SAPIENZA
UNIVERSITÀ DI ROMA

ÉCOLE POLYTECHNIQUE
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SCHOOL OF ARCHITECTURE, CIVIL AND
ENVIRONMENTAL ENGINEERING

TECHNICAL AND ARCHITECTURAL ENERGY STRATEGIES FOR THE SMART LIVING LAB, A SUSTAINABLE BUILDING WITH RELIABLE ENVIRONMENTAL OBJECTIVES

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Academic Year
2014/2015

Introduction

Considering that we spend almost 90% time of our life indoor, buildings play important role in everyday life as well as in the surroundings. When all aspects of the construction sector are considered as a whole, buildings are responsible for more than half of the greenhouse gas emissions and for 2/3 of global electricity demands. Growing population, increasing demands for building services and comfort levels assure the continuity of upward trend in energy demands in the future, which has brought forward all related well-known problems, e.g. the exhaustion of energy resources, heavy environmental impacts, etc. Such demands beyond daily necessity cannot been taken for granted anymore.

Currently, energy efficiency in buildings is a primary objective of energy policy at regional, national and international levels. On a local scale, this trend has been detected also in Switzerland, where almost 40% of energy consumption has been assumed to be used for heating, ventilation and lighting in buildings. The *smart living lab* project is born under this scenario, aiming to be a building icon and a sustainability example. Via reducing environmental impacts and its footprint on the local ecosystem, the project intends to reach certain authoritative objectives, like the ones given by the 2000 Watt-Society. The *smart living lab* is a research centre on future built environment in Fribourg, Switzerland. It accommodates interdisciplinary and inter-institutional research groups and provides infrastructures for experiment on developing innovative concepts and technologies related to inhabitation and work environment.

The purpose of this thesis is to identify the main technical and architectural macro-parameters and their contribution to energy consumption. The latter in the smart living building is calculated in the aspects of both quantity [kWh/m^2] and quality [kg CO_2/kWh]. Global sensitivity analysis (SA) was selected as the method to demonstrate the contribution of certain key design parameters to the building energy consumption and their correlations along with the changes of variables.

The twelve parameters can be classified in five principal groups:

- Active system parameters,
- Internal parameters,
- Transparency parameters,
- Envelopes parameters,
- Shape.

Several energy simulations have been conducted with the variation of each design parameter independently. Finally, due to the elaborated cases, the SA was completed with the identification of the predominant factors on the main energy outputs e.g. primary energy.

Introduzione

Gli edifici costituiscono una parte importante della nostra vita di tutti i giorni, considerando che circa il 90% del nostro tempo è passato indoor. Nonostante questo ruolo fondamentale, l'attenzione all'impatto ambientale che il settore edile comporta sull'ecosistema è diventato rilevante solamente negli ultimi anni, attraverso l'introduzione di sempre più stringenti normative in materia edilizia. I nuovi standard di valutazione energetica ed efficienza prestazionale costituiscono uno step necessario per la riduzione dei consumi del settore delle costruzioni, ritenuto responsabile della metà delle emissioni gas serra totali e dell'utilizzo di circa 2/3 dell'intera energia elettrica generata a livello mondiale.

La crescita della popolazione, l'aumento della domanda di servizi e delle richieste di comfort lasciano intuire che la tendenza è destinata a peggiore nell'immediato futuro, incrementando le conseguenti criticità a livello di utilizzo delle risorse, produzione di rifiuti e ripercussioni ambientali. Le previsioni di possibili scenari futuri evidenziano come la possibilità di garantire la richiesta energetica non possa essere data per scontata, ma che richieda un'attenta valutazione e ristrutturazione della domanda stessa. Risulta chiaro il motivo per cui l'efficienza energetica degli edifici sia un punto cardine delle politiche energetiche di tutti i Paesi. Tra gli Stati che fronteggiano questa problematica vi si ritrova pure la Svizzera, dove è stato stimato che circa il 40% dell'energia consumata venga impiegata per il riscaldamento, la ventilazione e l'approvigionamento elettrico degli edifici.

In questo scenario nasce il progetto dello *smart living lab* in Fribourg, il quale ambisce a diventare un emblema di sostenibilità attraverso la riduzione dell'impatto ambientale ed il raggiungimento di altissimi standard di performance energetica, indicati dalle future richieste della Società 2000 Watt. Lo *smart living lab* sarà un centro di ricerca internazionale, focalizzato sul tema dell'ambiente costruito e del vivere sostenibile, fornendo la possibilità ai vari team ospitati di sviluppare nuove tecnologie e soluzioni innovative legate al settore edilizio.

La tesi proposta, nata da un accordo internazionale fra l'università La Sapienza e l' École Polytechnique Fédérale de Lausanne (EPFL), si pone come obiettivo l'identificazione dei parametri di progettazione che maggiormente influiscono sull'energia utilizzata dallo *smart living lab*, in termini di quantità [kWh/m^2] e qualità [kg CO_2/kWh]. L'individuazione dell'influenza di questi fattori sulla prestazione energetica finale è stata condotta attraverso l'applicazione di un'analisi di sensitività (SA). I parametri considerati nello studio sono rappresentativi dell'aspetto sia tecnico/tecnologico che architettonico dell'edificio, e possono essere suddivisi in cinque principali gruppi:

- Parametri legati ai sistemi attivi di produzione dell'energia,
- Parametri legati alle condizioni di utilizzo interne,
- Parametri legati alle superfici vetrate,
- Parametri legati alla superfici opache interne/esterne,
- Parametri alle dimensioni geometriche.

L'utilizzo di un software per simulazioni termiche in regime dinamico ha permesso di creare un set di casi studio differenti, in cui i parametri sono stati fatti variare in maniera indipendente. Infine, grazie ai risultati ottenuti, è stato possibile concludere la SA e gerarchizzare i principali attori nelle prestazioni energetiche finali.

Summary

Technical and architectural energy strategies for the smart living lab, a sustainable building with reliable environmental objectives

Chapter 1: The smart living lab project; overview on the whole research programme in which this thesis has been developed; definition of the research methodology; definition of goals and implications.

Chapter 2: Analysis of the local environmental context; examination of the Swiss energy context; evaluation of the renewable resources available in the project area.

Chapter 3: Framework of the energy consumption in the Swiss building stock; state of the art on efficiency standards and environmental label; state of the art on very performing buildings in Switzerland; analysis of the case studies.

Chapter 4: Sensitivity analysis; why it has been used in this thesis; strengths and weaknesses of this methodology; explanation of how it has been applied to the smart living building and with which expected outputs/results.

Chapter 5: Design parameters and inputs used to define the energy behavior of the building; motivation of these choices and their range of variation; presentation of the set of simulations obtained (78 cases).

Chapter 6: Software used to run the simulations (Lesosai); results in terms of energy demand, final energy, primary energy and CO_2 emissions for each case; discussion of the results and main findings; evaluation of the results given by the sensitivity analysis.

Conclusions: Summary of the results; strength of the outcomes; individuation of criticisms and opportunities for future development.

Annexes: Input matrix; results simulations; technical report for each simulation.

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1 Research framework

The smart living lab project was born from the opportunity given by the final closing of the Cardinal brewery (Fribourg – CH) in 2011. The post industrial site has been detected as a potential transformation area from the Canton and the City, where a possible new innovation quarter, called blueFACTORY, could take place. The idea is to develop a technology and innovation park to achieve outstanding performances to guide the construction sector toward a new concept of sustainability. The district will be composed by several technological platform, including the smart living lab: a joint project between EPFL (École Polytechnique Fédérale de Lausanne), EIA-FR (Haute école d'ingénierie et d'architecture de Fribourg) and UNIFR (Universitè de Fribourg). The goal is to create an international centre of research in the built environment of the future, which could be a living and working space ahead of its time and an interdisciplinary centre of excellence pulling to innovation and new tech.

The project aims to achieve extraordinary environmental target values, guaranteeing the construction of a building that could be performant now and in the future, according to the latest requirements set up by SIA (Swiss society of engineers and architects) for the 2050 [1].

1.1 The 2000 Watt-Society targets

Global warming is a reality that the world is facing nowadays, trying to limit the effects and deal with the principal causes that are leading to climate changes. The consequences of the climatic variations are expected to be important and with a great impact on the whole Earth ecosystem [2]. It is worldwide recognized that one of the major contributor to the increase of temperature and the related impact on climate is the CO_2 emission due to human activity. The building sector is one of the most impactive. In 2000 it has been estimated that, in Europe, it accounts for more than 40% of total EU CO_2 emissions, 45% of the whole energy used, almost 50% of the resources removed from nature and 50% of the annual waste production [3]. Therefore it is clear that there is a need of invert the actual trend to guarantee a sustainable future. Ceasing the tendency is possible, considering that more than one quarter of the 2050s building stock is still to be built [4] and 60% of greenhouse gas (GHG) emissions can be cut off only using current best technologies [5]. In the Swiss scale SIA has released a concept, called 2000 Watt-Society, which could be seen as a possible solution. According to this vision the energy consumption per person in a society has to be limited to 2000 W, of which only 500 W should come from fossil fuels by 2150. Moreover it limits the yearly emissions of CO_2 per inhabitants to less than one ton. In order to help achieving the goal, an intermediate step has been set in 2050, when the rate of CO_2 per person per year should be less than 2 tons [6].

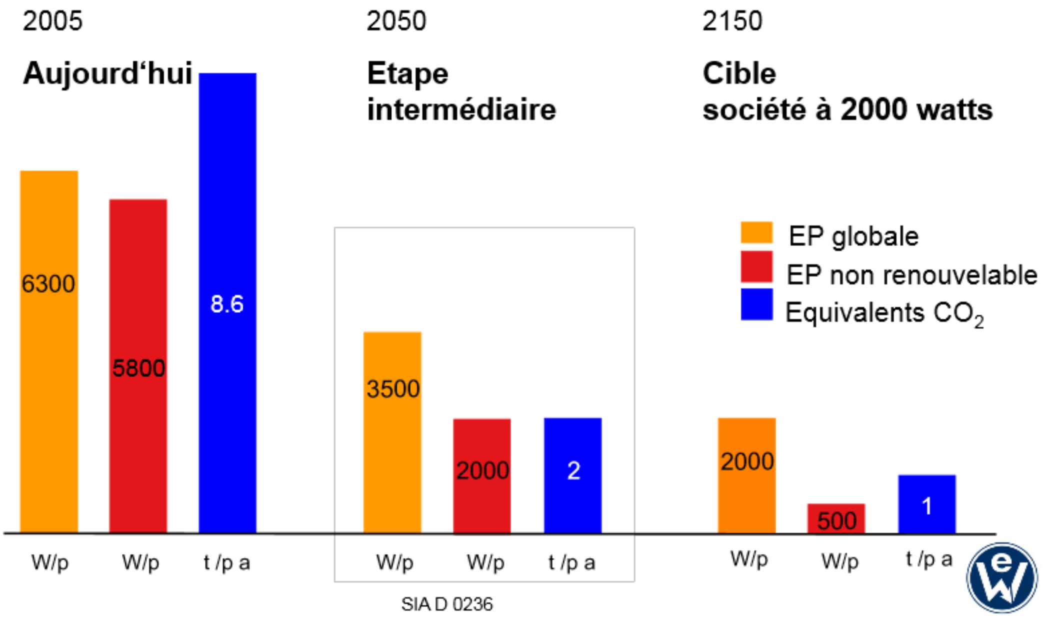


Figure 1: 2000-Watt society goals

The SIA vision is Omni-comprehensive, including all the aspects of human life inside the boundaries defined. The most influent is of course the construction sector, but the concept is extended to mobility, food and transportation, aiming to change completely the way of living of Swiss inhabitants.

