Building2050

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

SMART LIVING BUILDING

RESEARCH PROGRAM

EXECUTIVE SUMMARY

smart living lab

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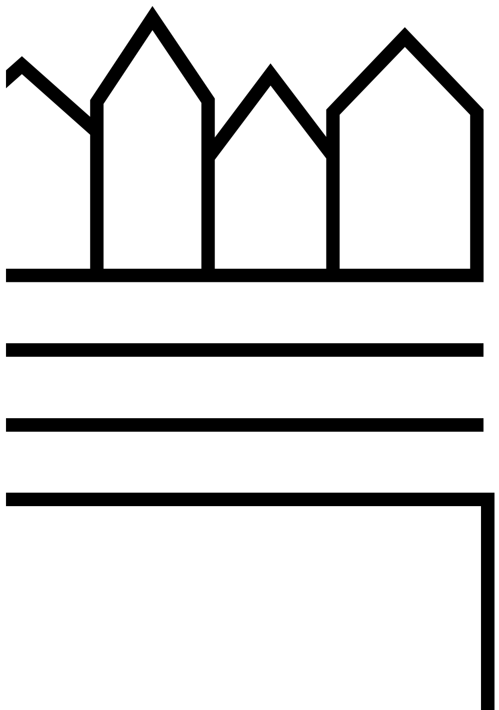
1. INTRO-DUCTION



1.1. CONTEXT

The smart living lab project is a pioneering, inter-disciplinary and inter-institutional platform that combines several fields of research related to construction technologies. It aims to be a centre of national scope, recognized on an international level and involving a variety of players and institutions. It brings together the skills of the Ecole Polytechnique Fédérale de Lausanne (EPFL), the School of Engineering and Architecture (HEIA-FR) and the University of Fribourg (UniFR) in the areas of technology and materials, as well as law and human sciences.

Following the relocation of Fribourg's Cardinal brewery in 2011, the industrial site was acquired by the city and state of Fribourg to turn it into a technological park, called blueFACTORY. This is the transforming site where the smart living building *(SLB)* is intended to emerge. The blueFACTORY site has inherent qualities with its proximity from the railway station. The neighbourhood offers a variety of destinations of use with housing, offices, commercial areas, etc.

One of the smart living lab's projects is the design and construction of its own building, which will be at the cutting edge of research and best practice on sustainability. Before starting the construction of the smart living building, a preliminary research called **smart living building *(SLB)* research program** has been set up, of which this report is the executive summary. Its objective is to sum up the research findings discovered in this frame, and to outline the way they can be used as fundamental requirements into the future operational design brief. A video (Costa Grisel et al., 2016) enables a five-minute understanding of the purpose and scope of the research. A glimpse of the program results is provided by an illustrated poster (Poncéty et al., 2016) which is linked to the following sections by references (i.e. *01-C* corresponding to *Part 1 Why?* of the poster, bubble *C*). The poster is available on the following link: *building2050.epfl.ch/poster*. The detailed results have already been partly published and should eventually represent about 20 peer reviewed conference papers and journal articles.

1.2. OBJECTIVES

The *SLB* will be a multi-functional building (residential, offices and experimental areas). The construction must correspond to the intermediary objectives set by the 2000-Watt Society model for the middle of the 21st century (hereafter called the 2050 objectives). These goals related to environmental impacts, are represented by three main indicators, namely the **cumulative energy demand** *(CED)*, the **non-renewable** part of the *CED* *(CED_{nr})*, and the **global warming potential** *(GWP)*. These environmental performances[1] should be reached without decreasing the users' comfort and the architectural quality. Thus, the research program has been set up to provide a better understanding of the following issues (Jusselme, 2015c):

- What are the objectives that could be defined regarding the performance and quality that the building will have to reach?
- Which are the architectural and technical strategies that should be implemented to reach these objectives?
- Which is the methodology that should be used to design and build this ambitious and innovative building?

1.3. FRAMING OF THE PROBLEM: THE BUILDING'S FIVE VITAL ORGANS

The increasing number of necessary components and related techniques takes the complexity of the building to a very high level. Climate change challenges in the construction sector demand highly efficient buildings and require a full understanding of the performances and interactions between all constituents. It is necessary to identify them in order to optimise the major performance contributors (in terms of *CED*, *CED_{nr}* and *GWP*). A sensitivity analysis based on actual building construction and operation allows for a global synthetic vision made up of groups of construction elements, which are the vital organs of a building (Jusselme et al., 2015b).

