ménard, M., Schneider, S., Org, M., Victor, K., Lenel, S., 2012. Réhabiliter des friches industrielles pour réaliser la société à 2000 watts » pour EP.

Seules les performances requises totales sont obligatoires. Les valeurs indicatives ne sont données qu'à titre d'information, et les travaux du groupe de recherche Building 2050 mettent en lumière une répartition différente de celle proposée ici, à savoir une proportion d'impacts liés à la "construction", supérieure à celle de "l'exploitation" (les valeurs calculées en construction tendent vers des valeurs supérieures à celles indiquées, tandis que les valeurs en "exploitation" sont calculées inférieures à celles proposées).

Ces valeurs sont rapportées à la surface de référence énergétique A_E, correspondant à la somme de toutes les surfaces de plancher des étages et des sous-sols qui sont inclus dans l'enveloppe thermique des bâtiments et dont l'utilisation nécessite un conditionnement. Cette surface est définie en détail dans les normes SIA 380 et 416.

Un schéma de principe environnemental du projet est demandé au candidat afin de visualiser l'ensemble des stratégies environnementales mises en place pour atteindre les valeurs cibles exigées ci-dessus.

3) Méthode et hypothèses

Méthode

Les analyses de cycle de vie seront réalisées suivant la norme SIA 2032.

Durée de vie de l'ouvrage : 60 ans

Durée de vie des composants : suivant annexe C de SIA 2032

Unité fonctionnelle : le m² de surface de référence énergétique A_E

Le périmètre de l'analyse de cycle de vie comprend tous les flux d'énergie et de matière de l'emprise au sol de la parcelle ainsi que des parkings dédiés au bâtiment du smart living lab (cf. ci-après). Les consommations liées à l'utilisation d'équipements spécifiques pour les travaux de recherche sont hors du périmètre de performance du MEP. Il sera retenu une activité de type bureaux à ce stade.

Les ACV sont à réaliser avec la base de donnée « Données des écobilans dans la construction 2009/1:2016 », disponible à l'adresse suivante :

https://www.kbob.admin.ch/kbob/fr/home/publikationen/nachhaltiges-bauen/oekobilanzdaten_baubereich.html

Un cadre spécifique à la réalisation de cet ACV est proposé dans l'outil Excel « Outils Perf Environnementale.xls » sous l'onglet ACV qui sera proposé dans le cadre du MEP.

Dans l'onglet "ACV" de l'outil précité, les données relatives à l'énergie finale devront être calculées par le biais d'une simulation énergétique suivant la norme SIA 380.

Nombre de parkings

240 places de parking (avec diverses fonctions) seront proposées sur tout le site de blueFACTORY. En première approche, il est affecté 5% de ces places au bâtiment du smart living lab, soit 12 places de parking. Ainsi, le bâtiment se verra attribuer l'impact de ces 12 places suivant les valeurs forfaitaires de la feuille de calcul Excel, onglet ACV.

Marge d'études préliminaires

Il est reconnu que plus un projet est détaillé, plus la connaissance des matériaux et composants mise en œuvre est élevée. Ainsi, les études préliminaires omettent la prise en compte d'impacts qui ne sont pas encore connus à ce stade de conception. C'est pourquoi une marge de sécurité de 15% sera retenue sur les valeurs cibles au stade des études conceptuelles pour pallier au manque d'informations sur les matériaux et composants non encore décrits et appréhendés.

Aménagement intérieur

Un budget forfaitaire est retenu pour l'aménagement intérieur (mobilier) et pour les futurs usages spécifiques (appareils électroménagers et électroniques) suivant les valeurs forfaitaires de la feuille de calcul Excel, onglet ACV. Ces valeurs se basent sur une campagne de mesures et d'observation des pratiques actuelles du smart living lab (*Hoxha, E., Jusselme, T., 2017. On the necessity of improving the environmental impacts of furniture and appliances in net-zero energy buildings. Science of The Total Environment 596–597, 405–416*).

Il est à noter que les concepteurs sont encouragés à étudier les possibilités de densification de l'espace, qui garantissent une utilisation maximale des ressources mises en œuvre, et le confort des usagers. Le bénéfice environnemental de la densification a été démontré lorsqu'il est mesuré par occupant. Au stade des études préliminaires, il est demandé de démontrer le potentiel de densification ; l'impact environnemental par occupant ne sera calculé qu'en phase d'exploitation du bâtiment.

4) ELSA

ELSA (Exploration tooL for Sustainable Architecture) est une méthode d'exploration du champ des possibles pour les concepteurs souhaitant vérifier les impacts de leurs choix de matériaux et équipements sur la performance environnementale de leur projet. Le groupe Building 2050 est à l'origine de cette méthode et propose un premier prototype en collaboration avec EPFL+ECAL lab et Human-IST (UNI FR), utilisable dans le cadre de ce projet.

Sur la base de la capacité architecturale du projet, 3 différentes volumétries ont été modélisées pour produire une base de données de références et d'alternatives de conception ayant toutes des caractéristiques différentes en termes de systèmes énergétiques, systèmes constructifs, typologies de façade, etc. Les performances environnementales de l'ensemble de ces alternatives ont été calculées grâce à des analyses de cycle de vie, et mises à disposition des futurs concepteurs au travers d'une interface graphique interactive.

L'exploration de cette base de données permet aux concepteurs de répondre aux questions suivantes :

- Quels sont les paramètres qui ont le plus d'influence sur la performance ?
- Quels sont les systèmes constructifs qui permettent d'atteindre les objectifs de performance ?
- Est-il nécessaire de couvrir toute la toiture de panneaux photovoltaïques ?
- Quelle doit être la performance de mes menuiseries si je veux vitrer complètement mes façades ?
- Etc.

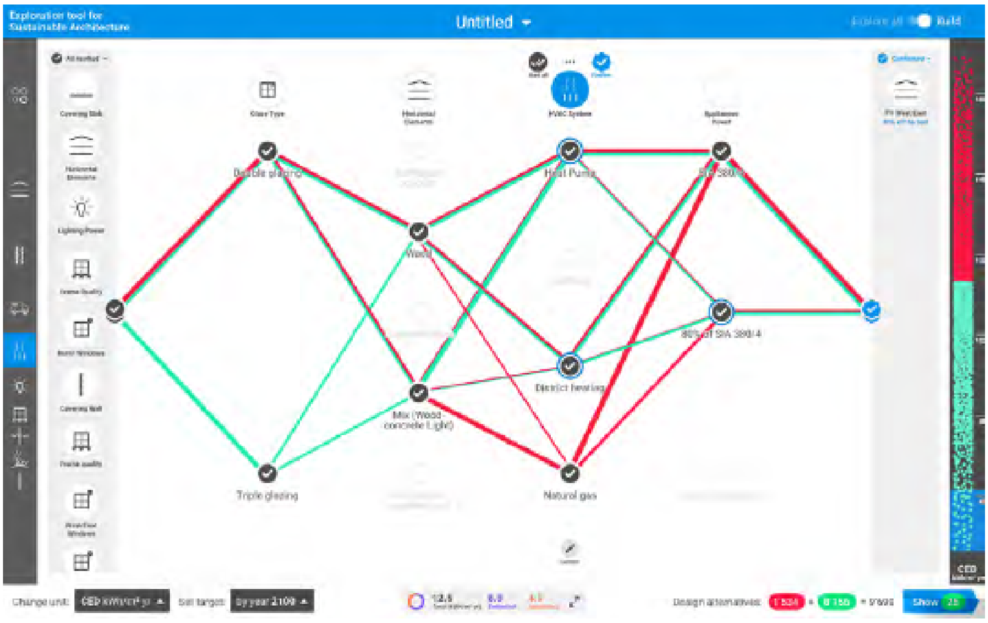


Figure 1 : capture d'écran du prototype ELSA

La base de données mise à disposition est spécifique au projet et intègre le programme prévisionnel ainsi que le climat local et propose des dizaines de milliers de variantes pré-calculées, permettant aux concepteurs une large exploration du champ des possibles, et ce de manière instantanée.

ELSA n'étant encore qu'un prototype issu de la recherche ne sera pas utilisé à des fins de validation des propositions architecturales, mais à des fins exploratoires pour éveiller la sensibilité des concepteurs à l'intégration des performances requises du projet au plus tôt dans le processus de conception. Ainsi, son utilisation est demandée pour construire un argumentaire sur les stratégies envisagées lors du Dialogue A.

Une introduction à l'utilisation de l'outil, ainsi que les codes d'accès seront proposés lors de la séance d'information du MEP du 14 décembre 2018.

De plus, tous les candidats sans exception devront participer à une séance de discussion qui se tiendra le jour du dialogue A afin de faire part de leur retour d'expérience sur l'utilisation de l'outil ELSA (cf. Document A §.5.2).