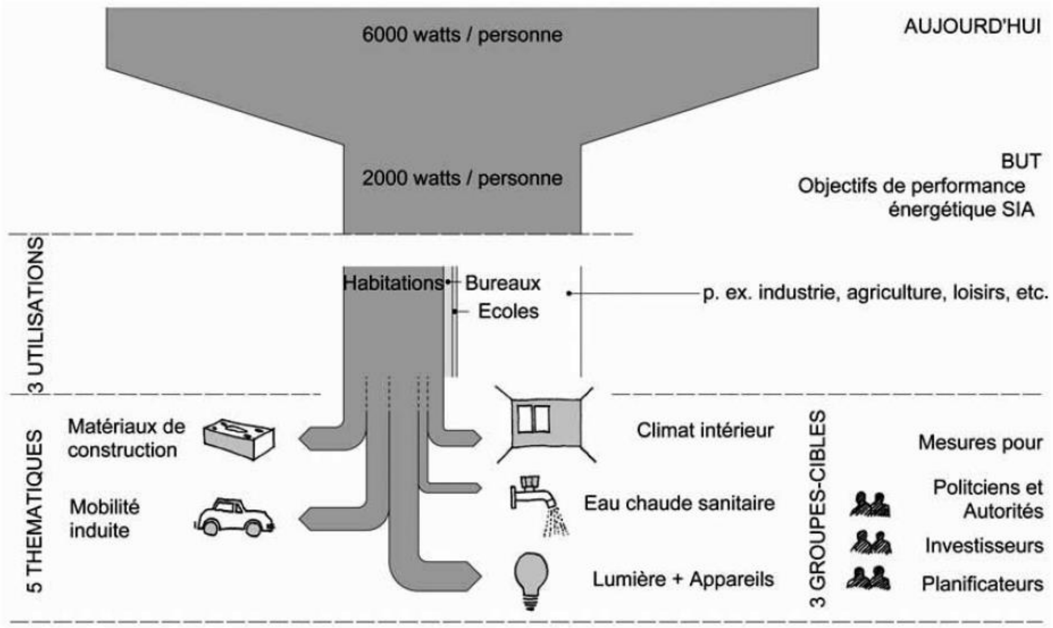


Figure 2: 2000-Watt society goals with regard to the city's residential, school, and office buildings (SIA – 2008)

The concept allows to keep a double approach to the problem, fixing threshold for both the energy and the emissions acceptable of each person. However, it is not easy to reduce simultaneously the two factors: studies about the environmental and energetic behavior of Swiss citizens show that up to 10% of the inhabitants sample considered is already living consuming less than 2000 W, however, none goes beyond the 1 ton of GHG emission. [7]

For the smart living lab research the 2000 Watt-Society concept has been used to define the target values for each field of the project, aiming to build a new quarter that will be an outstanding example of excellence and efficiency for now and the future.

1.2 Research boundaries

Aiming to apply the 2000 Watt-Society goals to the smart living lab research, the complete framework is not restricted to the buildings scale, but it is enlarged to the whole system around the future district. The project's goal is to define a new way of living and designing, organizing the quarter's life according to an innovative perspective, driven by the environmental impacts of human's activities. Obviously more than one aspect has been studied into the program: building, urban area, mobility and food.

1.2.1 The urban scale

As a matter of fact the project of blueFACTORY is ambitious and innovative, thus constructing a new quarter has an effect not only at the whole urban ecosystem and but also at the micro-scale. An example are the results of a recent study conducted on a sample of household in Switzerland: the impacts of food and mobility related to buildings represent up to 90% of the final value per inhabitants, showing the extent of interactions between the constructions sector on a scale bigger than the buildings one. Thus, the blueFACTORY development needs to understand and consider also the related influence on the macro-level, analyzing the possible effects and variations which will bring on the urban scale of the city of Fribourg. The definitive masterplan, in Figure 3, has been chosen among different projects thanks to a public competition. The winner was developed by brockmann+stierlin studio and offer a great boundary of intervention on the building that will represent the smart living lab.

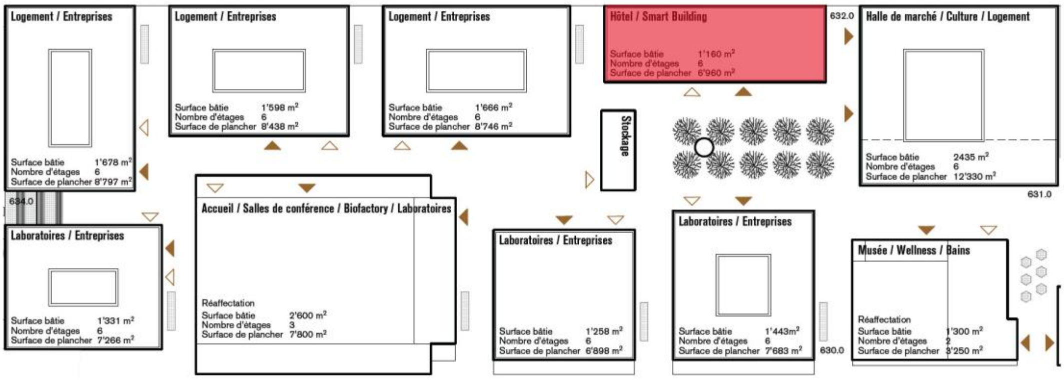


Figure 3: Masterplan blueFACTORY

The interactions between each building and the quarter with the city is essential to determine if the district is well integrated into the urban context and if it has, and in which way, influence on a bigger scale. It is clear that the green spaces and the facilities which are offered will change directly the mobility and the related impact on the urban level, making impossible to ignore this level aiming to a complete achievement of the goals of 2000 Watt-Society. A deeper analysis on the urban environment and the transformation that the district will bring is an integrated part of the research, completing the framework on the construction and design part of the enquiry.

On the other hand, also the building scale is investigated in order to assure the achievement of the goals proposed. The smart living lab will be the first and the most innovative construction to be built on the site, opening the outright way to 2000 Watt-Society. So, the building is going to be in the forefront of the current practices, and it will be an experimental center for future research teams.

1.2.2 The building scale

The smart living lab will be an outstanding building, constructed years ahead of its time: built in 2015 for meeting requirements and answering to the context of 2050. For this reason it has to be designed to allow integration of future innovation, on technical and technological perspectives, according to different external conditions or internal requirements due to changes in context and users. In order to do that, the methodology used to develop the facility ought to consider and integrate adaptability and flexible capacity.

Components must be easy to renovate or replace, without signing a limit to the evolution of the whole structure. High energetic and environmental performance are required now and in the future: the building will be in the forefront of the current practice.

Smart living lab will host:

- Offices: 86 workstation / 950 m^2, divided for the research partners,
- Experimental hall: 600 m^2, for highly innovative physical experiments,
- Educational spaces: 150 m^2, for meeting, training and seminar rooms,
- Housing: 1000 m^2, different typologies of users as students, young families or elderly.

All the spaces will be also with an experimental side to give to the research teams the opportunity of several different investigation about architectural solutions, users behavior, comfort and energy consumptions. The construction will be monitored and tested, in order to have feedback on the design choices and assumptions.

The research program is based on the hypothesis that it is already possible to design a building with a very high environmental performances, a high degree of usability of the spaces and the use of the local economic potential which could address the global climate change predicted for 2050. These features affects the design itself of the smart living lab and will guide into the choice of the strategies to follow to achieve the goal.

- Addressing the global change predicted for 2050:

It is possible to define the environmental targets for 2050 and the consequent energy savings required to the building; therefore it is possible to identify the major contributor in terms of building's components to achieve the results needed and optimize the design starting from that point. A scientific concept will be proposed in order to reduce these contributors according to the objectives.

- Very high environmental performances:

The smart living lab aims to achieve good environmental performances without any major cross-media pollution. Besides the GHG targets, in fact, it will be necessary to consider other indicators to be sure of achieving the best results with the lowest global impacts.

- High degree of usability:

The usability of a building is strictly related to the users actions and perceptions of a space. Moreover, it is clear that high levels of usability enhance the occupants psychological comfort.

- Use of local economic potential:

An important part of the design process of the smart living lab is represented by the technological transfer of technical solutions and methodologies. For this reason it is important to use available technologies that could deploy the local potential, implemented with new economic models.

1.3 The smart living lab objectives

The blueFACTORY will be a new quarter and a symbol of efficiency for the future and it will sign a new way of living. Focusing on the building level, instead, the smart living lab will be an icon and an example of sustainability, reducing the whole environmental impacts and the footprint on the ecosystem. Furthermore, it is clear that the research project deals with finding possible optimal solutions for minimizing the environmental impacts, achieving the best performance regarding to the target values fixed on the LCA point of view. In this context all the design choices will be weighted by the final results, trying to find the right balance between each components and its impacts. Thus, the research program aims to integrate all the building's aspects and features into a bigger framework, in which the final goal is to define the possible solutions for achieving the 2000 Watt-society targets, fostering intermutually connections.

In order to investigate the main aspects of the smart living lab and assure the achievement of the goals, the research has been split into different performance indicators, identifying the main fields of the project. For the purpose of creating a guide of the study that can give the bigger picture but, at the same time, the single factors, it has been used an interpretation of the Kaya equation, applied to the smart living lab [8] [9]. This formula is not exhaustive and it does not consider the qualitative aspects of the design, however it is useful to clarify the major performance contributors inside the project.

$$CO_2 = \frac{CO_2}{OE_n} \times \frac{OE_n}{EE} \times \frac{EE}{B_{vol}} \times \frac{B_{vol}}{pop} \times pop$$

Where:

CO_2 is the final smart living lab emissions, defined by the target value of 2000 Watt-Society;

pop is the population of the smart living lab;

OE_n are the operating energy needs;

EE is the embodied energy spent for the construction;

B_{vol} is the built volume of the building.

It is clear that this equation can fit different solutions and it could be a powerful tool to guide the research inside the exploration of each field.

- $\frac{CO_2}{OEn} \times \frac{OEn}{EE}$

These are the factors that represents the energy strategies of the building. It is composed by two different members, one is linked to the active energy system and the other to the passive and bioclimatic strategies. The first part is equal to the carbon intensity used for supplying energy to the building and it can be minimized through the use of system with high efficiency and low carbon content. The second is equal to the energy needs regarding to the embodied energy which is being spent during the construction phase and it can be minimized implementing performant materials with low grey energy. Apparently, to create an energy concept that could lead to the final target values defined, it is necessary to optimize the two parts in order to create the perfect balance between them, searching for the optimum equilibrium in terms of environmental impacts between energy which is being spent during the construction and during the operation.

- $\frac{Bvol}{POP}$

This is the indicator related to the field of flexibility of the building, and it represents the relationship between the volume and the users. In order to minimize this factor it is important to create adequate strategies for optimizing the spaces and the usage of the building itself.

- $\frac{EE}{Bvol}$

This factor is representing the energy intensity linked to the whole building implementation in regard of the built volume, to optimize that it is important to minimize the whole environmental impacts regarding the building's shape. The research field linked is the life cycle assessment, which assess the indicators and lead the other fields.

1.3.1 Flexibility

This field is strictly linked to users, their needs and habits. The main challenge of the domain is to guarantee a high degree of usability of the space, enhancing the psychological comfort of the users. The first step is to identify the requirements of the future population of the smart living lab through a sociological study and a targeted survey in the three institutions involved (UniFr, EIA, EPFL). This inquiry allows to characterize the inhabitants of the building from both a qualitative and a quantitative point of view, regarding to their preference and their practices on spaces, mobility and food. According to the analysis of the results it is possible to improve the usability notion and strategies, according to the ISO 9241-11, which defines:

- Usability*: is the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use.*
- Effectiveness*: accuracy and completeness with which users achieve specified goals.*
- Efficiency*: resources expended in relation to the accuracy and completeness with which users achieve goals.*
- Satisfaction*: freedom from discomfort, and positive attitudes towards the use of the product.*
- Context of use: *users, tasks, equipment (hardware, software and materials), and physical and social environments in which a product is used.*
- Work system*: system, consisting of users, equipment, tasks and a physical and social environment, for the purpose of achieving particular goals.*

Based on this concept it is possible to optimize the built space and enhance the design in order to improve the usability but minimize the impacts related to the construction. A second challenge to face is the time level: the potential of a building can be expressed also in adaptability to different uses and needs, according to the life cycle. The features and characteristic must be maintained in time, thanks to an innate capacity of the building to adapt itself to different or progressive use. This concept is strictly related to the flexibility of the design and it guarantees the capacity to accommodate itself to particular uses and changes.