These macro components simplify the understanding of the different mechanisms that ensure overall performance and allow for the establishment of a strategy enabling high-efficiency use of the available resources. The vital organs are necessary for the performance of a building and have their own specific performances. The global performance strategy is more accessible using a definition of vital organs, rather than speaking about all components. It is believed that splitting a building into "organs", as it is proposed, has the advantage of probably being continued in the future, independently of the evolution of architecture, technological breakthroughs and changing user habits. A vital organ performs well when it achieves its function with a low CO_2 content.

[1] *SIA, 2011. SIA 2040 / 2011 La voie SIA vers l'efficacité énergétique.*

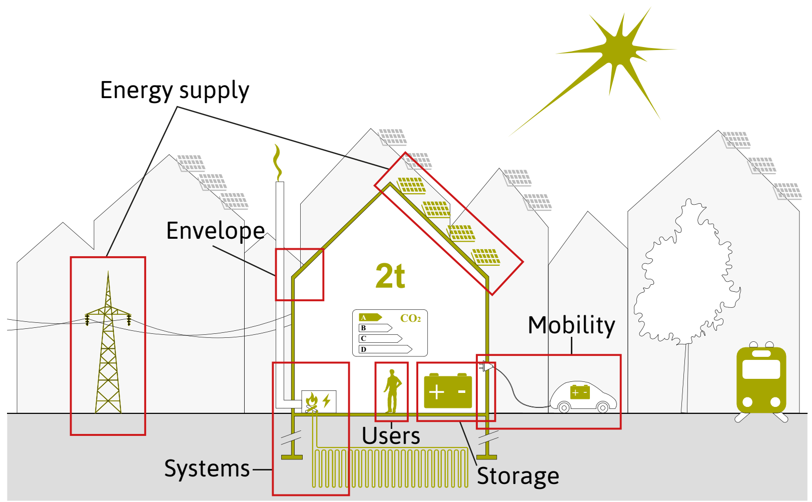


Figure 1 : Overview of the vital organs of a building

Envelope: The envelope is the interface between the external environment and the user's protected space. It is the reason why we construct buildings: to protect ourselves from the environment. The envelope is mainly composed of external walls and windows, slabs, the roof and so forth.

Energy supply: Energy is necessary for all buildings, and its availability is determined by the external context. The energy demand of the smart living building comes essentially from the need to heat the living space and domestic hot water, and from other requirements for electricity.

Energy Systems: The systems provide comfort to users by means of heating, ventilation, lighting and appliances. They are located inside the building and are powered by the energy supply. Energy storage decouples the needs for energy and its production. This subsystem is seen as an efficient way to couple the vital organs. It could be heat storage, electricity storage, fuel storage, thermal inertia storage, etc. The aim of such storage is to better correlate energy needs and a low-carbon energy supply.

Mobility: The induced mobility of buildings has significant environmental impacts. The location of the building in the external environment is a major parameter of mobility, but architectural features such as parking space for personal transportation and energy supply for mobility also affect this performance.

Building-User interactions: Knowledge about user needs (in terms of usage and comfort) is of prime importance in order to create a usable and efficient building. Usage intensity and its correlation with low-carbon energy is a key factor of this organ.

1.4. METHODOLOGY

The Kaya identity *(01-A)* is very useful to better identify the main drivers on which it is necessary to work in order to reach the 2050 objectives. As illustrated by Figure 2, it teaches us that there is a relationship between the *GHG* emissions, the global population, the Gross Domestic Product (*GDP*), and the energy consumption that emit these *GHG*. Understanding that the population *(01-A2)* and the *GDP (01-A3)* should continue to grow till 2050, the remaining strategies consist in decreasing the energy consumption generated by the *GDP* and to decrease the amount of *GHG* generated by the energy consumption (Jusselme et al., 2015a).

Figure 2 : Kaya identity at world scale

In the frame of this research program, the Kaya identity has been applied to buildings in Switzerland (Figure 3 and *01-B*). It defines what will become the main experimentations of this work, whose results are further detailed in section 2:

- The built area's intensity of use. How to decrease the average built surface area per capita? Doing that, is it possible to maintain the comfort goals? (cf. 2.1. User environment strategies)
- The efficient use of energy in the buildings. How to decrease the energy consumption of the buildings? (cf. 2.2. Bioclimatic strategies)
- The carbon content of the energy consumption. How to better use renewable energy? (cf. 2.3. Carbon based energy strategies)