E. Presentation of ELSA to the competitors

Here the presentation of ELSA performed during the kick-off session on December 14, 2018, where all four teams were present with their architects and engineers.

ELSA – Exploration tooL for Sustainable Architecture

smart living lab

1

Les objectifs SIA 2040

Le bâtiment du smart living lab devra respecter les valeurs cibles suivantes :

	Energie primaire totale E_p (kWh/m².an)	Energie primaire non renouvelable $E_{p,nren}$ (kWh/m².an)	Emissions de gaz à effet de serre M_{GHG} (kg/m².an)
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Performances requises	**209**	**120**	**13**

Tableau 1 : Valeurs cibles pour administration issues de la norme SIA 2040/2017 pour EP,nren et MGHG, et de « Kellenberger, D., Ménard, M., Schneider, S., Org, M., Victor, K., Lenel, S., 2012. Réhabiliter des friches industrielles pour réaliser la société à 2000 watts » pour EP.

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2

Approche cycle de vie

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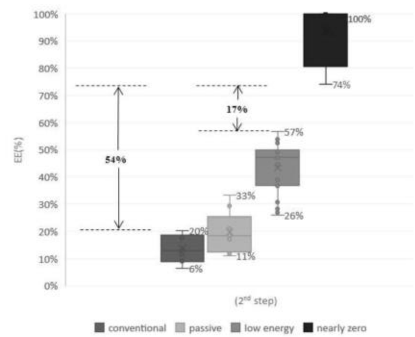
3

La part de l'énergie grise

Dans un bâtiment à **énergie 0**, il ne reste plus que de **l'énergie grise**…



Chastas, P., Theodosiou, T., Bikas, D., and Kontoleon, K. (2017) 'Embodied Energy and Nearly Zero Energy Buildings: A Review in Residential Buildings'. Procedia Environmental Sciences 38, 554–561

smart living lab

4

Un vrai intérêt, mais pas d'outils adaptés

Selon une étude auprès de 500 architectes et ingénieurs en Europe:

60% intègrent souvent ou très souvent des objectifs de performance **cycle de vie** dans leurs pratiques

MAIS

Seulement **27%** disposent d'un **logiciel** pour évaluer la performance
vs 61% qui utilisent des références techniques et architecturales
vs 33% qui utilisent la règle du pouce…

Jusselme, T., Rey, E., and Andersen, M. (2018) Findings from a Survey on the Current Use of Life-Cycle Assessment in Building Design. held 10 December 2018 at Hong-Kong. PLEA 2018

smart living lab

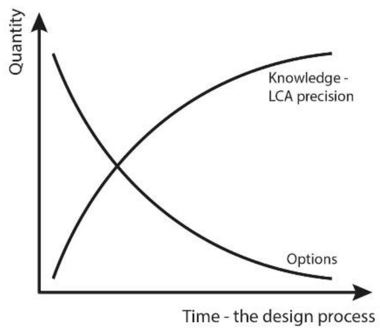
5

Un problème de timing

En phase **d'esquisse**: il y a une grande **flexibilité** de conception

MAIS

Le projet n'est **pas détaillé**
L'ACV a donc **peu de valeur ajoutée** car elle reflète plus les hypothèses que les qualités du projet.



Patrick MacLeamy - HOK

smart living lab

6

Un problème de timing

Il faut en moyenne **3 mois** pour faire une esquisse

… qui nécessite **3 variantes** de projet

Or il faut **1 semaine** pour évaluer la performance ACV

→ *Disposez-vous de **3 semaines d'études** à consacrer à l'ACV?*

Jusselme, T., Rey, E., and Andersen, M. (2018) Findings from a Survey on the Current Use of Life-Cycle Assessment in Building Design. held 10 December 2018 at Hong-Kong. PLEA 2018

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7

ELSA en résumé

Un **objectif** de performance à atteindre

smart living lab

8

ELSA en résumé

Quelles **contraintes** cela a-t-il sur les choix architecturaux et techniques?

9

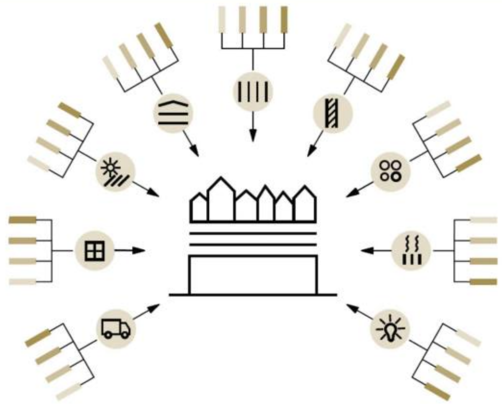
ELSA en résumé

Une **application en ligne** pour vous guider dans vos premiers choix

10

ELSA en résumé

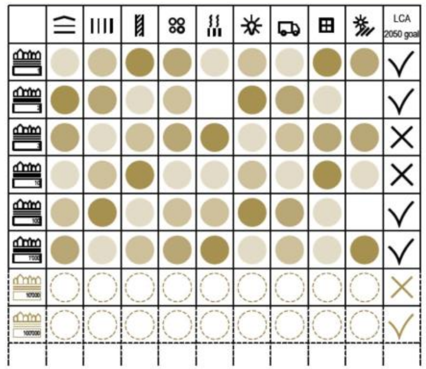
Une approche **paramétrique…**



11

ELSA en résumé

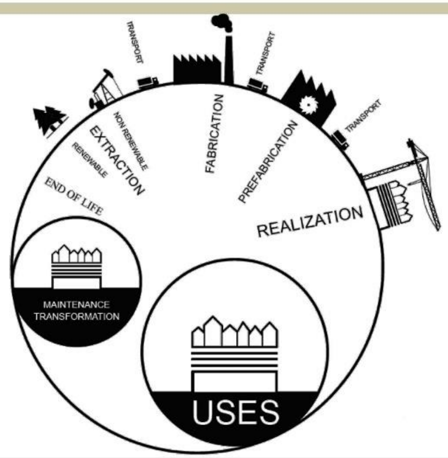
… qui crée une base de données de **références spécifiques** au projet…



12

ELSA en résumé

La performance **cycle de vie** de chaque référence a été calculée.



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13

ELSA en résumé

L'outil permet une **exploration** de ces références en fonction de leur performance.

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14

ELSA en résumé

L'exploration de la base de données est également guidée par des **choix de conception**…

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15

ELSA en résumé

L'outil permet de comprendre la **conséquence** de ces choix sur la performance, mais également sur les autres paramètres.

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16

ELSA en résumé

Chaudière **bois** uniquement

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ELSA en résumé

La finalité étant de **s'orienter** rapidement vers une référence ou une famille de références qui permet d'atteindre les objectifs.

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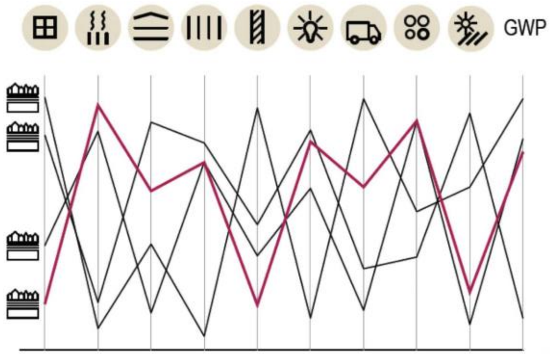
ELSA en résumé

L'interface est dynamique et utilise des **coordonnées parallèles**.



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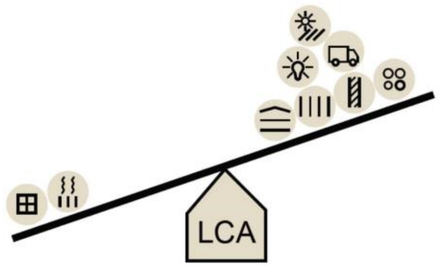
ELSA en résumé

ELSA permet également de comprendre la **sensibilité des indicateurs** de performance vis-à-vis des paramètres explorés.



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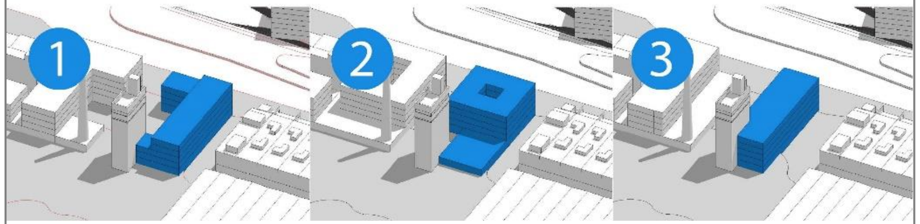
3 volumétries disponibles



Une surface de plancher similaire, mais des **volumétries différentes**

Chaque volumétrie dispose de plus de **20 000 références**.