1.3.2 Life cycle analysis

This field is responsible for defining the final target values for environmental impacts, regarding the 2000 Watt-Society goals, and monitored each other domain in the larger scale, in order to assure the achievement of the results. Performances are evaluated in relation to two indicators: CO_2 emissions and energy consumption. However, other indicators will be used to ensure comprehensiveness of the impacts: climate change, ecotoxicity, ionizing radiation and land use. Energy and GHG emissions quotas are allocated to the smart living lab requirements in order to match the goals of the project. The final target value is divided into the three different domains and the final results must be verified according to a multi-criteria approach to avoid pollution transfer.

In order to guide the program on the whole smart living lab lifecycle stages (design, construction, use and end of use), sensibility analysis will be done allowing to highlight the most sensitive parameters on the environmental performance.

1.3.3 Energy concept

This field is divided into two sub categories, representative of the bioclimatic strategies plus the passive strategies and the active system. Applied to the building these two are the energy saving measures and the supply systems. The passive strategies are strictly related to the context and the envelope's design and it has, consequently, a strong influence on the grey energy spent for the implementation of technologies and technical solutions inside the building. The aim of this part is to reduce this embodied energy maximizing the efficiency and optimizing the thermal and comfort of users. Considering that the building's skin is the filter between the internal and the external context, the first step is to characterize them and set up a bioclimatic strategy that must be verified and optimized through thermal dynamic simulations allowing to emphasize the most influential physical parameters having an effect on comfort and operating energy needs within the smart living lab. The effectiveness of the solution proposed is tested and validated on a life cycle point of view, balancing the energy savings on the energy spent for implementing materials inside the envelope. This poise allows to implement only the most effective components, limiting the embodied energy but preserving the thermal performances required, how it is shown in Figure 4.

Figure 4: Operating energy vs embodied energy

Once that the first draft of the buildings physics is defined, it is possible to implement the energy concept with the active systems. In order to limit the carbon emissions related to this part, high energy conversion efficiency and low-carbon sources must be implemented. Determining the available renewable resource and qualifying them to meet the building's requirements is the first step to assess the active strategy for smart living lab. These needs and resources will have to be overlaid and to be able to verify the correlation in time and assure a maximum self-sufficiency. The whole energy concept must be detailed in order to offer enough energy conversion efficiency to meet the needs using the limited resources available. The deployment of renewable energy is necessary considering that the carbon content of the Swiss electrical grid is constantly changing and achieving a share of 50% of RE in 2050 (which it will increase up to 75% in 2150) as recommended by the 2000 Watt-Society concept, is affected and conditioned by the capacity of the supply system to manage the peak loads. Active system and passive strategies, together, form the energy concept of the building and therefore cannot be analyzed separately.

1.3.4 Research fields

Referring to the reinterpretation of the Kaya equation, it is possible to understand how the different field of research interact between each other and how they are connected to the whole building performance. Splitting the project into different domain it is necessary to assure a deep and precise investigation, assuring the exploration of all the major possibilities to achieve the goal.

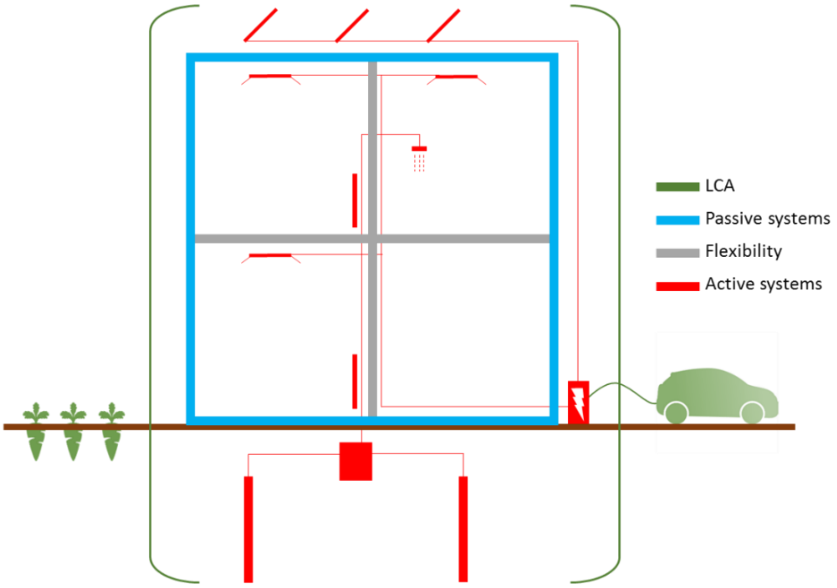


Figure 5: Technical diagram of research field programs

1.4 Aim of the study

Inside the smart living lab research framework this thesis is placed into the definition of the first draft of the energy systems and it has its own goal and role. The thesis aims to set a methodology for optimizing the energy concept and finding a way to inquiry deeper into the most effective components of the building on the final energy results (in terms of energy demand and primary energy). In order to balance the smart living lab behavior on a whole life cycle point of view, in fact, it is important to understand which level it is possible to reach on the final target value with the current practices, since that the building will be constructed in 2020.

The main goal of this work can be synthesized in the Figure 6, where it is shown the way that must be followed to reach the 2000 Watt-society objectives in terms of kg CO_2/m^2 (and so easily kg CO_2/person). The purpose of the thesis is to identify the main contributors to the reduction of the values in two axis, the axis x defines the energy demand of the building [kWh/m^2], and the axis y represents the quality of the energy used [kg CO_2/kWh].

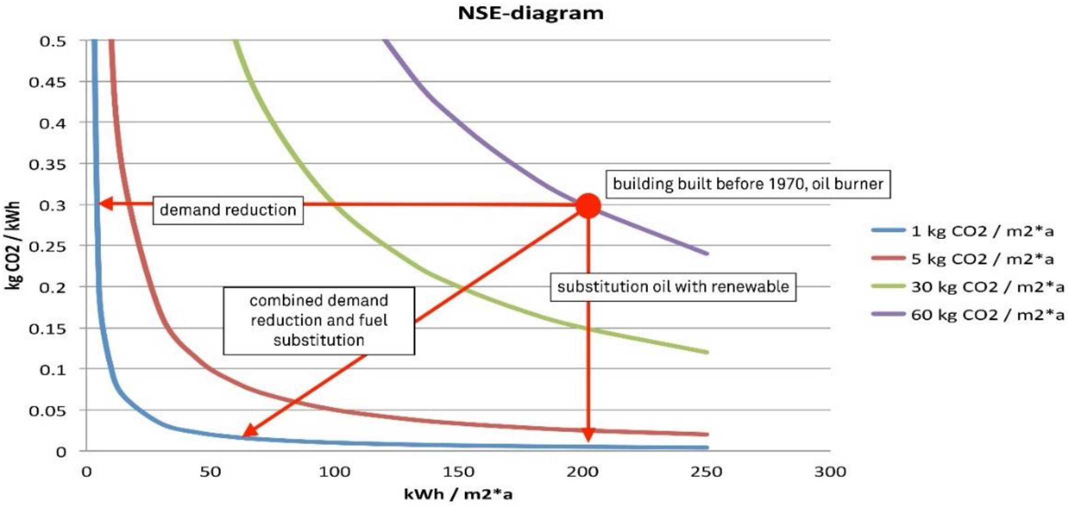


Figure 6: NS-E Diagram: current state and path to zero emission buildings [10]

This work will lead to a better understanding of the major technical and architectural macro-parameters, inside the smart living lab building, and how to design and define them to address the building's requirements. An overview of the main challenges and technologies that could be used for designing the most efficient building is addressed and it deals with finding the optimum solution among the best practice of the most performant constructions.

The study is structured as a step by step analysis, which starts from a general point of view and the characterization of the research objectives and arrives to the clustering of different projects based on the results of a sensitivity analysis and of the thermal simulations conducted.

The main phases are:

- Definition of the external context:

  The first step is to understand which is the environmental context of smart living lab. The energy concept is based on passive and active strategies, which rely and respond to external stimuli and resources; moreover it is important to quantify and understanding the potential related to the site and the climate. The analysis touches all the aspects that are linked directly to the building's energy performances.

  The feature that has been studied more deeply is the one related to the renewable sources available in the area. So the potential of sun, wind, water, geothermal and biomass energy has been investigated.
- Identification of the available technologies on case studies:

  In order to set up an energy concept that could be applied in 2020 it is important to understand clearly which are the main possibilities available. The investigation on the most innovative buildings built in Switzerland, according to the latest energy performance label is essential to identify which solutions could be useful for smart living lab and how each of them is helpful to achieve the final goal.
- Identification of the methodology to be used:

  The aim of the thesis is to define a methodology that can be used for the optimization, in terms of efficiency and CO_2 emissions, of the energy concept. For this reason the analysis of the sensibility of each factor on the final target value is the pivot point on which the concept is studied. In this phase the main methodologies for sensitivity analysis are studied and the most suitable for the case of smart living lab is identified.
- Application of the methodology:

  The core of the thesis is the application of the methodology chosen; starting from the definition of the design parameters (windows ratio, shape of the building, …) and technical solutions (HVAC system, PV panels, ….) that must be investigated and arriving to the real analysis of the relative influence of each of them to the main energy indicators of the building (energy used, CO_2 emissions, …).

- Analysis of the results:
  Finally, the results are analyzed in order to understand which correlations and which clusters of projects can achieve the target value or can be pointed out as best solutions and basis for an optimization process.

2 Environmental context

2.1 Swiss energy situation

Environmental context is defined as the external conditions or surroundings in which the building acts and which tend to influence its development and behaviour. Defining environmental context means to understand the conditions of the site and the resources available in the nearby areas. For this reason, it is useful to make a global overview on the Swiss energy context, so as to clarify the general context.First of all, it is proper to say that energy use in Switzerland produces the lowest CO_2 emissions per unit of Gross Domestic Product in IEA member countries, matched only by Sweden. Switzerland was also one of the lowest CO_2 emissions per capita countries in the IEA members in 2010. The carbon intensity of energy supply is so low because renewable and nuclear energy have a high share in total primary energy supply (TPES) [11].

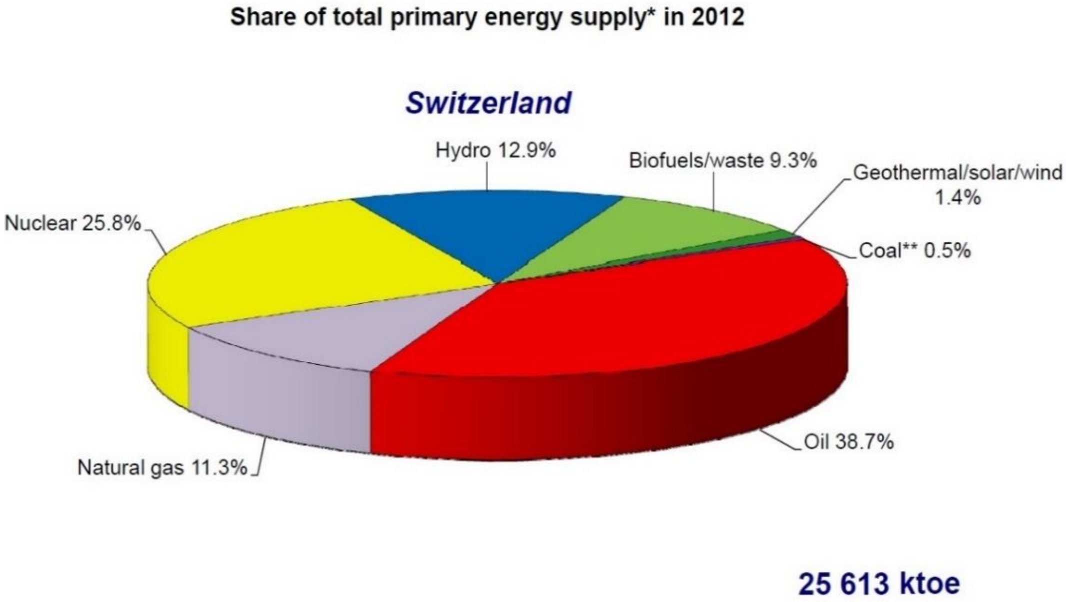


Figure 7: Share of total energy supply in 2012

However, the situation is going to be changed in the next few years due to the decision taken in 2011 (after the accident at the Fukushima Daiichi nuclear power plant) that new nuclear power plants would not be built and the existing ones would be turned off gradually [12]. Since nuclear energy provides 40% of Switzerland's electricity generation, the decision to phase it out is very significant and has made it necessary to redefine the country's energy policy. Simultaneously, the government (Federal Council) started to promote initiatives to reduce by a fifth of its greenhouse gas emissions by 2020 with domestic measures only. This radical change resulted in the definition of the new energy strategy for 2050, which can be summarized in the following priorities:

- Reducing energy consumption,
- Broadening electricity supply,
- Maintaining electricity imports,
- Expanding electricity transmission grid,
- Strengthening energy research,
- Setting examples for confederation, cantons, cities and communes,
- Setting Beacon projects guidance,
- Encouraging international co-operation.