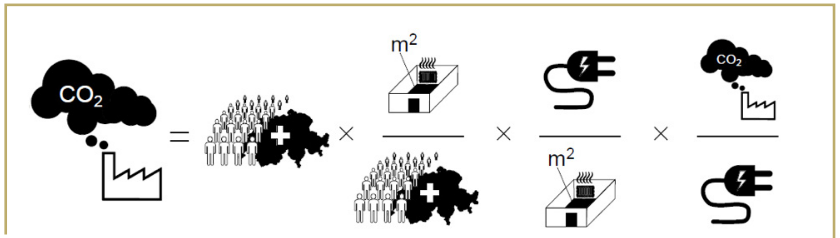


Figure 3 : Kaya identity applied to buildings in Switzerland

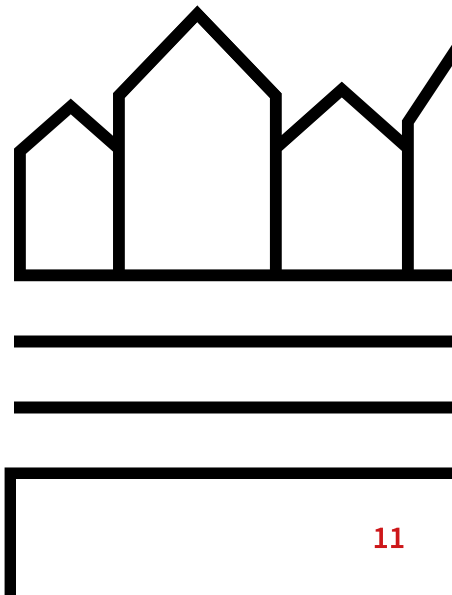
Another part of the research was dedicated to the design process. The ambitious performances *(smart)* expected from the building as a usable space *(living)* and a research facility *(lab)* induced an interdisciplinary and multi-criteria approach. This increases the number of design actors, fields of expertise, and at the end the complexity of the design process. Thus, a specific work has been carried out to answer the following questions, which results are further detailed in section 3:

- Which is the design process that will allow performance, quality and innovation? (cf. 3.1 The design process)
- Which method would enable an easy integration of the 2050 objectives at the early design stage? (cf. 3.2 LCA in the early stages of design)

There is not yet any validated masterplan of the blueFACTORY site, but researchers and students have performed the first urban studies, and used them as an initial frame to develop some *SLB* architectural feasibilities. It allowed them to detail the building's program with a projection of what could be the surface decomposition *(03-B)* of the *SLB*. These drawings have been used as case studies for all the energy and environmental simulations performed in the frame of this work, but do not pretend to be the real future building program as it is another undergoing process.

2. THE SMART LIVING DESIGN STRATEGIES

Following the main drivers identified by the Kaya identity applied to buildings in Switzerland, three main design strategies were investigated through different experimentations.



2.1. USER ENVIRONMENT STRATEGIES

The aim of the user environment strategy is to integrate and balance user knowledge and the Building2050 objectives through a prototype that offers a variety of workspaces *(04-C1)*. In order to decrease *GHG* emissions, the experimentation intends to enhance its usage intensity and the flexibility of its spaces *(04-C3)*. However, existing methodologies to study space use are time consuming and limited to qualitative methods, including observations, surveys and interviews.

An appropriate balance between energy consumption and user requirements needs to be found based on an understanding of the interrelations between user behaviours *(04-C2)*, building component design and the environmental impacts of the building. In spite of the clear evidence of the use of a large number of furniture and appliances in the daily life, none of the previous works have considered them in the boundary of building *LCA* studies. In this experimentation, furniture and appliances were included in the scope of the performance assessment.

Adopted approach for the *SLB* research program on user environment

In order to specify the building functionalities and surfaces *(03-A)*, quantitative and qualitative social studies have been performed (Maeder et al., 2015).

First, a top-down study identified qualitative values relative to the project by exploring the documentary production and the positions of the committees involved. The top-down approach helped establish a conceptual base and build a consensus regarding what were identified as the **four key principles of the smart living lab**: cooperation, innovation, wellness and ecology.

Second, while many works on management and ergonomics explore the links between the workplace and productivity, these studies are far fewer in the academic world, where the notion of productivity is harder to define. A bottom-up approach, conducted in parallel, provided a quantitative analysis of the employees' expectations, who will be those first affected by the building in terms of layout and work environment. An online survey was set up, and the questionnaire was returned by 1,598 participants *(03-D1; 03-D2; 03-C)*. This material led to a better understanding of future users' behaviour and comfort wishes.