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21

15 paramètres

Paramètres	Descriptions			
Menuiserie / façade	25%	40%	55%	70%
Vitrage	Double vitrage (U=1.3)	Triple vitrage (U=0.6)		
Cadre de la menuiserie	Bois/Alu	Alu	PVC	Bois
U parois opaques (W/m²K)	0.1	0.2	0.3	
PV toiture	0%	30%	60%	90%
PV façade (S/E/W)	0%	10%	20%	30%
Chauffage	PAC	Bois grannulés	Chauffage à distance	
Eclairage	85% SIA	SIA	120% SIA	
Structure horizontale	Béton armé	Bois contre-collé	Bois ossature	Bois/bac acier
Structure verticale	Terre cuite	Béton armé	Bois contre-collé	Bois ossature
Matériau d'isolation	Laine de verre	PSE	PU	Laine de roche
	Cellulose	Laine de bois		
Revêtement de sol	Résine	Carrelage	Linoleum	Parquet
	PVC	Moquette		
Revêtement de façade	Panneaux de ciment	Enduit minéral	Clins de bois	Zinc
	Acier	Enduit organic		
Transport	100 km	200 km	500 km	1000 km

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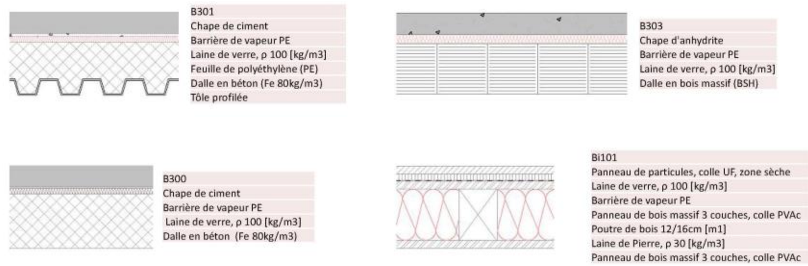
22

Exemple: 4 planchers



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23

L'interface

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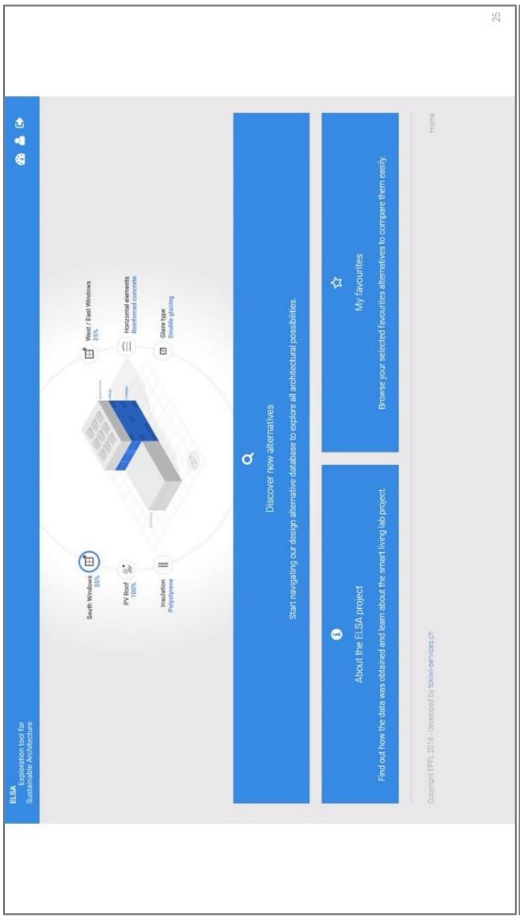
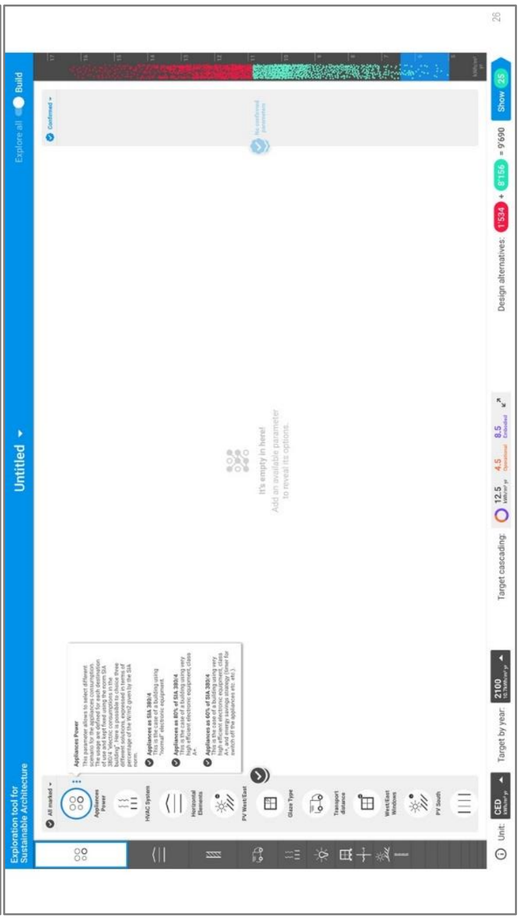
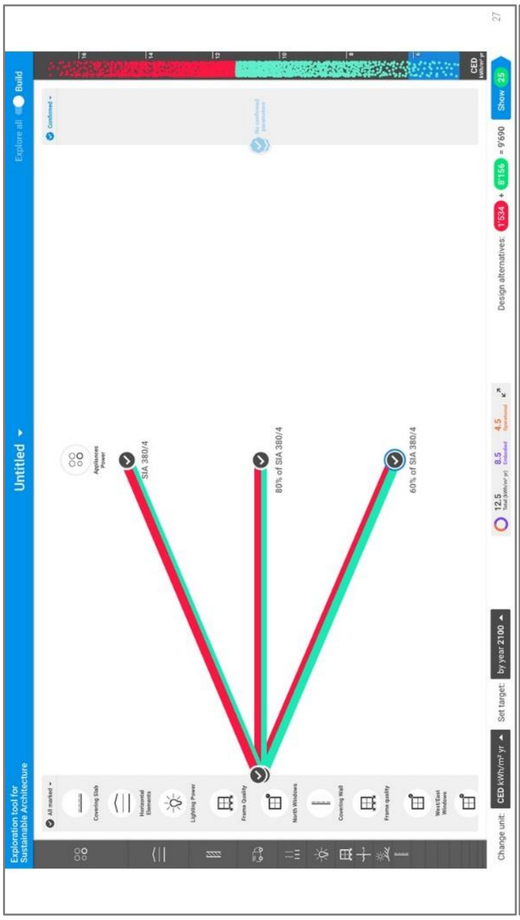
24


ELSA
Exploration tool for Sustainable Architecture
Discover new alternatives
Start navigating our design alternative database to explore all architectural possibilities.
About the ELSA project
Find out how the data was obtained and learn about the smart living lab project.
My favourites
Browse your selected favourites alternatives to compare them easily.
25