In the short term, i.e. right now, the responds to the increase of the energy demands, the gas import and especially the use of renewable energy are going to increase [13]. This will bring a change in the energy mix, with a decrease of CO_2 content per kWh. In the Figure 8 it is shown the trend of the energy production of the last 50 years that in the next 20 years is going to be totally different.

Today the electricity generated from renewable energy sources has already amounted to 59% of the total, including hydropower, biofuels and wastes that cover alone 95% of the renewables supply.

The Table 1 states the actual production of electricity in Switzerland and in the Canton of Fribourg on all the different sources and the different CO_2 content per kWh.

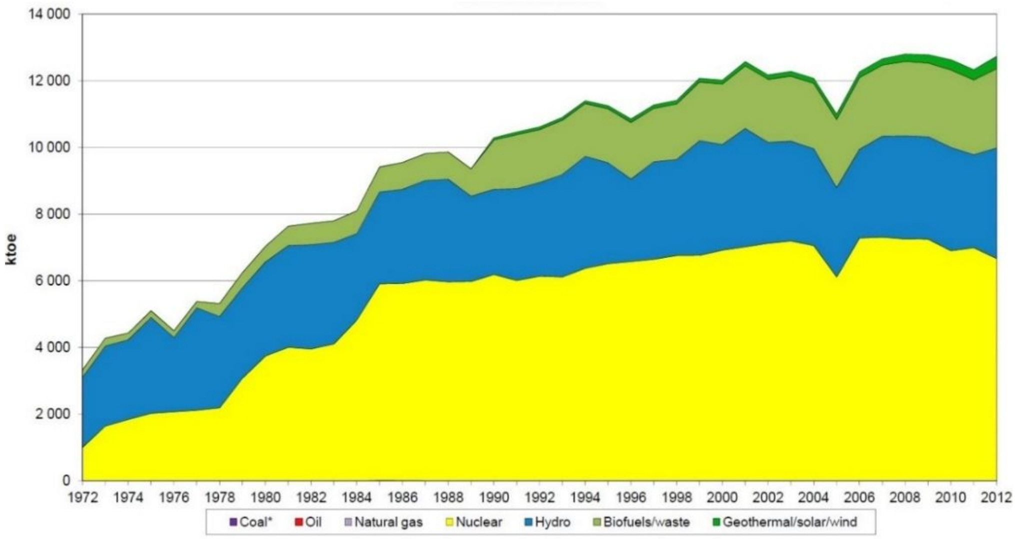


Figure 8: Energy production

	Switzerland		**Fribourg**		
	Production Electricity *[GWh]*	***Production Heat*** *[GWh]*	***Production*** *[GWh]*	***Cost of kWh*** *[cts/kWh]*	***Quantity of CO2*** *[g Co2/kWh]*
Oil	53	127	0	8	979.2
Gas	923	1044	0	8 - 12	468
Biofuels	527	437	1500 (potential)	16 - 24	178.2
Waste	2209	3079			7.3
Nuclear	25441	380	0	4 - 5	23.6
Hydro	40305	0	647.2	6 - 9	12.6
Geothermal	0	2481	205.8	11 - 15	55.1
Solar PV	320	0	16.5	80 - 100	95.1
Solar thermal	0	515	-	16 - 24	41.8
Wind	88	0	0	25 - 29	26.4

Table 1: Sources of energy in Switzerland [11][13][14][15]

2.2 Site analysis

Site analysis aims to define the constraints and the weaknesses, as well as opportunities and strengths of the area. Since the blueFACTORY area was an object of a public urban design competition, several studies were conducted on it already. The documents delivered for the competition provide possibility of verifying and completing the information of the site according to the specific cantonal and more general regulations [16]. These documents offer access of checking the plans and official cartography of the actual situation of the site relevantly. In the Table 2 and Table 3, the main issues of the site analysed, the value associated to each parameter and the references were reported.

Location	blueFACTORY Site – Fribourg CH	
Surface	53 000 m^2	*Guichet Cartographique du Canton de Fribourg*
Altitudes	Average: 630 m Maximum: 665 m Minimum: 617 m	*Google Earth*

Table 2: Site context

Sun availability	Maximum: 1702 h in 2013- average 1750 h Minimum: 203 h in winter 2011 – average 250 h	*Database prevsion-meteo.ch*
Temperature	Maximum: 32.2 °C in 2013 Minimum: -18.9 °C in 2012	*Database prevsion-meteo.ch*
Precipitation	Average: 683 mm Last year: 834 mm in 2014	*Database prevsion-meteo.ch*
Wind	No main direction Average speed: 11.5 km/h Maximum speed: 113 km/h	*Database prevsion-meteo.ch*

Table 3: General climatic context

2.3 Resources analysis

The aim of this analysis is to present all energy resources available in the blueFACTORY area, their exploitability and in what manner is possible to do it.

2.3.1 Sun

Switzerland has a global horizontal irradiation (GHI) mean value between 1100 kWh/m^2 and 1300 kWh/m^2. This value is relatively good when compared to the one of Germany, which is one of the world leaders in solar energy production. In the effect, Switzerland's solar irradiation is even higher than that of Germany. More specifically, Figure 9, the Canton of Fribourg receives approximately 1250 kWh/m² of GHI [17].

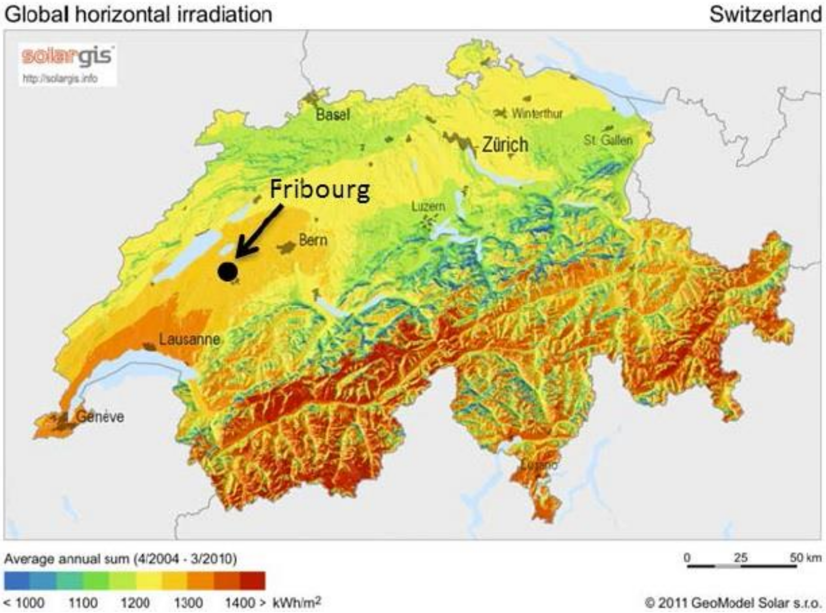


Figure 9: Switzerland global horizontal irradiation

In spite of availability, the use of solar power can be elaborated resulted from the great difference of GHI during the year. As it is shown in the Figure 10, about 50% of the radiation is concentrated in only three months.

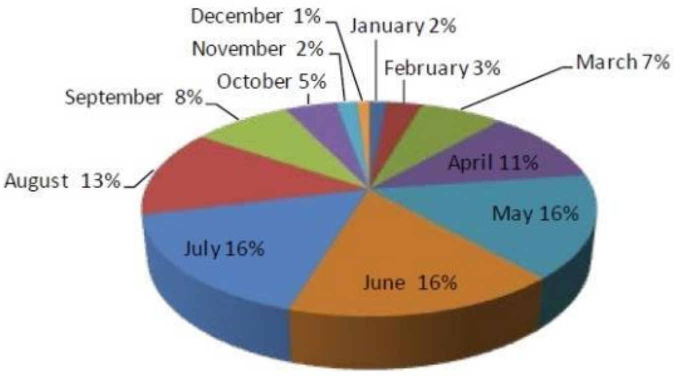


Figure 10: Distribution of the solar radiation during the year 2014

This obviously affects the design of solar systems. For instance, the requirements for lighting and appliances (the base load during the year) have been quantified for the smart living lab according to SIA norms [18]. The requirements of a normal working day in are shown as the grey line in the Figure 11, and compared to the power available from the sun in two different months. The latter has been calculated by PVGIS [19], using a catchment area of 813 m2 (the surface of the roof in the smallest architectural draft), a tilt for the panels of 0° and an efficiency of 16%.

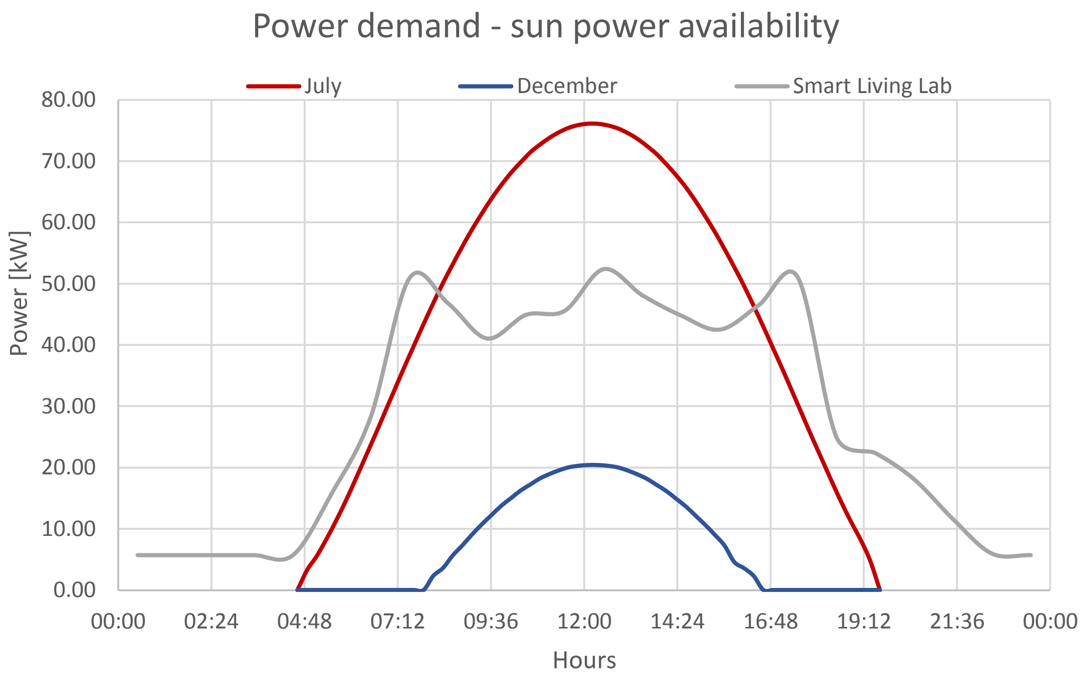


Figure 11: Predicted power demand for the smart living lab

In some months, e.g. July, it is possible to cover most electricity demands by a photovoltaic system. In other months, e.g. December, the radiation is insufficient for the requirements.