FINDINGS

(Verma et al., 2017)

In order to qualify the occupancy rate and space navigational pattern, a novel cost effective method, that is scalable in terms of both the duration of the study and the number of participants, has been proposed. Quantitatively accurate knowledge was provided thanks to Bluetooth low energy signal strength analysis.

(Maeder et al., 2015)

- 94% of the future users want to control lighting, opening windows, blinds and doors.
- 86% of the future users consider the view, luminosity, design and office-layout as important or very important.

(Hoxha et Jusselme, 2017)

For a nearly net zero energy building, the furniture is responsible for around 10% and appliances for 25% of the overall building's impacts of the global warming indicator.

THE DELIVERABLES OF THIS RESEARCH INCLUDE

- a social database of user knowledge,
- a prototype of the user environment,
- a sociological method to assess the user comfort qualitatively,
- a strategy to measure the real building intensity of use,
- a set of recommendations or guidelines that can help designers conceive the work spaces in the smart living building.

2.2. BIOCLIMATIC STRATEGIES

The envelope, especially the glazing part and the side-effects induced on ventilation and lighting are of major influence on the building's environmental impacts and user comfort *(04-B3)*. To reduce the impacts of the façade itself, it is important to work on the materials involved in the construction. On the other side, to minimize the impacts related to the building's consumption, it is important to improve ventilation and daylighting, which have clear influences on the façade's design *(04-B2)*.

Building Automation Systems *(BAS)* have been widely studied and have demonstrated a significant energy-saving potential in many situations. Nevertheless, advances in *BAS* technologies have typically been focused on primarily optimizing the trade-off between energy use and objective comfort and overlooked the importance of the occupants' interactive experience with their environment.

Adopted approach for the *SLB* research program on bioclimatic strategies

A prototyped office space consisting of two rooms was designed and built. Comfort assessment and acceptability of the design solutions were investigated by a user survey. Participants answered a questionnaire about their comfort perception according to the operated ventilation, windows and shading (manually or automatically) in these rooms.

In order to improve the operating consumption by storing internal or external heat gains, thermal inertia is widely used as a bioclimatic strategy. Previous studies highlighted the difference between the thermal behaviour results obtained with tests on earth materials, like experiments in controlled climatic chambers and real-world applications. In the literature, the potential of earth as a bioclimatic lever has not yet been investigated in real conditions.

An application of Compressed Earth Bricks *(CEB)* has been used as a case study to analyse the thermal behaviour of an earthen wall and the potential of coupling it with night ventilation to stabilize temperatures and increase indoor comfort. Results obtained in two different rooms, representative of lightweight and heavyweight earthen construction, have been compared.

FINDINGS

(Brambilla et al., 2016, 2017b)

Inertia does not always provide environmental benefits. On the contrary, embodied impacts of materials are often higher than potential benefits.

(Brambilla et al., 2017a).

Thanks to a pilot study, it has been shown that the perception of control is positively correlated with the perceived comfort and overall satisfaction.

- The general preferences for low-tech conditions seem to have psychological reasons, since only few participants who reported higher satisfaction in low-tech conditions exercised their choice to change the configuration of windows or shadings.
- The observed spectrum of (reported) satisfaction level was found to be more dispersed in the high-tech conditions as in the low-tech conditions.

(Brambilla et al., 2017c)

The contribution of *CEB* walls to the passive cooling strategy in office buildings, according to different ventilation scenarios has been quantified.

2.3. CARBON BASED ENERGY STRATEGIES

The objective of this research was to synchronize a low-environmental-impact electricity supply and the building's electricity consumption.

Nowadays it is still of common practice to use yearly-averaged values of electricity impact factors for *LCA*. It is also well accepted to size and design renewable and storage energy system on the basis of an annual energy balance (e.g. *NZEB*). Demand side management is usually considered as an important lever for energy peak shaving.

Adopted approach for the *SLB* research program on carbon based energy

This research effort represents the first attempt to assess impact factors *(CED, CED_{nr}, GWP)* for the Swiss grid at an hourly time step, during a whole year. The influence of their differences as well as the resulting patterns in the temporal evolution of these impact factors have been investigated.

The dynamic environmental footprints of the electricity available from the grid was here compared to the ones that could be produced or stored on-site. This comparison is meant to be used as a decision tool, to design a performing building energy system that will guarantee positive resource payback time. The potential of a carbon-based electric load shifting has been proposed for *GHG* emission mitigation at the building level. The assessment results - still under investigation - will indicate if such a strategy is efficient.