Exploration tool for Sustainable Architecture
Untitled
Explore all
Build
26


Exploration tool for Sustainable Architecture
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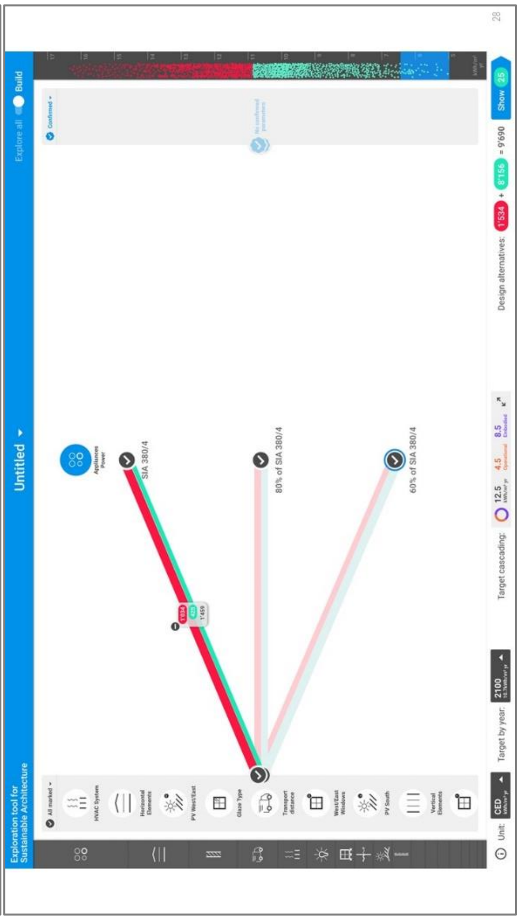
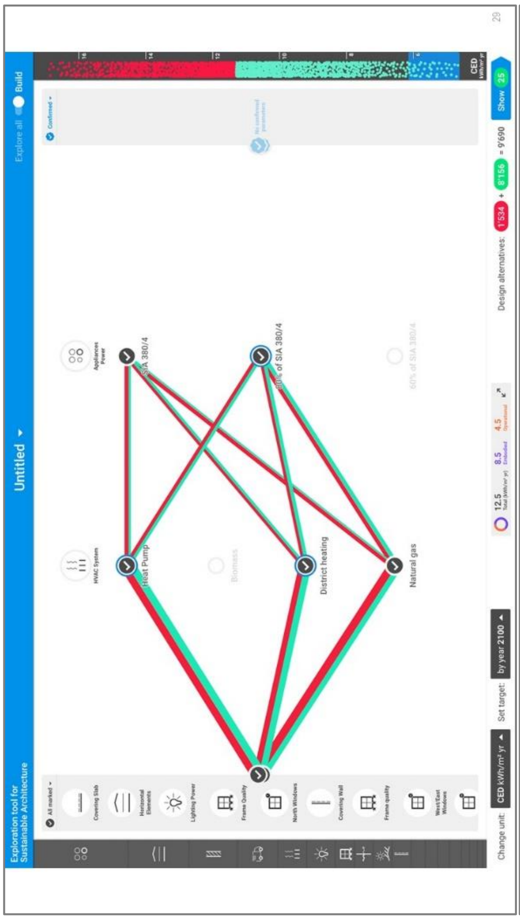
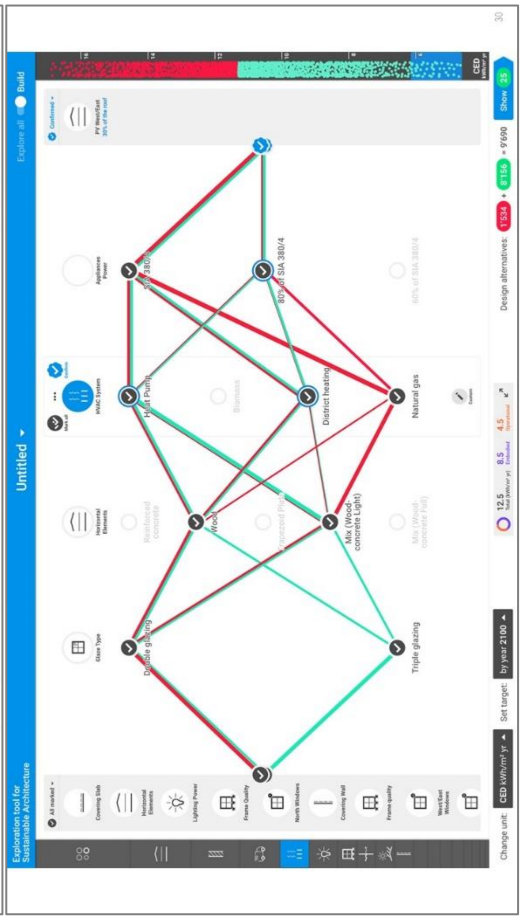
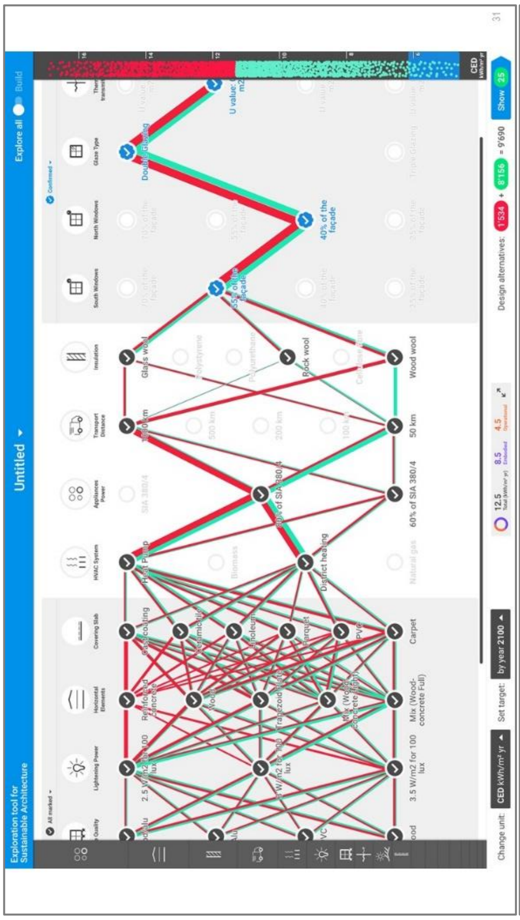
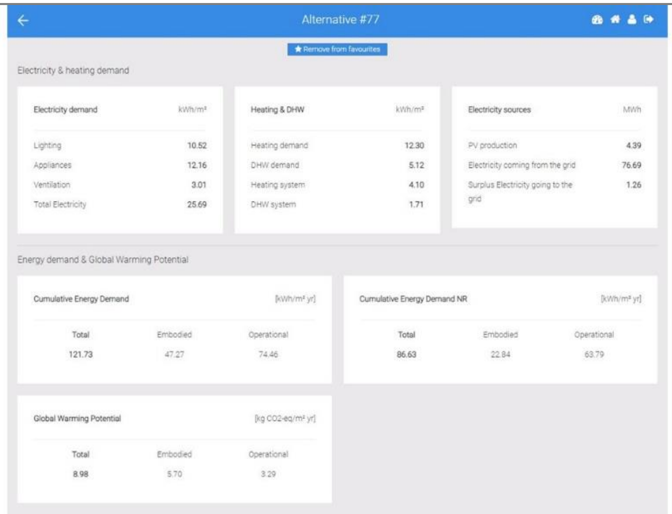
SIA 380/4
80% of SIA 380/4
60% of SIA 380/4
Explore all
Build
27


Exploration tool for Sustainable Architecture
Untitled
SIA 380/4
80% of SIA 380/4
60% of SIA 380/4
Explore all
Build
28









Limites

ELSA analyse **seulement la performance environnementale** des références proposées, pas le confort, le coût, la faisabilité technique, etc…

Rendu attendu

- **Construire une argumentation** sur la performance ACV de votre proposition
- **Une stratégie** illustrée par des choix de conception / une famille de projets
- **Une référence détaillée** la plus proche de votre proposition

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SAV

- **Pour toutes questions:** par mail suivant le canal habituel
- **Une visio-conférence de prévue** le jeudi 17 Janvier de 10h à 12h
  → *au moins 1 spécialiste environnement par équipe*

smart living lab

Suivi recherche

- **Un suivi de l'utilisation de l'outil:** monitoring de la plateforme web
  → *Consentement à signer pour participer*
- **Une séance de débriefing** le mardi 19 février 2019, probablement entre 17h00 et 18h30
  → *au moins 1 spécialiste environnement par équipe + 1 architecte*

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Questions ?

?

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F. Excel-based reporting framework for LCA calculations

Here the Excel tool that was created by the Building 2050 team and used by the practitioners as a reporting framework for the smart living lab competition as discussed in section 5.1.3. ELSA has been used to specify the carbon budget of the building component.

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Analyse de Cycle de Vie (ACV) - Dialogue B et Rendu final

Cet onglet vous offre un cadre pour le calcul et la présentation de vos résultats de l'Analyse du Cycle de Vie (ACV) de votre proposition architecturale. Il permet également de s'assurer que le projet répond au critère Minergie-A sur la quantité d'énergie renouvelable.

Données générales

Durée de vie du bâtiment	60	ans
Surface de Référence Energétique du projet (SRE)	4162	m^2
Objectifs cibles SIA 2040	209	E_P (kWh/m^2)
	120	$E_{P,nren}$ (kWh/m^2)
	13	M_{GHG} (kg/m^2)

Construction & Exploitation

Les graphes ci-dessous présentent les résultats obtenus des empreintes environnementales du projet en énergie primaire (E_p), énergie primaire non renouvelable ($E_{p,nren}$) et émissions de gaz à effet de serre (M_{GHG}). Ils vous permettent d'analyser et de comparer les différentes catégories entre elles, et ont pour ambition d'être utilisés comme un outil d'aide à la décision en phase de conception du projet.

Aide à la compréhension des graphes:

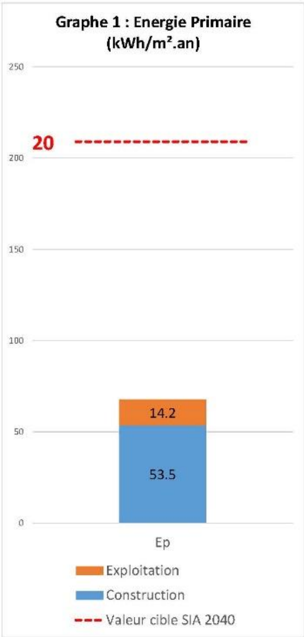
Les graphe 1, 2 et 3 présentent la répartition des impacts environnementaux (E_p, $E_{p,nren}$ et M_{GHG}) du projet par phases : phase de construction et phase d'exploitation. Les valeurs cibles SIA 2040 à ne pas dépasser selon l'annexe B10 du Mandat d'Etudes Parallèles sont également indiquées sur les trois graphes (traits pointillés rouges).