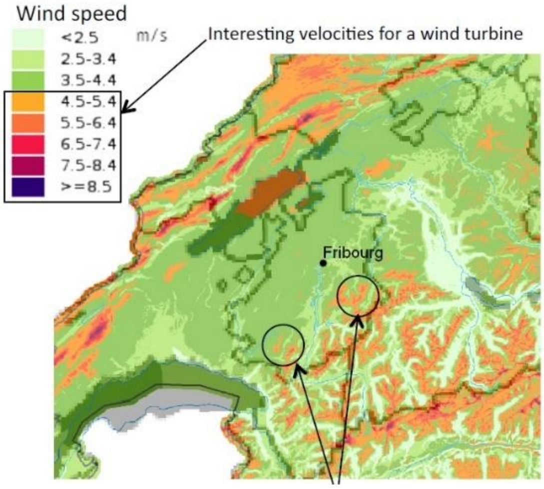
2.3.2 Wind

Shown in the previous paragraph, the energy production from wind in the canton of Fribourg is unavailable. In order to have some improvement in this field the government released the “Concept éolien Fribourgeois” in 2008 [20]. In this report the potential of wind energy for the whole canton is estimated. Some criteria of wind turbines implementation sites selection are given as well. The most important ones are:

- Minimal wind speed: 4.5m/s;
- Minimal distance of the wind turbines to the habitations: 300m;

- Potential energy production of minimum 10 GWh/year for the site, which implies that the site should have the capacity to receive several turbines.

As it is shown in the Figure 12 the wind speed in Fribourg is quite low (average 3.1 m/s [21]), even for Switzerland. What is more, the lack of a wind preferential direction is another issue shown in the figure below.



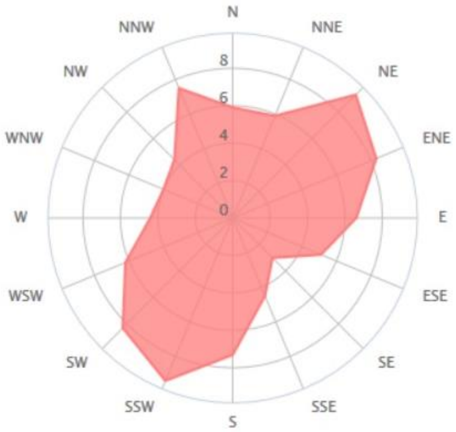


Figure 12: Mean wind speed at 50m above ground in Switzerland

Figure 13: Wind direction distribution, percentage on a whole year

The combination of this two factors result to the conclusion that the implementation of a standard machine is not workable. The only solution that can be used is providing small wind turbines and using the domestic wind. Therefore, it is still difficult for this type of installation to become economically viable and energetically reliable. It might be interesting to use this kind of installation just for demonstration or study purposes.

2.3.3 Water

Hydroelectric power is a very abundant resource but has been fully utilized in Switzerland. According to the State of Fribourg [12], "95% of economically practicable hydroelectric power plant are already implemented. In other words, 91% of the hydraulic power of the canton is already been exploited." This means there is very few potential of this renewable resource; and it is difficult to install another hydraulic power plant or little hydraulic solutions in the Canton of Fribourg.

2.3.4 Biomass

Biomass is considered as all organic materials those are directly or indirectly produced through photosynthesis. They can be simply divided into two main groups: dry woody and moist biomass. The first is used mostly to produce heat (3.25% in Swiss consumption). The second is used to produce biogas (only the 0.04% in Swiss consumption) [22]. The use of the first group is a viable solution for the smart living lab. In fact, although it is impossible to produce it on the site because of the lack of ideal space and climatic conditions, it seems as an attractive alternative. Thanks to the site in proximity to the railway station, it would be easy to obtain supplies of new biomass; while storage inconvenience is usually a main constrain in other cases. This convenience of supplying provide possibility to couple one boiler with a steam turbine to produce not only heat but also electricity.

2.3.5 Release waste

Another big resource for the smart living lab building is industrial wastes produced by nearby manufacture areas: Chocolate factory Villars, for example, is estimated wasting hundreds of kWh heat every year during chocolate production [23]. It would be advisable to reuse this free power not only for the smart living lab building but also for the buildings in a bigger scale, which in the other words, is to create a district heating system among different buildings in the blueFACTORY.

2.3.6 Geothermal

Being shown in the table, geothermal energy, both deep and low enthalpy one, is not well used in Switzerland. There are only a few cases related to this energy, although a strong desire to increase the use of this energy has been presented by the nation. A preliminary study on the energy potential of a deep geothermal project in Fribourg is requested by the Energy Service of the Cannon of Fribourg and will be conducted by the SwissTerraPower consortium [24].

Regarding the BlueFACTORY, three scenarios are currently being simulated in the deep geothermal project. Certain preliminary estimation were calculated:

1. Drilling absolute depth of 3'000m would produce approximately 31 GWh/year thermic energy;
2. Drilling absolute depth of 3'800m would produce approximately 8.6 GWh/year electrical and 23 GWh/year thermic;
3. Drilling absolute depth of 4'600m would produce approximately 10 GWh/year electrical and 25 GWh/year thermic.

These show that scenario 2 and 3 could cover widely electricity needs of the site, while very different from scenario 1 in which electricity generation is not provided. Moreover, if a deep geothermal project was realized, the thermal energy produced would be around an order of magnitude greater than the needs of the site. Hence, the potential geothermal project should be considered not only for the blueFACTORY area, but also for a larger scale, i.e. the city of Fribourg.
However, taking the difficulty and the remoteness of the geothermal energy into account, the energy concept of the smart living lab building should not be based on one deep geothermal project only. Nontheless, the heat pump implantation (CAP) is feasible with probes between 150m and 200m on the site.

2.4 Main outcomes

The summary table below on the resource analysis presents that the available energy resources for the blueFACTORY include solar energy, low depth geothermal power and some waste heat or urban wastes/biomass in the site; while the unavailable ones are wind-energy and hydro-energy.

Sun	High GHI values (average annual sum 1250 kWh/m^2), but very various between summer and winter	*SOLARGIS*
Hydro	Only 9% of the potential is still available	*Etat de Fribourg*
Future district heating	New grid development between Granges Paccot, Fribourg and Agy 1700 MWh/a	*Solar Decathlon Energy Concept*
Geothermic	8.6 GWh/y electrical, 23 GWh/y thermal of potential for the BlueFactory	*The SwissTerraPower consortium*
Wind	Low potential of wind speed and no main direction to be exploited	*windfinder*
Industrial waste	Villars industrial site: heat availability	*Concept energetique Blue Factory, Energie Concept, rapport 29/11/2013*

Table 4: Resource at site

In regard to the geometric size, the potential energy production by the smart living lab itself is demonstrated in the Table 5.

Photovoltaic	152 MWh/y per horizontal 813 m^2	PVGIS
Solar thermal	72 MWh/y per surface 160 m^2	*Appel A concept énergétique Blue Factory, Groupe e, rapport 2013*
Geothermic	232 MWh/y per probe's length: 1500 m SH + 800 m DHW 63 MWh/y geocooling	*Appel A concept énergétique Blue Factory, Groupe e, rapport 2013*

Table 5: Resources at building's level

Consequently, the main finding of this site analysis is that there is no big constraint related to the site for the energy concept. All results are symbolically summarized in the Figure 14.

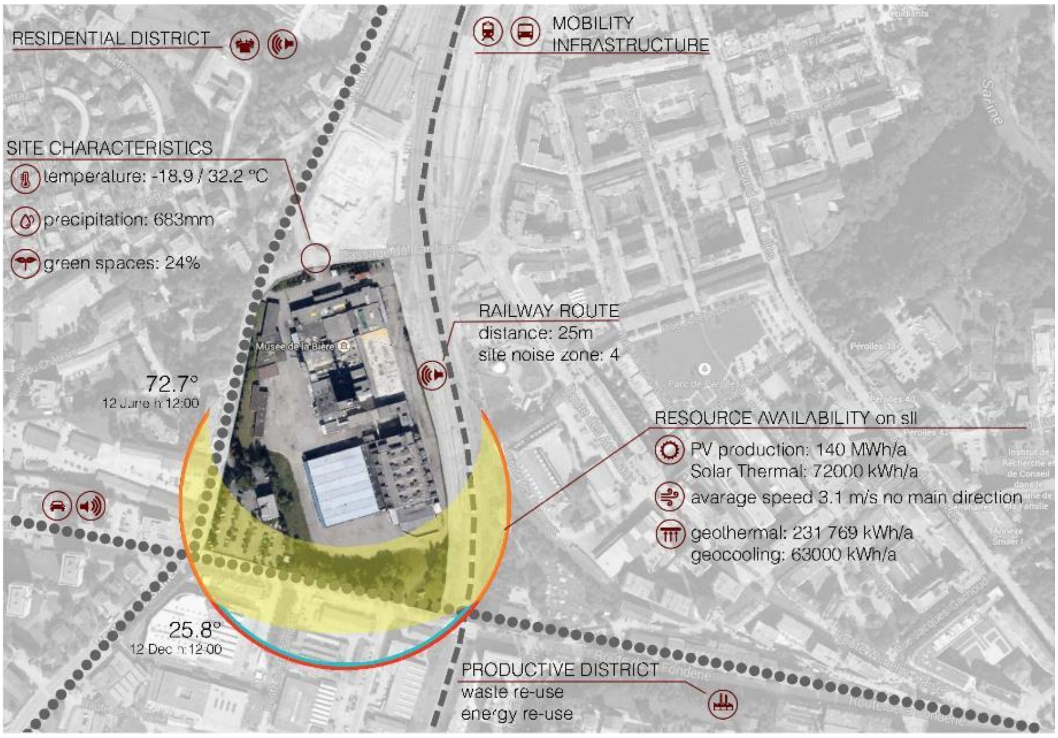


Figure 14: The main features deducted from the analysis of the context

3 State of the art

3.1 Switzerland building stock

3.1.1 Energy demand

In European Union, building sector is responsible for 40% of the energy consumption, followed by transport (32%), industry (24%) and agriculture (2%); the energy use is currently responsible for a substantial share of greenhouse gases emissions, for about 36% [25].

This European trend is completely followed also in Switzerland, where it has been estimated that almost 40% of Swiss energy consumption is used for heating, ventilation and lighting in buildings. As shown in the Table 6, mainly 70% of residential energy is used for space heating [22].

Purpose	***Residential***	***Office and Service***	***Industry***	***Transport***	***Sum***	***Sum %***
Space Heating	47.9	19.1	5.7	0.0	72.6	33.1
Hot water	8.8	3.1	0.9	0.0	12.8	5.8
Heat process	1.6	0.6	24.5	0.0	26.7	12.2
Lighting	1.5	4.1	1.8	0.0	7.4	3.4
Cooling and vent	1.2	4.6	0.3	0.0	6.1	2.8
Entertainment	1.4	1.1	0.2	0.0	2.8	1.3
Mechanical process	4.1	4.8	10.8	0.0	19.7	8.9
Transportation	0.0	0.0	0.0	66.6	66.6	30.3
Other	2.2	0.9	1.9	0.0	5.0	2.3
Total [TWh]	68.7	38.3	46.2	66.6	219.8	100
Total %	31.2	17.4	21.0	30.3	100	

Table 6: Energy consumption in Switzerland in 2012, (Unit: TWh)

Accordingly, the government has developed a series of regulations designed to reduce energy consumption in buildings. Within this context, in the last years, several measures are in place to promote efficiency and strong requirements for new and existing buildings have been carried out.