FINDINGS

(Vuarnoz et al., 2017)

Based on the obtained output data, CO_2 emissions of a given case study exhibit a difference of 4%, depending on if they are assessed with mean annual or hourly emission factors. Therefore, a discrimination of the CO_2 content of the grid electricity has been proposed, regarding the different energy needs of the building in Switzerland.

(Vuarnoz et al., 2016)

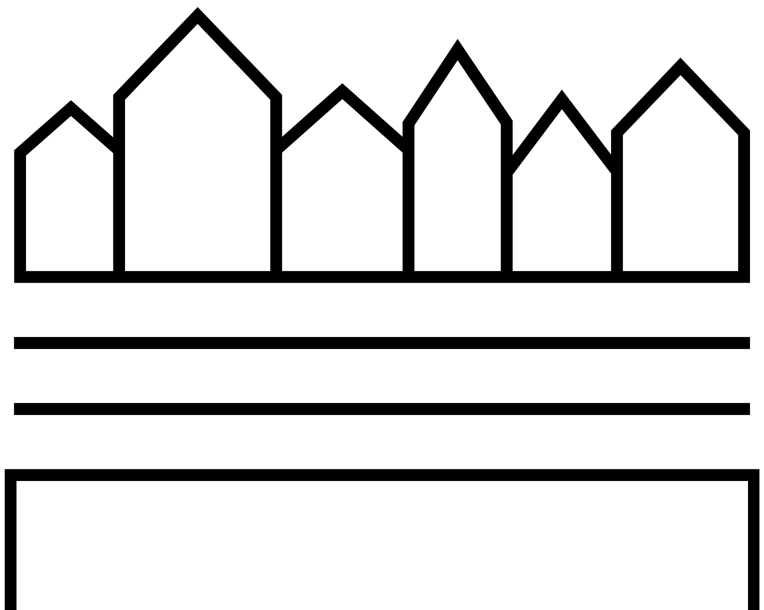
A novel energy strategy to operate buildings according to the carbon footprint of the available energy has been proposed. Its energy and environmental performance are assessed by a holistic and versatile modelling framework, which allows the simulation of a building energy system at the hourly time step.

Offices have lower potential of *GHG* mitigation by load shift than dwellings and the most effective period is the winter time.

(Nembrini et al., 2017)

Communication with the users is the key component for enabling carbon-based load shift.

3. THE SMART LIVING DESIGN PROCESS



3.1. THE DESIGN PROCESS

The current building production process in Switzerland is defined by SIA procedures, which propose the architectural competition as the main means to respond to a fixed brief and to reach architectural quality. The decision is quickly made by a heterogeneous jury, which does not share evaluation criteria and does not have proper tools to check technical performance. SIA procedures do not specify the type of collaboration between different stakeholders, especially architects and engineers' collaboration, which is a key factor for reaching both the architectural qualities and environmental performance objectives of the smart living building.

Adopted approach for the *SLB* research program on design process

The definition of a building process for the smart living building, taking into account the environmental performance, the program, the urban context and the future users has been studied. The research hypothesis – the architectural quality of the future smart living lab building is influenced by its production process throughout its entire life cycle – has been converted into a main issue: how to reach simultaneously architectural qualities, user comfort and an environmental performance?

PROPOSAL

(Radu et al., 2016).

An iterative and incremental brief is proposed to improve the RIBA model by gradually introducing the criteria of architectural qualities and environmental performance, and by allowing users to specify their needs.

Collaborative conception phases (test studies and preliminary design) between several studios, organized in thematic sequences that allow a continuous evaluation of design proposals and the appropriation of a low carbon tool (ELSA) is proposed.

3.2. LCA IN THE EARLY STAGES OF DESIGN

To face climate change, *GHG* emission targets will be set worldwide for the built environment, one of its major contributors. As a result, Life-Cycle Assessment *(LCA)* will become an important driver in the building design stakeholders' decisions, for increasing the operating performance while minimizing embodied impacts. However, the integration of *LCA* to the design process adds a high degree of complexity *(05-B3)*. In addition, it allows assessing the environmental performance but does not help finding design alternatives. New techniques such as design solutions exploration methods are promising tools to understand general performance trends, and to increase the usability of the results, but have not been applied to *LCA* so far. One of the challenges to face is that - due to the high number of parameters involved in *GHG* emission assessment in buildings - it is currently impossible to investigate all the design solutions in a reasonable computational time.

Adopted approach for the *SLB* research program on early stage *LCA*

A unique exploration method enabling to integrate lifecycle performance at early design stages has been developed through this research program and translated into an operating prototype named ELSA, which stands for Exploration tooL for Sustainable Architecture (elsa.epfl.ch).