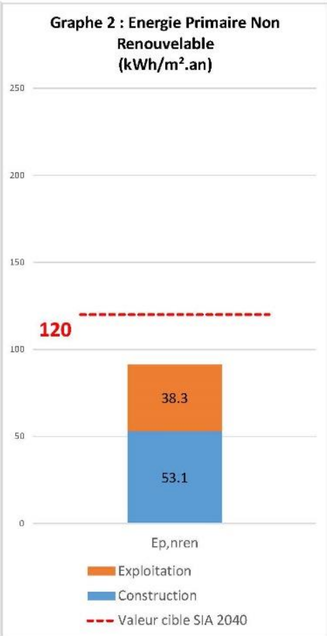
Les graphes 4 et 5 présentent la répartition des impacts environnementaux (E_p, $E_{p,nren}$ et M_{GHG}) du projet par catégories.

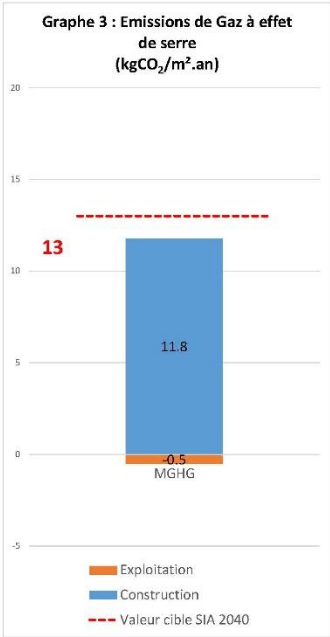
Les catégories suivent une décomposition identique à celle de l'outil ELSA (Exploration tooL for Sustainable Architecture), également utilisé dans le cadre de ce présent Mandat d'Etudes Parallèles. Ainsi, les catégories 1 à 9 correspondent aux impacts environnementaux pendant la phase de construction, tandis que les catégories 10 à 15 indiquent les impacts environnementaux pendant la phase d'exploitation du bâtiment.

Les graphes 4 et 5 précisent également les "valeurs cibles Building2050". Ces valeurs sont issues des travaux de recherche du groupe de recherche Building2050 et obtenues à partir de l'outil ELSA. Elles permettent d'arbitrer au mieux vos choix de conception au regard des impacts environnementaux. Cependant, il est important de noter que ces données sont transmises pour aider à analyser les résultats mais ne constituent pas une obligation dans le cadre du présent Mandat d'Etudes Parallèles.

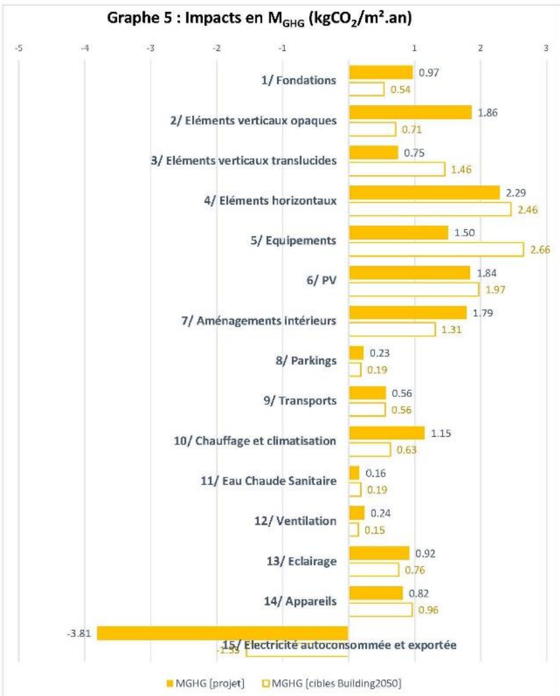
Répartition des impacts environnementaux du projet par phase







Répartition des impacts environnementaux du projet par catégories



Phase de Contruction

Le tableau ci-dessous vous permet de calculer les empreintes environnementales (E_p, $E_{p,nren}$ et M_{GHG}) de chaque élément du bâtiment (cases "orange" à compléter) pour la phase construction. Il convient d'intégrer l'ensemble des éléments du bâtiment connu au moment de la saisie de l'outil. Il est demandé d'être le plus exhaustif possible (le niveau de détail doit correspondre au stade d'avancement requis pour le dialogue B et le rendu final). Les différents éléments détaillés ci-dessous par catégorie ne sont pas exhaustifs et sont donnés à titre d'exemple. Il convient d'adapter les terminologies (colonne A) à votre projet et de rajouter des lignes si nécessaire (ligne "Autre à préciser" à dupliquer autant que nécessaire).

De plus, il est reconnu que plus un projet est détaillé, plus la connaissance des matériaux et composants mis en oeuvre est élevée. Ainsi, les études préliminaires omettent la prise en compte d'impacts qui ne sont pas encore connus à ce stade de conception. C'est pourquoi une marge de sécurité de 20% a été retenue au stade des études conceptuelles pour pallier au manque d'informations sur les matériaux et composants non encore décrits et appréhendés. Cette marge est valable pour les catégories 1, 2, 4 et 8. Les valeurs affichées sur les graphiques correspondent donc aux valeurs du projet additionnées d'une marge de sécurité de 20% pour ces catégories. Les lignes grisées sont quant à elles imposées. Elles sont par conséquent non modifiables.