The first results of this work are already noticeable, with a general reduction (in terms of kWh/m^2) of the buildings energy consumption. As shown in the Table 7, in only 12 years the consumption at the level of building stock has been reduced of more than 10 kWh/m^2, mainly thanks to the reduction in the space heating frame.

YEAR	***2000***	***2012***
Space Heating	61.3	52.1
Hot water	11.5	9.6
Cooling and Ventilation	1.3	1.3
Entertainment	1.9	1.6
Cooking and Dishwashing	3.2	2.9
Lighting	2.0	1.7
Laundry	0.9	1.2
Refrigeration	2.5	2.1
Other electrical device	1.6	2.4
Total	86.2	74.7

Table 7: Estimated residential building energy consumption 2000 and 2012 (Unit: kWh/m2)

The data shown in the Table 7 regards, as stated before, all the Swiss building stock, so they include constructions of the last century and new high efficiency buildings.

On the latter it has been focus principally the attention, because is from them that the energy concept of the smart living lab will be inspired.

3.1.2 Energy systems

Obviously, the different energy consumption showed in the paragraph above, are reach used several energy systems. In this part the attention has been focused only on the heating systems that are used. In the Table 8 it is possible to see which are the systems most used in the whole Switzerland and in the Canton of Fribourg.

Heating system	Switzerland	Repartition	Fribourg	Repartition
No heating devices	2405	0.14	198	0.30
Oil	831'939	49.82	31'938	48.03
Coal	1'966	0.12	44	0.07
Gas	256'820	15.38	2'880	4.33
Electricity	167'260	10.02	8'560	12.87
Wood	199'965	11.97	7187	10.81
Heat pumps	167'722	10.04	14'726	22.14
Solar heating	2'726	0.16	404	0.61
District heating	29'618	1.77	427	0.64
Others	9'632	0.58	135	0.20
TOTAL	1'670'954	100	66'499	100

Table 8: Heating system repartition. Encyclopédie statistique de la Suisse, 2012.

As it is shown more than the 50% of the cases are still using fossil fuels, but what it is interesting to underline is the high percentage of heat pumps in Fribourg (22% against the 10% of the Swiss average). This because the Canton indicate this technology as the most efficient and economical to heat the buildings, given also incentives to realize such kind of solution.

As already said above this data includes the whole building stock, so in order to have a useful overview on the best practice in Switzerland, a set of case studies has been composed. The objective of this stage was to carry out a state of the art regarding the most performant buildings correlated with the smart living lab, highlighting their energy consumption, the different technical solution and architectural techniques allowing to meet the smart living lab's specific requirements.

Multiple criteria has been used for this collection, but stringent feature was to be certified as Minergie® building.

3.2 Minergie® label

Minergie® is a popular voluntary labelling system for high-efficiency buildings, supported by the cantons, the federal government and the private sector. The label is applicable for new and renovated buildings and it comes in several levels of standards (Minergie®, Minergie®-P, Minergie® -A and the add-on -ECO that can be added to each of the other standards). They all set an overall limit on energy use for heating, hot water, ventilation and air conditioning. This maximum annual weighted energy consumption for new residential buildings is 38 kWh per square metre (heated gross floor area) and for renovated residential buildings it is 60 kWh per square metre [26].

In general a Minergie® building consumes around 60 percent less energy than a conventional building. This energy efficiency is attained through an approach which considers a building to be an integral system. Only the amount of energy delivered to the site is relevant. A building can, therefore, compensate a not particularly optimal heating system by defining top values for its insulation, for example. Minergie® is also designed to be economically competitive and therefore one of its rules is that the construction costs of new Minergie® buildings should not be more than 10% higher than the average conventional building. The high number of buildings certified as Minergie®, (by April 2012, more than 25 000 buildings with a total floor area of 25 million m^2 had been Minergie® certified [27]) shows that this figure is feasible and that constructing energy efficient homes, combined with a higher level of comfort, is in fact affordable.

Within the framework of the Minergie® registered trade mark, several label are offered.

- The Minergie® Standard requires that general energy consumption must not to be higher than 75 % of that of average buildings and that fossil-fuel consumption must not to be higher than 50 % of the consumption of such buildings.
- The Minergie®-P-Standard defines buildings with a very low energy consumption, it is especially demanding in regard to heating energy demand. This standard corresponds to the internationally-known passive house standard.
- The Minergie®-ECO-Standard adds ecological requirements such as recyclability, indoor air quality, noise protection etc. to the regular Minergie® Requirements.

In the Figure 15 all the information shows above are summarized, with the differences between the Swiss building stock and the Minergie® target.

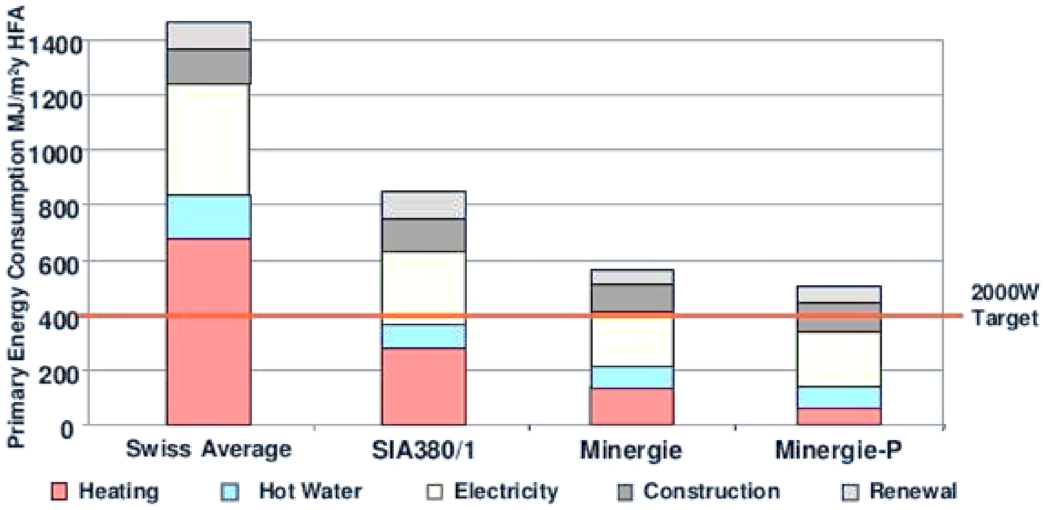


Figure 15: Primary energy consumption in Swiss buildings [28]

3.3 Case studies

3.3.1 Energy demand

For the realization of this state of art, a careful selection of case studies has been done. The criteria used for the selection of such cases were discussed and approved by all research team members. Stringent criterion is the geographic positioning, case study building must be in Switzerland. This is to try to maintain the external condition the more homogeneous as possible and in this way better underline the real performance of the building. The decision to only choose buildings in Switzerland also allows greater accuracy in the DHW and electrical consumption (lighting and appliances), which may vary from country to country depending on people's habits. Second parameter, as said above, is the "quality" of the building, in the sense of energy efficiency. So only buildings with the Minergie® label have been chosen. The third criterion is the intended use. As shown in the first chapter, the smart living lab will be a mixed-use building with a large area for housing and office, but also experimental space and meeting room, which makes it very rare. Last parameter is the date of construction of the building, which could not be older than 2004. So all the case studies of the last 11 years have been gathered. Homes, offices, schools, light industries and mixed buildings, with particular attention to the first two types, have been selected. At the end 21 buildings for housing, 9 offices, 2 light industries and 4 mixed buildings were chosen. To collect all this data, PhD thesis, the database Minergie® and the contact with the designers were used [29][30]. As it can be seen on the figures below, despite the fact that all buildings are certified and in Switzerland, there is a big difference in consumption, because of the different technologies and solutions used.