This was made possible through an original combination of different techniques, developed towards this end: a variation of analytical target cascading methodology, which needed to be adapted to the building scale *(01-D)*, parametric simulations *(05-B4)* and sensitivity analyses *(05-B6)*. The proposed approach aims to appraise design alternatives instantaneously by highlighting the environmental consequences of architectural choices using specific data visualization techniques *(05-B7)*.

FINDINGS

(Jusselme et al., 2017)
It is impossible to apply an exploration method to *LCA* in a reasonable computational time without its adaptation. A workflow coupling different techniques (*LCA*, exploration method, sensitivity analysis and target cascading) has been proposed as a new *LCA*-based data-driven design method.

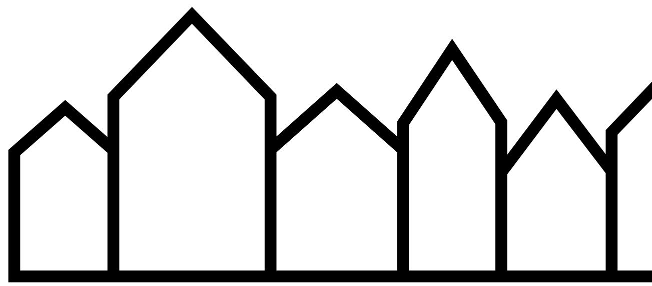
(Jusselme et al., 2016)
A workflow has been prototyped as a web graphical interface and demonstrated the ability of the method to provide low carbon design alternatives.

(Cozza et al., 2017)
A first pilot study with architecture students gave significant results about the prototype operability and proposed recommendations for assessing usability of building performance simulation tools.

(Hoxha et al., 2016)
Impact targets for the Swiss context are defined by applying the target cascading approach to the smart living building, which aims at reaching the 2050 goals of the 2000-watt society vision.

4. TEN KEY RECOMMEN-DATIONS

To facilitate the transition towards the operational phase, ten key recommendations have been extracted from the research program. They will have to be further specified in order to become part of the future design brief. Some of these topics are directly extracted from the findings of the smart living research program. Others came from the literature. They do not pretend to be exhaustive, but mandatory according to the *SLB* objectives.



1. ITERATIVE PROCESS AND OPEN DESIGN BRIEF

Innovation and quality are directly linked to the design process. A "learning by doing" process *(05-A3)* is recommended to enable stakeholders to follow the path towards these goals. It requires frequent upgrades of the design brief, following the project's stage of knowledge.

2. LIFE CYCLE ASSESSMENT *(LCA)* AS A MANDATORY DECISION MAKING TOOL

To construct a low-carbon and low-energy building, *LCA* is mandatory from the early design stage *(05-B2)* to the building operational phase. At an early design stage: parametric assessment, sensitivity analysis and target cascading should be used to address the low detail resolution issues. During the operative stage: environmental impacts as specific as possible to the product system should be used (real nature of the implemented materials, and energy sources) with an hourly step assessment of the energy flows.

3. TARGETS & SCOPE FOR THE BUILDING

Scope: The building's performance assessment should consider its embodied and operative impacts from cradle to grave, including all components in the perimeter of the building's envelope (e.g. furniture and appliances that could represent up to 30% of the *GWP* impact).

Targets: The building will have to reach the SIA2040 objectives (SIA, 2011). Its performance will be measured following two different approaches, with corresponding units:

- [kg CO_2-eq.m²/year] and [kWhep.m²/year] to address the norms and common practice
- [kg CO_2-eq. FTE /year] and [kWhep. FTE /year] to assess the intensity of use measured in FTE

Due to uncertainty, the 2050 targets should be reduced by 20% at the early design stage. This performance should be analysed at yearly steps over the lifetime of the building from 0 to 100 years.

4. COMFORT

The design process should be user-centred, considering the requirements and preferences of the specific population (referring to the survey and the users' experiment). The office dimensions should not exceed 4 to 6 occupants; however, the variability of indoor environment is essential to assure a higher acceptance of densification. Indoor environment should be monitored. With building automation, manual override must be implemented. In addition, enhancing users' connections to the outside environment has been proved essential.

5. HUMAN/BUILDING INTERACTION

An interactive protocol of communication between users and the building must be implemented. It is important to inform users about the best way of using the building to meet the environmental targets, instead of automation only. Real time monitoring is also necessary to adjust buildings' performances.