		Description KBOB							Impact projet		
	Détails	**Code KBOB**	**Unité**	**E_P**	**$E_{P,nren}$**	**M_{GHG}**	**Durée de vie**	**Quantité**	**E_P**	**$E_{P,nren}$**	**M_{GHG}**
	Unité			**kWh**	**kWh**	**kg**	**ans**		**kWh/m².an**	**kWh/m².an**	**kgCO$_2$/m².an**
Exemple : Excavations	*Excavations mécaniques*	*62.001*	*m3*	*1.68*	*1.67*	*0.412*	*60*	*2500*	70.00	69.6	17.2
1/ Fondations											
Excavations	Excavations mécaniques, en	062.001	m3	0.004	1.27	0.32	60	6 962	0.00	0.04	0.01
Fondations	Béton pour bâtiment (sans	1.002	kg	0.13	0.201	0.099	60	1 339 175	0.70	1.08	0.53
	Béton maigre (sans armatu	01.001	kg	0.009	0.139	0.059	60	197 306	0.01	0.11	0.05
	Acier d'armature	06.003	kg	0.211	3.55	0.682	60	81 515	0.07	1.16	0.22
						SOUS-TOTAL 1	**Sans marge**		0.77	2.38	0.81
							Avec marge		0.93	2.86	0.97
								Valeurs cibles Building2050	*2.79*	*2.07*	*0.54*
2/ Eléments verticaux opaques											
Parois porteuses	Béton pour bâtiment (sans	01.002	kg	0.13	0.201	0.099	60	1 365 317	0.71	1.10	0.54
	Acier d'armature	06.003	kg	0.211	3.55	0.682	60	83 106	0.07	1.18	0.23
Poteaux	Béton pour bâtiment (sans	01.002	kg	0.13	0.201	0.099	60	31 243	0.02	0.03	0.01
	Acier d'armature	06.003	kg	0.211	3.55	0.682	60	1 902	0.00	0.03	0.01
	Bois lamellé-collé, colle UF,	07.002.01	kg	8.24	2.76	0.614	60	49 130	1.62	0.54	0.12
Isolation	Panneau de fibres mou, Pavatex	10.009.01	kg	6.9	3.14	0.445	60	46060	1.27	0.58	0.08
	Gravier de verre cellulaire,	10.013.01	kg	0.244	1.56	0.127	60	21 450	0.02	0.13	0.01
Bardage	Bois massif mélèze, séché	07.011	kg	6.66	0.812	0.143	40	12 276	0.33	0.04	0.01
Portes extérieures opaques	Portes extérieures bois, do	12001	m²	175	330	77.6	35	24	0.03	0.05	0.01
Fenêtres extérieures opaques	Fenêtres extérieures bois, d	12001	m²	175	330	77.6	35	211	0.25	0.48	0.11
Protection solaire	Protection solaire, stores à	05.018	m²	36	297	65	30	698	0.20	1.66	0.36
	Brise soleil fixe - Grille méta	6011	kg	1.05	15.7	3.51	60	3 533	0.01	0.22	0.05
	Écran anti-éblouissement							432			
	Lamelles bioplastique (?) Re	07.013	kg	8.14	2.76	0.614	30	642	0.04	0.01	0.00
						SOUS-TOTAL 2	**Sans marge**		4.58	6.06	1.55
							Avec marge		5.50	7.27	1.86
								Valeurs cibles Building2050	*10.51*	*4.68*	*0.71*
3/ Eléments verticaux translucides											
Portes extérieures	Portes extérieures bois, avec vitrage	12002	m²	122	411	97.7	35	90	0.08	0.25	0.06
Cadre	Cadre fenêtre bois	5005	m²	711	573	128	60	289	0.82	0.66	0.15
Vitrage - jardin d'hiver int.	Triple vitrage, verre ESG/VS	05.016	m2	32	484	110	60	184	0.02	0.36	0.08
Vitrage - jardin d'hiver ext.	Verre plat, enduit	03.005	kg	0.233	4.71	1.16	60	295	0.00	0.01	0.00
Vitrages - Façade standard	Triple vitrage, verre ESG/VS	05.016	m2	32	484	110	60	1 036	0.13	2.01	0.46
								SOUS-TOTAL 3	**1.05**	3.29	0.75
								Valeurs cibles Building2050	*15.38*	*8.93*	*1.46*
4/ Eléments horizontaux											
Planchers/Toiture	Béton pour bâtiment (sans	01.002	kg	0.13	0.201	0.099	60	704 186	0.37	0.57	0.28
	Acier d'armature	06.003	kg	0.211	3.55	0.682	60	42 864	0.04	0.61	0.12
	Panneau de bois massif 3 c	07.001	kg	9.57	2.99	0.523	60	3 286	0.13	0.04	0.01
	Panneau d'aggloméré type	07.013	kg	8.24	2.76	0.614	60	61 740	2.04	0.68	0.15
	Bois massif épicéa / sapin /	07.011	kg	7.47	6.66	0.812	60	234 613	7.02	6.26	0.76
	Bois lamellé-collé, colle UF,	07.002.01	kg	8.56	2.16	0.397	60	85 790	2.94	0.74	0.14
	Profil en acier, nu	6.012	kg	3.71	3.46	0.734	60	2 515	0.04	0.03	0.01
Isolation toiture / terrasse	Panneau de fibres mou, Pav	10.009.01	kg	6.9	3.14	0.445	60	35 420	0.98	0.45	0.06
Isolation plancher sous-sol	Gravier de verre cellulaire,	10.013.01	kg	0.244	1.56	0.127	60	42 450	0.04	0.27	0.02
Isolation balcons	Panneau de fibres mou, Pav	10.009.01	kg	6.9	3.14	0.445	60	13 720	0.38	0.17	0.02
Isolation porte-à-faux	Panneau de fibres mou, Pav	10.009.01	kg	6.9	3.14	0.445	60	4 200	0.12	0.05	0.01
Étanchéité toiture / terrasse	Gravier rond	03.012	kg	0.003	0.064	0.012	60	53 200	0.00	0.01	0.00
	Lé d'étanchéité bitumineux	9003	kg	0.257	12.5	3.25	60	1 158	0.00	0.06	0.02
	Revêtement terrasse - bois	7010	kg	5.78	0.69	0.125	30	7 130	0.33	0.04	0.01
	Sous-structure terrasse - Bo	7009	kg	5.78	0.69	0.125	30	2 377	0.11	0.01	0.00
	Couvertine - Tôle d'alumini	6001	kg	5.29	26.7	5.62	60	1 318	0.03	0.14	0.03
Étanchéité plancher sous-sol	Lé d'étanchéité bitumineux	9003	kg	0.257	12.5	3.25	60	934	0.00	0.05	0.01

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	Feuille de polyéthylène (PE	9007	kg	0.909	24.8	5.33	60	26	0.00	0.00	0.00
Verrière toiture / atrium/ pergola	Façade, à montants et trave	05.008	m²	66.1	760	177	60	364	0.10	1.11	0.26
							SOUS-TOTAL 4	Sans marge	14.64	11.29	1.91
								Avec marge	17.57	13.55	2.29
								Valeurs cibles Building2050	*42.01*	*19.71*	*2.46*
5/ Equipements											
Installations de ventilation	Ventilation bureau, canaux en tôle, besoins en air 2 m3/hm2 SRE	32.005	m2	5.85	73.6	17.1	60	4162	0.10	1.23	0.29
Installations sanitaires	Bureau, degré de complexité faible, appareils et conduites compris	33.001	m2	1.2	19.6	4.48	60	4162	0.02	0.33	0.07
PAC	Pompe à chaleur saumure-eau 8 kW	31.017	Stk.	506	5520	2180	60	7	0.01	0.15	0.06
Installations de chauffage	Sondes géothermiques, pour la pompe à chaleur saumure-eau	31.016	m	2.87	130	28.1	60	600	0.01	0.31	0.07
Installations de chauffage	Distribution de chaleur, bâtiment administratif	31.022	m2	2.68	32.7	7.62	60	4162	0.04	0.55	0.13
Plafond rayonnant (standard)	Diffusion de chaleur par le	31.025	m2	4.47	26.4	5.77	60	4162	0.07	0.44	0.10
									0.00	0.00	0.00
									0.00	0.00	0.00
									0.00	0.00	0.00
									0.00	0.00	0.00
Installations électriques				190	114	23.8	30	4162	6.33	3.80	0.79
								SOUS-TOTAL 5	6.59	6.81	1.50
								Valeurs cibles Building2050	*27.83*	*15.72*	*2.66*
6/ PV											
PV façade	Installations photovoltaïque façade	34.027	kWp	905	7460	2140	60	72	0.26	2.14	0.61
PV toiture	Installations photovoltaïque toiture plate	34.026	kWp	959	8020	2320	60	132	0.51	4.25	1.23
								SOUS-TOTAL 6	0.77	6.39	1.84
								Valeurs cibles Building2050	*14.77*	*9.80*	*1.97*
7/ Aménagements intérieurs											
Cloisons intérieurs	Plaque de plâtre cartonnées	03.008	kg	0.079	1.35	0.293	60	59755	0.02	0.32	0.07
Cloisons intérieures	Verre plat, non enduit	03.006	kg	0.13	4.06	1.1	60	12500	0.01	0.20	0.06
Portes	Portes intérieures bois	12.003	m²	290	193	43	60	75	0.09	0.06	0.01
	Portes intérieures bois, avec vitrage	12 004	m²	245	308	69	60	88	0.09	0.11	0.02
Revêtement de sol	Dalle en pierre naturelle rectifiée, Suisse, 30 mm	11.015.02	m²	16	118	11.9	60	432	0.03	0.20	0.02
	Linoleum, 2,5mm	11.014	m²	19.3	26.3	6.36	20	1605	0.37	0.51	0.12
	Dalle en céramique/grès, 9 mm	11008	m²	4.22	68.8	14	60	115	0.00	0.03	0.01
	Revêtement coulé à 2 comp., industrie (résine époxy), 2,25 mm	11 001	m²	1.44	65.1	17.2	60	1946	0.01	0.51	0.13
Plancher surélvé	Panneau de bois massif 3 couches, colle PVAc	07.001	kg	9.57	2.99	0.523	60	47376	1.82	0.57	0.10
	Sous-structure - Bois massif épicéa, séché à l'air, brut	7 009	kg	5.78	0.69	0.125	60	16296	0.38	0.05	0.01
	Vrac - gravier rond (référence)	03.012	kg	0.003	0.064	0.012	60	235200	0.00	0.00	0.00
	Barrière de vapeur papier, Isocell (référence Papier Kraft)	9 006	kg	14.5	8.05	1.69	60	14820	0.86	0.00	0.00
Revêtement de parois	Enduit argileux 10mm	04.004	kg	0.016	0.164	0.023	60	37044	0.00	0.02	0.00
Revêtement de plafond	Panneau d'argile 60mm	03.020	kg	0.005	0.129	0.023	60	81600	0.00	0.04	0.01
	Plaque de plâtre cartonnées	03.008	kg	0.079	1.35	0.293	60	2316	0.00	0.01	0.00
	Panneau de bois léger à paille de bois liée par du ciment	07.005	kg	2.02	1.34	0.554	60	12080	0.10	0.06	0.03
Escalier atrium	Bois massif hêtre / chêne, séché en cellule, raboté	07.008	kg	6.32	0.685	0.126	60	1809	0.05	0.00	0.00
	Profil en acier, nu	06,012	kg	3.71	3.46	0.734	60	3690	0.05	0.05	0.01
Garde-corps	Profil en acier, nu	06.012	kg	3.71	3.46	0.734	60	2201.925	0.03	0.03	0.01
Tri des déchets	Système de tri des déchets	21.001	Stk.	18	114	23.7	30	10	0.00	0.01	0.00
Kitchenette	Cuisine, bois massif, 16 éléments	21.009	Stk.	2530	3170	697	30	2	0.04	0.02	0.06
	Plan de travail en résine synthétique	21.005	m²	148	118	23.9	30	15	0.02	0.00	0.00
	Armoire-évier en acier chromé	21.012	Stk.	40.6	226	46.5	30	6	0.00	0.00	0.00
Céramique sanitaire	Céramique sanitaire	07.008	kg	0.401	11.2	2.32	60	800	0.00	0.04	0.01
Mobiliers									11.00	5.50	1.10
								SOUS-TOTAL 7	14.97	8.35	1.79
								Valeurs cibles Building2050	*21.03*	*8.49*	*1.31*
8/ Parkings									0.51	0.49	0.19
							SOUS-TOTAL 8	Sans marge	0.51	0.49	0.19
								Avec marge	0.61	0.59	0.23
								Valeurs cibles Building2050	*0.89*	*0.63*	*0.19*
9/ Transports									5.55	4.04	0.56
								SOUS-TOTAL 9	5.55	4.04	0.56
								Valeurs cibles Building2050	*5.55*	*4.04*	*0.56*