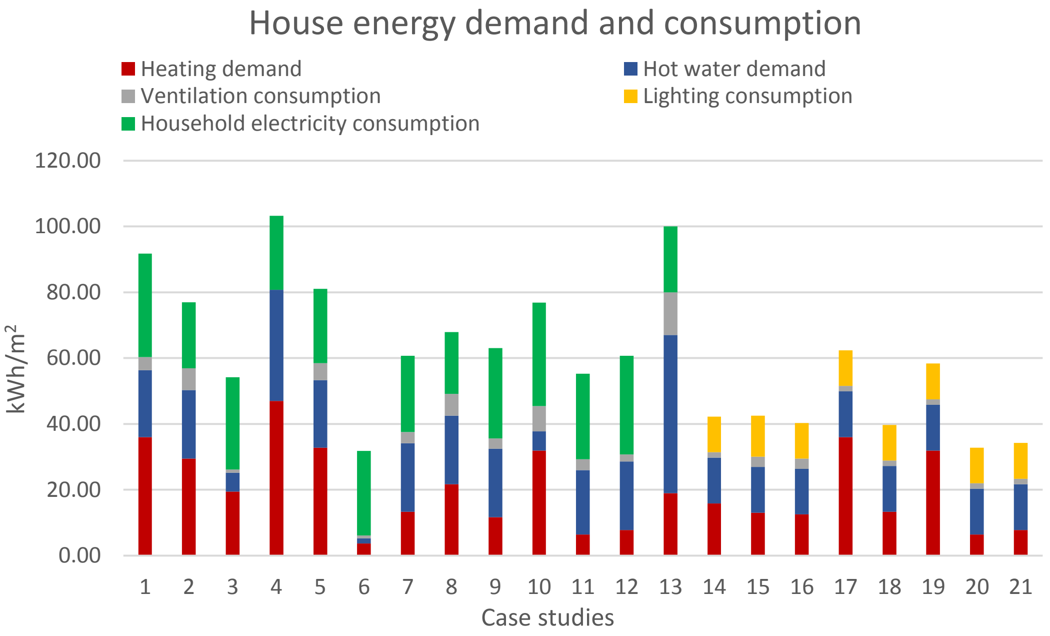


Figure 16: Case studies energy demand-consumption for dwellings

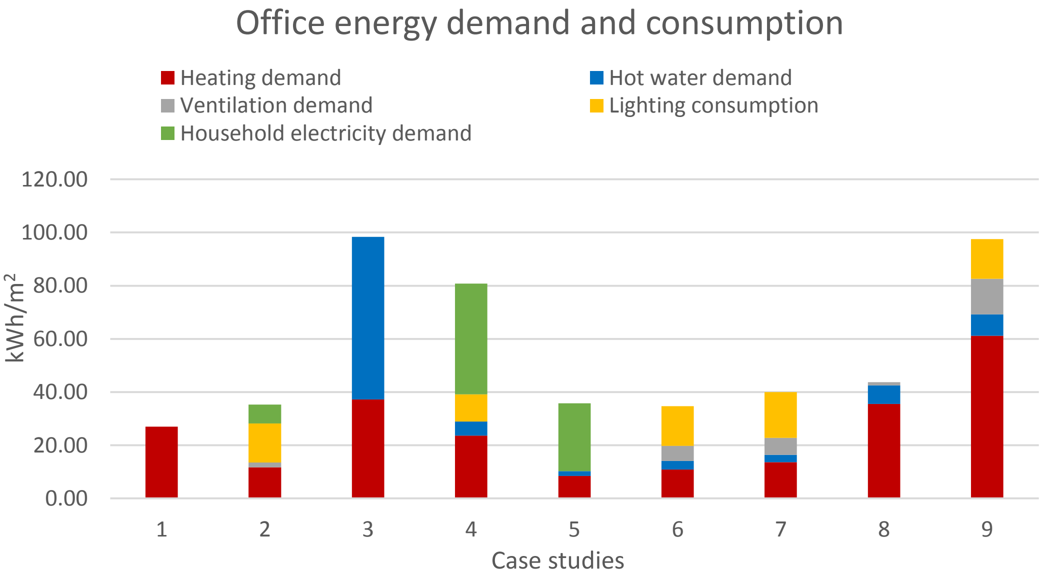


Figure 17: Case studies energy demand-consumption for offices

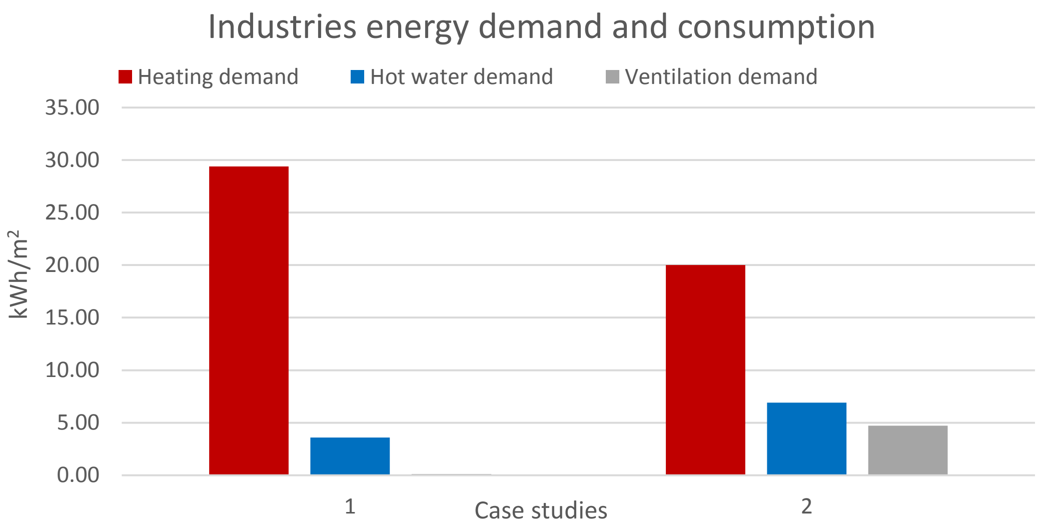


Figure 18: Case studies energy demand-consumption for industries

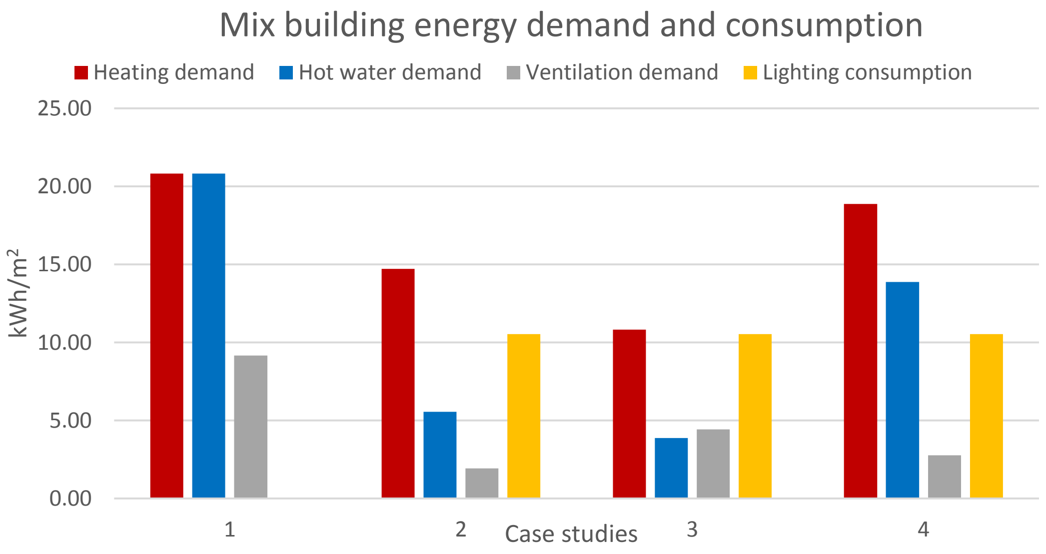


Figure 19: Case studies energy demand-consumption for mix buildings

The tables show the results for all the family of cases, to better understand the differences for each field of consumption for each destination of use. Nevertheless, for some of the cases there is a lack of data, and some fields (ex. lighting) are evaluated using the SIA standards, and not making a real calculation for each case. This is something done directly by the architects, that assume this general values without taking in account the real properties (ex. exposition) of the building. So this value becomes interesting to better understand his importance in the total energy consumption. In the Table 9 are reported again the data of the Figure 16, but this time showing the exactly value of every single case for houses.

This has been done to underline how big is the difference of this case with the ones of the building stock.

Case study	*Heating demand [kWh/m²]*	*Hot water demand [kWh/m²]*	*Ventilation consumption [kWh/m²]*	*Lighting consumption [kWh/m²]*	*Electricity consumption [kWh/m²]*
John-mfh01:	36.00	20.31	4.00	-	31.39
John-mfh02:	29.44	20.83	6.67	-	19.97
John-mfh03:	19.44	5.78	0.92	-	28.06
John-mfh04:	47.03	33.72	-	-	22.50
John-mfh05:	32.78	20.56	5.10	-	22.64
John-mfh06:	3.69	1.50	0.92	-	25.72
John-mfh07:	13.33	20.81	3.36	-	23.17
John-mfh08:	21.67	20.83	6.67	-	18.72
John-mfh09:	11.67	20.81	3.11	-	27.44
John-mfh10:	31.94	5.78	7.72	-	31.39
John-mfh11:	6.39	19.56	3.31	-	25.97
John-mfh12:	7.81	20.81	2.10	-	30.00
Solarcity	19.00	48.00	13.00	-	20.00
House A.15 Wyss	15.83	13.89	1.67	10.83	-
House A.17 Wyss	13.06	13.89	3.06	12.55	-
House A.18 Wyss	12.50	13.89	3.06	10.83	-
House A.19 Wyss	36.00	13.89	1.67	10.83	-
House A.24 Wyss	13.33	13.89	1.67	10.83	-
House A.27 Wyss	31.94	13.89	1.67	10.83	-
House A.28 Wyss	6.39	13.89	1.67	10.83	-

Table 9: House energy demand-consumption

As it was already clear looking at the figure Minergie®, if in the past the most important parts of the consumption were the space heating and the hot water, now the bigger ones are becoming the electrical ones (lighting and appliances). This trend is going to keep, so it is a problem that also the smart living lab building should face.

3.3.2 Energy systems

Also for the case studies, as it has been done for the building stock, has been analysed the different systems used to provide to this energy demand. In the Figure 20 instead the results are summarized.

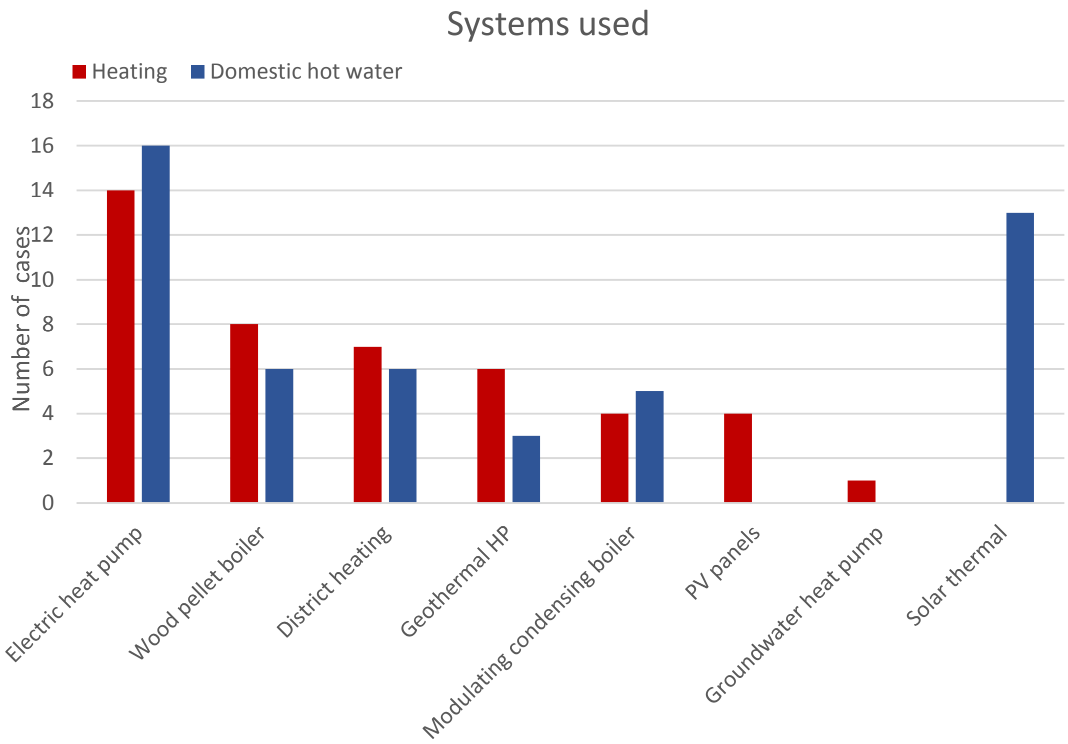


Figure 20: Systems used in the analysed case studies

It is clear that the most frequently used technology, both for the SH and the DHW, is the heat pump. Regarding only the DHW, solar thermal energy is a solution almost always used, also if it is often coupled to other systems, and it's very rarely used alone to fulfil the total requirements. It is visible also that systems powered by fossil fuel are much more less than in the stock (here are only the 14%), and that coal and oil are totally disappeared.

To conclude, the active systems that are most used in the nowadays best practice are the heat pump, the wood pellet boiler and the solar collector, all of them used with the technology of the PV. The latter does not look very used regarding this cases but this is only for an economic reason. In the last two years the production by PV has increased a lot and the cost is lowering. In the 2020 the PV energy is expected to have the same cost of wind or biogas energy [14]. It is a technology that will be therefore very important in the energy concept of the smart living lab.

4 The methodology applied: Sensitivity analysis

4.1 Goal of the analysis

Sensitivity analysis (SA) is a method to assess the influence of variations in one model's assumptions on the variations of the final output, both in quantitative and qualitative ways. It is helpful to understand the possible correlations between the uncertainty in the output of a system and the uncertainty in the related inputs. Although SA in literature is becoming more and more important due to its adaptability to different tasks, in the engineering field most studies only analyse the influence of load and economic parameters, and very few focused on optimizing models and technical factors (31).

The sensitivity analysis performed in this study aims to understand what parameters in building performance can mostly influence energy behaviours. This is the first step in the framework of the smart living lab research, which tries to define possible solutions that can achieve the 2000 Watt-Society goals in terms of environmental impacts. By doing so, the most significant parts in the design phase and the most influential parameters, which should be paid more attention to or analysed better, would be identified according to the final outputs.

The performance of SA is affected by the strength of the correlations between the design parameters based on external contexts and the goals design. Moreover, the way in which the analysis is set is self-influential to the results. Hereby, it is essential to choose the best approach according to the aims of one particular project. Accordingly, the importance of considering the validity of results only in the described framework is obvious while not generally adaptable to all cases [32] [33] [34].

4.2 Sensitivity analysis overview

SA can be used for various purposes. Its usefulness can be reflected in many different aspects when the uncertainty of a model is assessed, which is depended on the following processes:

- Testing the robustness of a model's output at the presence of uncertainty in inputs;
- Clarifying the existing correlations between inputs and outputs in a fixed system;
- Reducing the uncertainties via increasing the robustness of the comparatively influential inputs;
- Simplifying one model via eliminating ineffective parameters and redundancy;
- Identifying possible errors in a model or in the relevant assumptions;
- Calibrating a model through successive analysis steps.

In this study the final goal of SA is to optimize the SLL building design model through a step-by-step analysis process, which aims to detect the possible implications of inputs on the final output. Two different types of sensitivity are evaluated: local sensitivity and global sensitivity. The former one considers the effects of variation predictions in each individual input; and the latter one includes the uncertainties in all input data.

Being defined as differential sensitivity analysis usually, local SA demonstrates the importance of the choice on the base of each input. Several criticisms on local SA are mentioned. For instance, the space of input factors around the base value is reduced; the interactions are not considered in one model; there is no self-verification, and there is no explanation on the magnitude of the output variation accounted by inputs.