6. FLEXIBILITY

In order to improve the building's environmental performance, the evolution of its usability has to be taken into consideration. The building should be able to be upgraded according to new needs over time, like new ways of working or living. Moreover, technical installations must be easily accessible and well documented for future modifications, while technologies implemented for flexibility should be avoided as most of them are never used. A flexible use of space cannot be ensured by the building's flexibility only. A smart management of human resources will also be essential to achieve this goal.

7. IT: PERFORMANCE & FLEXIBILITY

Computers and electronic equipment account for an important part of the embodied impact (more than 20% of the *GWP* of the building). For this reason, it is very important to set up an efficient strategy for the IT systems, e.g. reducing the number of monitors, preferring laptop vs. workstations, preferring softphone VoIP rather than IP phone...

The IT strategy is also crucial for the flexibility of the space to enable workplace sharing. A proper IT management is mandatory to have compatible material between different institutions (dock station, network...).

8. SMART MATERIALS AND TECHNIQUE COMBINATIONS

A wide range of technological systems and architectural solutions can be used to reach the *CED*, CED_{nr} and *GWP* objectives for the year 2050. A priori no materials or systems are forbidden in the future building, if the inefficiency of some materials and techniques is correctly balanced by the efficiency of the others in a smart combination. The use of tools like ELSA is suggested to understand which are the right combinations and how the elements influence each others' results.

9. RENEWABLE ENERGY AND STORAGE

Energy storage should be integrated in the building's energy system in order to increase the onsite use of renewable energy and not to maximise energy exports to the grid. Adequate dimensioning of the renewable and storage energy system should be determined by clear given objectives (e.g. *NZEB*, building autonomy, ...) and must be endorsed by *LCA* to confirm the respect of given targets.

The *LCA* balance should integrate impact factors of energy sources as close as possible to reality, and energy exports towards the grid must be accounted in an appropriate and detailed method shared by all stakeholders.

10. HOUSING AS A RESEARCH MATERIAL

Offices represent 6% of the *GHG* emissions in Switzerland, compared to 50% due to housing. Therefore, the smart living lab researchers should address housing issues through the building facilities themselves.

5. CONCLUSION

The smart living building research program was a preliminary step towards the construction of the future smart living building. It involved researchers within an inter-disciplinary and multi-criteria approach. Thanks to the program, three major outcomes have been identified:

- The knowledge level of the smart living lab stakeholders has been significantly improved regarding user's needs, building energy performance, low carbon strategies and architectural quality.
- The specific research findings have been published and will at a larger scale benefit the scientific community.
- The experimentations performed in the frame of the research program have outlined the potential of the smart living building to be a research facility itself.

The holistic nature of this research scope induces many opportunities of cutting-edge topics. The interdisciplinary and inter-institutional collaboration within the smart living lab must be maintained or even improved for further successful research.

Towards the operational phase of the *SLB*, the program results must now be translated into a specific design brief based on the research findings, the ten fundamental topics and the five vital organs.

More than 30 researchers, 80 practitioners and 20 international experts were involved in this program. Indeed, more than these results, the research program initiated the research activities of the smart living lab. It allows the stakeholders to share a new culture and language through common researches.

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HUMAN-IST UNI-FR	*human-ist.unifr.ch*
LAST EPFL	*last.epfl.ch*
LASUR EPFL	*lasur.epfl.ch*
LIPID EPFL	*lipid.epfl.ch*
TRANSFORM HEIA-FR	*transform.heia-fr.ch*
ATELIER OÏ	*atelier-oi.ch*

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EPFL

UNI FR

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ETAT DE FRIBOURG
STAAT FREIBURG

REFERENCES

The list disclosed in this section contains the papers that have been published or that will be published in the frame of this research program. The reference to other works produced outside the context of the smart living lab can be found directly in the reference section of the paper mentioned below.

Brambilla, A., Alavi, H., Himanshu, V., Lalanne, D., Jusselme, T., Andersen, M., 2017a. "Our Inherent Desire for Control": a Case Study of Automation's Impact on the Perception of Comfort, in: CISBAT 2017, Lausanne, Switzerland. In prep.

Brambilla, A., Bonvin, J., Flourentzou, F., Jusselme, T., 2017b. Thermal inertia effects as measure to increase buildings environmental efficiency. In prep.