Résultats Construction	E_P	$E_{P,nren}$	M_{GHG}
Total Construction par m² et par an	kWh/m².an	kWh/m².an	$kgCO_2/m^2$.an
	53.5	53.1	11.78
Valeurs cibles Building2050	*140.8*	*74.1*	*11.86*

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Exploitation

Les tableaux ci-dessous vous permettent de calculer les empreintes environnementales (E_p, $E_{p,nren}$ et M_{GHG}) pour chaque poste de consommation pour la phase d'exploitation du projet (cases "orange" et "jaune" à compléter). Dans cette partie, une simulation énergétique selon la SIA 380 sera nécessaire, ainsi que l'outil PVopti fourni par Minergie.
- Tableau 1 : Type d'énergie pour le chauffage et l'eau chaude sanitaire
- Tableau 2 : Energie finale et chaleur utile par postes de consommation
- Tableau 3 : Production photovoltaïque autoconsommée et exportée au réseau
- Tableau 4 : Récapitulatif des impacts environnementaux par postes de consommation

Tableau 1	Vecteur énergétique 1		Vecteur énergétique 2		Solaire thermique	
Production de chaleur	Type	Taux de couverture %	Type	Taux de couverture %	Taux de couverture %	Taux de couverture total %
Chauffage	Electricité	100%				100%
E_p	3.008		0.000		1.230	0.000
$E_{p,nren}$	2.520		0.000		0.086	0.000
M_{GHG}	0.102		0.000		0.014	0.000
Eau Chaude Sanitaire	Electricité	100%				100%
E_p	3.008		0.000		1.230	0.000
$E_{p,nren}$	2.520		0.000		0.086	0.000
M_{GHG}	0.102		0.000		0.014	0.000

Facteurs de conversion pondérés		
E_P	$E_{P,nren}$	M_{GHG}
kWh/kWh	kWh/kWh	kg/kWh
3.008	2.520	0.102
3.008	2.520	0.102

Tableau 2	Selon SIA 380		Facteurs de conversion				Impact projet		
Postes de consommation	Chaleur utile	Energie finale	Source	E_P	$E_{P,nren}$	M_{GHG}	E_P	$E_{P,nren}$	M_{GHG}
	$kWh_{th}/m^2.an$	$kWh/m^2.an$		kWh/kWh	kWh/kWh	kg/kWh	$kWh/m^2.an$	$kWh/m^2.an$	$kgCO_2/m^2.an$
Chauffage	29.2	11.29	Selon tableau 1	3.008	2.520	0.102	33.96	28.45	1.15
Eau Chaude Sanitaire	3.6	1.60	Selon tableau 1	3.008	2.520	0.102	4.81	4.03	0.16
Climatisation	-		KBOB : 45.020	3.008	2.52	0.102	0.00	0.00	0.00
Ventilation	-	2.34	KBOB : 45.020	3.008	2.52	0.102	7.03	5.89	0.24
Eclairage	-	9.00	KBOB : 45.020	3.008	2.52	0.102	27.07	22.68	0.92
Appareils	-	8.00	KBOB : 45.020	3.008	2.52	0.102	24.06	20.16	0.82
	TOTAL	32.23							

Tableau 3	Selon PVopti		Facteurs de conversion				Impact projet		
Production PV	PV-opti	$kWh/m^2.an$	Source	E_P kWh/kWh	$E_{P,nren}$ kWh/kWh	M_{GHG} kg/kWh	E_P $kWh/m^2.an$	$E_{P,nren}$ $kWh/m^2.an$	M_{GHG} $kgCO_2/m^2.an$
Autoconsommation directe et stockée	cf. cellule E36	13.60	KBOB : 45.020	3.008	2.52	0.102	-40.91	-34.27	-1.39
Injection sur le réseau	cf. cellule E37	29.90	KBOB : 46.001	1.400	0.289	0.081	-41.86	-8.64	-2.42
	TOTAL	43.50							

Tableau 4 - Récapitulatif	Impact		
Postes de consommation	E_P $kWh/m^2.an$	$E_{P,nren}$ $kWh/m^2.an$	M_{GHG} $kgCO_2/m^2.an$
10/ Chauffage et climatisation	33.96	28.45	1.15
Valeurs cibles Building2050	*28.80*	*10.32*	*0.63*
11/ Eau Chaude Sanitaire	4.81	4.03	0.16
Valeurs cibles Building2050	*7.97*	*2.85*	*0.19*
12/ Ventilation	7.03	5.89	0.24
Valeurs cibles Building2050	*7.73*	*4.83*	*0.15*
13/ Eclairage	27.07	22.68	0.92
Valeurs cibles Building2050	*40.03*	*24.98*	*0.76*
14/ Appareils	24.06	20.16	0.82
Valeurs cibles Building2050	*50.19*	*31.22*	*0.96*
15/ Electricité autoconsommée et exportée	-82.77	-42.91	-3.81
Valeurs cibles Building2050	*-66.51*	*-28.27*	*-1.55*

Résultats Exploitation	E_P	$E_{P,nren}$	M_{GHG}
Total Exploitation par m² et par an	$kWh/m^2.an$	$kWh/m^2.an$	$kgCO_2/m^2.an$
	14.2	38.3	-0.52
Valeurs cibles Building2050	*68.2*	*45.9*	*1.14*

TOTAL : Construction & Exploitation

Total général par m² et par an		$kWh/m^2.an$	$kWh/m^2.an$	$kgCO_2/m^2.an$
		67.7	91.4	11.3
Comparatif avec valeurs cibles SIA 2040	Valeurs	209	120	13
	% du seuil	32%	76%	87%

Exigence Minergie-A

Rappel de l'exigence Minergie-A :
La production annuelle de l'installation photovoltaïque doit couvrir les besoins globaux en énergie d'exploitation du bâtiment (énergie finale pondérée).

Besoins globaux en énergie d'exploitation (énergie finale	354186	kWh
Production PV	361678	kWh

	7492	kWh
Besoins globaux en énergie d'exploitation (énergie finale	85.1	kWh/m2
Production PV	86.9	kWh/m2
	1.8	kWh/m2

G. Results of the smart living lab competition

Here, the presentation of the four teams selected to participate in the Smart Living Lab competition (Figure 74).

Figure 74: The four teams that participated in the Smart Living Lab competition. Top-left: Behnisch Architekten, Drees & Sommer Schweiz AG, ZPF Ingenieure AG. Top-right: Baumschlager Eberle Architekten AG, Dr. Lüchinger + Meyer Bauingenieure AG, Lauber IWISA AG, B+S AG. Bottom left: estudioHerreros SLP, Dr Schwartz Consulting AG, Transplan Technik-Bauplanung Gmbh, Transsolar Energietechnik Gmbh, xmade Gmbh. Bottom right: Itten + Brechbühl SA, CSD Ingénieurs

The winner of the competition was the team Behnisch Architekten, with its project “HOP”. An outdoor view and an indoor rendering that they produced to illustrate their project are provided in Figure 75 and Figure 76.

Figure 75: Outdoor view of the laureate project for the Smart Living Lab building

Figure 76: Indoor rendering of the laureate project for the Smart Living Lab building.

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Curriculum Vitae

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Education

2015 - 2020	**PhD candidate,** Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland Interdisciplinary Laboratory of Performance-Integrated Design (LIPID) Development of a LCA-based data-driven method for low carbon buildings at early design stages. Parametric LCA, sensitivity analysis, data visualization, target cascading. Supervisor: Prof Marilyne Andersen, Co-supervisor: Prof Emmanuel Rey
2002	**M.Sc. Industrial and Product Design,** Université Technologique de Compiègne (UTC), France
2001	**Dipl. Eng. environmental sciences**, (Ingénieur Maître) Institut génie de l'environnement, éco-développement (Ig2e) Lyon I, France **B.Sc. environmental sciences,** Institut génie de l'environnement, éco-développement (Ig2e) Lyon I, France

Research and Development

2019 -	**Associate Professor** - University of Applied Sciences and Arts Western Switzerland - School of Engineering and Architecture, Fribourg Energy Institut; smartlivinglab.ch Low-energy and low-carbon buildings.
2014 - 2019	**Research Associate** - Ecole Polytechnique Fédérale de Lausanne smartlivinglab.ch / Building 2050 In charge of a 3M CHF interdisciplinary research program
2008	Life Cycle Assessment of a solar aeraulic facade with SimaPro 7.1.
2004	Eurasia : Director of the Non Governmental organization 1-year study about sustainable architecture in 25 countries in Asia and Europe. Publications and conferences.
2004	CSTB : International benchmark about green building standards and certifications CTBA : Development of a design support method for the building wood industry

Selected Teaching Activities

2019 -	**Associate Professor** - University of Applied Sciences and Arts Western Switzerland School of Engineering and Architecture Fribourg Mechanical Engineering Department Building physics, renewable energies, life cycle assessment.
2013 - 14	**Lecturer** - National School of Architecture - Lyon 320h per years Building physics, energy efficiency, life cycle assessment M.Sc and B.Sc levels
2008 - 14	**Lecturer** - National School of Architecture - Grenoble 160 to 320h per years Building physics, energy efficiency, life cycle assessment M.Sc and B.Sc levels
2012	**Lecturer** - Grenoble Institute of Technology Building Physics

Engineering Activities

2015 -	**Founding Partner / Managing director / CINO - Combo Solutions** www.vizcab.io Startup developing SAAS products supporting low-carbon building design. Management of 10 engineers, architects, data scientists, Front-Back developers 2.5M€ Fundraising
2006 -	**Founding Partner / Managing director - Milieu studio** www.milieu.fr Building physics consulting company Individual and collective housing, offices, commercial, culture, etc. Selected building references: School Saint Isidore (Nice, 15 000 m², nZEB), Office F2 ZAC Bouchayer-Viallet (Urbiparc, Grenoble, 2 700 m², nZEB), High School V. Hugo (Région Bretagne, Hennebont, 600 m²), 71 dwellings Grand Angle (ZAC Viry Centre, Brémond+Vinci), ZAC Fraternité Décines (18 000 m²), ZAC Caserne Aubry Renaissance (20 000 m²), ZAC Evry Centre (19 000 m², concours 2006), offices Gennevilliers, em2c (70 000 m²), Fonsorbes – Groupe Casino (11 000 m²), ZAC Tertiaire Demi Lune Roissy (Sogelym STEINER, 55 000 m²) etc. Architects: exNdo architectures, BIG, SCAU, Jacques Ferrier architectures, Intégral Lipsky + Rollet architectes, Wilmotte & Associés, Sou Fujimoto Atelier, Nicolas Michelin et associés, Maison Edouard François, Brenac et Gonzalez, Dumétier Design, Atelier Grether, Franklin Azzi architecture, Tectoniques, AFAA, Mikou design studio…
2006 - 2019	**Founding Partner - exNdo Architectures** www.exndoarchi.com Architecture office
2004	**ADEME** - French Environment and Energy Management Agency Project manager: technical and economic expertise of 12 buildings with the HQE® certification in Rhône-Alpes. Feedback on the years 1999-2004.
2003	**CTBA** – Wood Technical Center Intern : eco-design for the wood building industry.
2002	**SONY** - Environmental Design Center Europe Stuttgart Intern : LCA of a loudspeaker

Committee memberships

2016 -	Low-carbon committee member - Bluefactory BFFSA
2018	Technical committee member - One Planet Living green certification label
2014 - 2019	Scientific committee member - Smart Living Lab

Peer-reviewed papers

2020

Hoxha, E., Liardet, C., **Jusselme T.**, (2020) Office Densification Effects on Comfort, Energy, and Carbon Lifecycle Performance: An Integrated and Exploratory Study. Sustainable Cities and Society, 102032. https://doi.org/10.1016/j.scs.2020.102032.

Jusselme, T., Rey, E., Andersen, M., (2020) Surveying the environmental life cycle performance assessments: Practice and context at early building design stages. Sustainable Cities and Society 52, 101879. https://doi.org/10.1016/j.scs.2019.101879

2019

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Nault, E., **Jusselme, T**., Aguacil, S., Andersen, M., (2019) Strategic environmental urban planning - A contextual approach for defining performance goals and informing decision-making. Building and Environment 106448. https://doi.org/10.1016/j.buildenv.2019.106448

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2017 **Jusselme, T.,** Brambilla, A., Costa Grisel, V., Cozza, S., Hoxha, E., Liardet, C., Poncety, A., Vuarnoz, D., Andersen, M., and Rey, E. (2017) Smart Living Building Research Program - Executive Summary

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Book Chapters

2019 **Jusselme, T.** (2019) 'Research at the Service of Design'. in Research-Driven Building Design: Towards 2050. Park Books-in prep.

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Jusselme, T., Hoxha, E., Liardet, C., Verma, H., Christie, D., Pattaroni, L., and Messer, M.-A. (2019) 'Intensification of Use: An Exploratory Study'. in Research-Driven Building Design: Towards 2050. Park Books-in prep.

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2018 **Jusselme, T.,** Mariolle, B., (2018) Milieux / Introduction, in: Post carbon ruralities : milieux, scales and stakeholders of the energy transition., Coll. Espace rural & projet spatial. A. Coste; L. d'Emilio; X. Guillot, Saint Etienne, p. 256.

2007 **Jusselme, T.,** Fradin E., 2007. « Bâtir Ethique et Responsable - Panorama des pratiques d'architecture durable dans les pays étrangers », p73-89. Editions Le Moniteur

Conferences

2019 **Jusselme, T.,** 2019. La conception modulaire au service du bâtiment bas carbone. Conférence Ecoparc, Neuchâtel, September 6. 2019

2018 **Jusselme, T.,** (2018) Integrated design in relation to the overheating risk, thermal comfort and energy demand in hot climates, CEPT Ahmedabad, INDIA, December 19, 2018

Jusselme, T., (2018) Energy efficiency trends in European buildings, CEPT Ahmedabad, INDIA, December 20, 2018

2017 **Jusselme, T.** 2017. « Le bâtiment à énergie positive – un aperçu ». HEIG-VD, Centre St. Roch, Suisse.

2015 **Jusselme, T.,** 2015. Smart Living Lab: Du projet de recherche à la construction du smart living building. Fribourg, Suisse, October 2, 2015

	Jusselme, T., 2015. Smart Living Lab: quels enjeux pour le bâtiment à horizon 2050? ? 3ème conférence Zéro carbone - transition énergétique : nouveaux rôles pour les bâtiments et les quartiers ? Fribourg, Suisse, November 2, 2015
2012	**Jusselme, T.** (2012) Les Bâtiments Du Futur Au Solar Decathlon Europe. Le Bourget du Lac : Institut National de l'Energie Solaire, France
	Jusselme, T. (2012) 'L'énergie Grise Dans Le Bâtiment, La Pratique d'un Bureau d'étude'. in Cluster Rhône Alpes Eco Energies held 2012 at Cité de l'Environnement.
2006	**Jusselme, T.,** Fradin E., Lafont G., 2006. CSTB "Enjeux et pratiques de la construction durable dans les Pays émergents", conférence 10DBMC – Lyon

Patent

2016	**Jusselme, T.** (2016) Method of Identifying Technical Design Solutions : US Patent App. 15/638,985 / EP20160178041.

Prix / Distinctions

2019	**SBE2019 Best Paper Award** - granted for best conference paper
	EnerJ-meeting 2019 Startup prize from the Jury for Combo Solutions
	Challenge Start-ups Construction Tech - award for Combo Solutions
2017	**Award IPME**, from the French Sustainable Development Minister Segolène Royal, for Combo Solutions
	Award Green Tech Verte, from the French Home Affair Minister Manuel Valls, 150k€ for Combo Solutions
2016	**Award « Habitat et Bien-Etre »,** from TUBA - Axeleo for Combo Solutions
2012	**Medal of the city** of Villefontaine for the Canopéa project of Solar Decathlon
	1st prize Solar Decathlon 2012 Madrid: Canopéa; in charge of the passive strategies and sustainable development within the Team Rhône Alpes www.solardecathlon.eu
2010	**4th prize Solar Decathlon** 2010 Madrid: Armadillo Box; in charge of the passive strategies and sustainable development within the ENSAG - GAIA - INES team // www.solardecathlon.eu
2006	**" Innovation Prize "** - 1st Biennial of sustainable housing - Grenoble

Languages

French	Native language
English	Full professional proficiency
German	Good knowledge (B2)
Spanish	Beginner (A1)