Brambilla, A., Hoxha, E., Jusselme, T., Andersen, M., Rey, E., 2016. LCA as key factor for implementation of inertia in a low-carbon performance driven design: the case of the smart living building in Fribourg, Switzerland, in: Expanding Boundaries: Systems Thinking in the Built Environment. Presented at the Sustainable Built Environment (SBE), vdf Hochschulverlag AG an der ETH Zürich, Zurich. doi:10.3218/3774-6

Brambilla, A., Jusselme, T., 2017. Preventing overheating in offices through thermal inertial properties of compressed earth bricks: a study on a real scale pro-totype. In prep.

Cozza, S., Tuor, R., Sonderegger, A., Jusselme, T., Lalanne, D., Henchoz, N., Andersen, M., 2017. The user experience of building performance simulation tools: a pilot-study for usability assessment. In prep.

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.

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. doi: 10.1016/j.scitotenv.2017.03.107.

Hoxha, E., Jusselme, T., Andersen, M., Rey, E. 2016. Introduction of a dynamic interpretation of building LCA results: the case of the smart living (lab) building in Fribourg, Switzerland. Sustainable Built Environment (SBE) Conference, Zurich. doi: 10.3218/3774-6.

Hoxha, E., Liardet, C., Jusselme, T. 2017. Measuring the effect of office densification on the energy and carbon lifecycle performance. In prep.

Hoxha, E., Cozza, S., Jusselme, T. 2017. Analytical target cascading as an LCA-based inverse assessment method towards low carbon building design. In prep.

Jusselme, T., Brambilla, A., Hoxha, E., Jiang, Y., Vuarnoz, D., Cozza, S., 2015a. Building 2050 - State-of-the-arts and preliminary guidelines. EPFL - Fribourg.

Jusselme, T., Brambilla, A., Hoxha, E., Jiang, Y., Vuarnoz, D., Cozza, S., 2015b. Building 2050 - Scientific concept and transition to the experimental phase. EPFL Fribourg.

Jusselme, T., 2015c. Building2050 - Research program. EPFL Fribourg.

Jusselme, T., Cozza, S., Hoxha, E., Brambilla, A., Evequoz, F., Lalanne, D., Rey, E., Andersen, M., 2016. Towards a pre-design method for low carbon architectural strategies, in: PLEA2016. Los Angeles, USA.

Jusselme, T., Rey, E., Andersen, M., 2017b. Integrative approach towards a LCA-based data-driven design method. In prep.

Maeder, T., Kaufmann, V., Pattaroni, L., Christie, D., Ravalet, E., Munafò, S., Baranger, V., 2015. Smart living lab: démarche de design social. Rapport de synthèse et recommandations. Laboratoire de sociologie urbaine.

Nembrini, J., Lisowska Masson, A., Vuarnoz, D., Lalanne, D. 2017. Exploring the Potential Impacts of Shifting Energy Consumption in Work Environments. In prep.

Niederhäuser, E.L., Magnin, G., Schafer, T., Vuarnoz, D. 2017. Development and validation of an intelligent algorithm for synchronizing the low-environmental-impact electricity supply with the building's electricity consumption. In prep.

Radu, F., Esquivié, F., Dräyer, C., Jiang, Y., Jusselme, T., 2016. ArQua : Architectural quality for the smart living design process. In prep.

Vuarnoz, D., Cozza, S., Jusselme, T., Magnin, G., Schafer, T., Couty, P., Niederhauser, E.L. 2017. Carbon based energy strategy for buildings. In prep.

Vuarnoz, D., Jusselme, T., 2017. Temporal variation in the environmental impact assessment of the Swiss grid. In prep.

Verma, H., Alavi, H., Lalanne, D., 2017. Studying Space Use: Bringing HCI Tools to Architectural Projects. In Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17). ACM, New York, NY, USA, 3856-3866. doi: 10.1145/3025453.3026055

Vuarnoz, D., Jusselme, T., Cozza, S., Rey, E., Andersen, M., 2016. Studying the dynamic relationship between energy supply carbon content and building energy demand, in: Plea 2016. Los Angeles.

Vuarnoz, D., Hoxha, H., Jusselme, T. 2017. Comparison between a normative and a reality-based model of building life cycle assessment. In prep.

COMMUNI-
CATION

Based on the research studies, other communication documents were produced:

Costa Grisel, V., Vuarnoz, D., Take off production, Poncéty, A., Jusselme, T., 2016. Video - The smart living building research program. Building2050 research group - EPFL. http://building2050.epfl.ch/home

Poncéty, A., Brambilla, A., Hoxha, E., Vuarnoz, D., Cozza, S., Costa Grisel, V., Liardet, C., Jusselme, T., 2016. Graphical representation of the smart living building research program. http://building2050.epfl.ch/poster

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