However, knowing the influence of individual parameter variations on final results also brings multiple benefits:

- Identifying two parameter groups: the influential group and the ineffective group to the outputs. This is important to keep the analysis accuracy when the model is simplified and the focus is selected.

- Identifying specific parameter that impacts the results without complete development. This is the first step of a deep analysis where the assessment of macro-inputs can define the first selection;
- Identifying parameter that should be removed from the model because of poor description or high uncertainty that would decrease the reliability of final outputs.

Local sensitivity analysis focuses on the effect of uncertain inputs around a point (the base case), while global sensitivity analysis highlights the influence of uncertain inputs over the whole input space [35].
Therefore, global SA assesses:

- The definition of the probable distribution of the results, including the acceptable maximum and minimum values and the possibility that the output will exceed a determined value;
- The identification of the significance of uncertainties due to computational simplifications, modelling assumptions and algorithm used.

Different possible approaches and methods to sensitivity analysis are reported in the Table 10.

	Method	***Subtype***	***Characteristics***
Local	Local	–	Exploring a reduced space of input factor around a base case; low computational cost; simple implementation; easy interpretation; no consideration on interactions between inputs
Global	Regression	SRC	SRC and *t*-value are suitable for linear models; SRRC is suitable for non-linear but monotonic models; moderate computational cost; fast computation; easy implementation; and high SRC value with meanings of important variable
		SRRC	
		t-value	
	Screen	Morris	Larger number of inputs and computationally intensive models; qualitative measure for ranking factors; and no self-verification. It is not suitable for uncertainty analysis
	Variance based	FAST	Decomposing the variance of model outputs for each input; model-free approach; consideration on both main and interaction effects; quantitative measures; and high computational cost. FAST is not suitable for discrete distributions
		Sobol	
	Meta-model	MARS	Suitable for complex and computationally intensive models; and quantifying on output variance due to different inputs. The accuracy is depended on the meta-model.
		ACOSSO	
		SVM	
Notes: SRC, standardized regression coefficients; SRRC, standardized rank regression coefficient; FAST, Fourier amplitude sensitivity test; MARS, multivariate adaptive regression splines, ACOSSO, adaptive component selection and smoothing operator, SVM, support vector machine.			

Table 10: Different typology of sensitivity analysis method described in literature [36]

4.3 The six-steps procedure

Sensitivity analysis is a term of methodology; and there are various approaches that can be used to perform it. Nevertheless, the general procedure is common. If the analysis is used as the first step in an optimization process, taking a high dimensional problem as an example, it is possible to apply the analysis iteratively to achieve more and more accurate outputs in each time. Then the methodology of sensitivity analysis is articulated in six consecutive steps:

1. Definition of the system: This is the most important step. It identifies all factors that will be used in the analysis, and describes the validity boundaries of the results and the procedure that must be followed. In this phase, it is important to delineate what question should be answered with the initial screening analysis, what relevant output variable would be used as a controller, and what appropriate model and type of SA would be performed.
2. Determination of parameters: The assessed parameters are determined based on the first step. The parameters are chosen among all factors that must be investigated regarding the initial question. In iterative process, this step is named as screening phase, in which the first analysis is used to select important design parameters for further analysis.
3. Parameter density function assignment: After all aspects are set, each parameter is assigned with a probable density function, which will be used in the consecutive statistical assessment.
4. Application of random sampling method: In order to generate an input matrix with combined parameters, an appropriate random sampling method is applied. It is important because this step sets the specific method to realize sensitivity analysis, creates the matrix, and builds the base of assessing relative influence among outputs.
5. Output distribution calculation: The output distribution in the given input matrix is calculated. In this way it is possible to have to each combination of parameters the related output value.
6. Influence assessment: Last but not the least, the influence and the relative importance of each design parameters based on the final input matrix and output array is assessed.

The above methodology for a sensitivity analysis is linear and clear. However, it cannot immune from constrains and limitations. A sensible and helpful way to avoid these is to identify an appropriate approach for the expected result: regarding the accuracy degree, the analysis type, the outputs and the defined parameters, a suitable type of SA can be determined based on the settings of the assessment.

One of the most common issues is the computational expense: the usual assessment of SA is running a model a number of times. A sample matrix with larger scale can lead to more accurate results, while also bring out problems. The complexity of a model, e.g. a model including building performance and dynamic simulations, might determine a significance in the time requested for each single run. The more complex the model is, the more the time requested. What is more, SA is basically situated in the space composed by multidimensional inputs. This space grows exponentially along with the increase of inputs and/or the related uncertainty. Whether or not the number of parameters involved in the analysis can be reduced directly influences the computational time spent on calculating the output array. Hereby, the first criterion for SA is the dimensionality of analysis. The second criterion is the capability of detecting correlations between inputs. On one hand, most SA methods assume inputs independent to one another even if in reality they are strongly related. This strong interrelation can be noticed also in models where the simultaneous variation of two related inputs is much bigger than that of each input individually. This phenomenon can only be detected by the global SA rather than the local one. On the other hand, the local SA can consider both non-linear and linear correlations in inputs by variance-based methods and linear regression respectively. Whether to select global or local SA, to choose specific solution from variance-based methods or linear regression, and the assumptions in the model is necessary to be started clearly before performing a SA. In accordance with the goals and the features of inputs, Morris approach was used in this study.

4.4 Morris approach

In the proposed research, sensitivity analysis is used as a screening method to detect the most influential parameters to both final outputs and future development. The correlations among the involved parameters are neglected, while only the ones within the model are considered. There are several approaches that can be used for this sensitivity analysis, and Morris method is one of them. Morris approach is also called the Elementary Effects (EE) method. It is a one-parameter-at-time (OAT) screening approach and a global sensitivity analysis. In Morris approach the baseline the baseline changes every step and the final results are calculated by averaging at different points in the input space. OAT is based on the evaluation of each single parameter in turn. A comparison between estimations in standard values and the evaluation results on the extremes is conducted to figure out what parameters the design criteria chosen as outputs are more sensitive, by partial derivatives or linear regression. The procedures of doing so are: changing one input variable and keeping others at their nominal values, and then repeating the turn for other parameters. This gives two different indexes to describe the sensitivity of the model: the estimated main effects of inputs on outputs and the interactions (or the nonlinear effects) between inputs. The former one ranks the parameters by their importance, although the direction of the effect is unknown; and the later one indicates possible correlations among inputs.

The main purpose of the Morris method is to identify which design parameters may be considered to have effects, which are:

- Negligible (low average, low standard deviation).
- Linear and additive (high average, low standard deviation).
- Non-linear or involved in interactions with other input parameters (high standard deviation).

As a result, the outcomes of a sensitivity analysis will be a ranking list of important design parameters based on the strength of their impact on outputs.

The great advantage of Morris method is its computation cost less than other global SA. The number of computations required is relatively low, and can be figured out by the formula:

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

In the formula, N is the number of simulations, r is the number of elementary effects per factor, and k is the number of design parameters.

However, this approach also has its own disadvantages. For instance, the method prefers to give qualitative results rather than quantitative ones in the terms of input rankings. Hence, the Morris method cannot verify itself, which means that it is impossible to know how much of the total variances of outputs have been considered. Nonetheless, Morris method cannot provide uncertainty analysis, because the samples created by the matrix generation do not converge to the population mean of the model outputs [37].

Despite these, Morris method is the most used tool for building energy models due to its adaptability as the first step for optimizing process. Also with low computational cost and simulation tools, Morris can rank all parameters (or family of factors) and demonstrate the most appropriate and relevant ones in accordance with the goals of the modelling [38].

4.4.1 Elementary Effects methodology

Elementary effects (EE) are used to account sensitivity. They are approximations of the first order of the partial derivatives [39]. EE are calculated following a random generated matrix of input combinations. The average and standard deviation of each EE is used to assess the influence of each variable to the final outputs, sort negligible and influential parameters, and distinguish linear or nonlinear correlations. Morris approach uses quasi-random sampling as sample generation. Random combinations are given based on the probability density functions associated to each parameter. OAT method relies on the assumption that when variables are changed within same distance, the variable that causes the biggest variation of outputs is the most effective one. Usually, input variations are tested individually by changing the value between couples of models simulations. The inputs variation effects of each step are evaluated by its elementary effect (EE). Take a simple system for instance:

$$Y = y(k_1, k_2, \dots, k_n)$$

and a set of model simulations for each parameter variation; the EE of each factor k_i can be determined as:

$$EE(Y) = \frac{y(k_1, k_2, \dots, k_{i-1}, k + \Delta(k_{i+1}, \dots, k_n) - y(k_1, \dots, k_n)}{\Delta}$$

Here Δ is the step magnitude. Each input (y) can be changed within a region of interest defined by the assigned probability function, and may assume a discrete number of values with a distance of equal size called levels. This level is represented as value p.

Morris method uses a similar procedure. The differences is that it creates a trajectory thorough the variable space as it is shown in the picture instead of changing each parameters in a completely detached way. Hereby, the simulations share points in each of this created trajectory, and Morris method uses $k + 1$ model parameters to calculate the EE for each input.

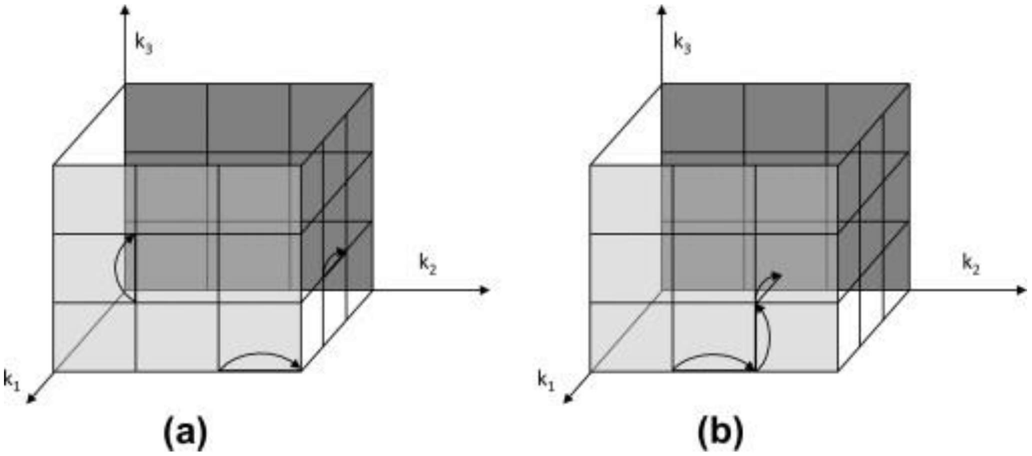


Figure 21: Inputs region in common OAT (a) where the k variables have different variations, and for Morris method (b) with the trajectory [40]

In order to create different trajectories, Morris method uses a series of matrixes. The selectable values for each variable k are denoted by p value and the relative magnitude Δ, and then defined as a multiple of $1/(p-1)$ in the field [0,1]:

$$x = \left\{0, \frac{1}{p-1}, \frac{2}{p-1}, \frac{3}{p-1}, \dots, \frac{p-2}{p-1}, 1\right\}$$

The basic value is chosen in the ranging from 0 to $(1-\Delta)$ randomly. This ranging is used to assure that the relative sampling point will stay in the existence field of inputs value even if Δ is added to the basic value. The first point is only used to build the trajectories that will form the final sample matrix rather than in the simulation. This creation starts from a random direction matrix and contains n samples that must be assessed to calculate the associated resulting EE array for each input.

By doing so, the influence of each parameter on the expected value can be assessed, and its variation can be calculated through the Elementary Effects Method, so that the sensitivity index of each input can be evaluated according to the selected output.

For each parameter, more than one EE can be calculated depending on the sample matrix and steps of values. The model sensitivity to each factor is represented by the mean value and the standard deviation of EE

$$\mu = \sum \frac{EE_i}{r}$$

$$\sigma = \sqrt{\frac{(EE_i - \mu)^2}{r}}$$

Here μ is the mean value of EE. The standard deviation is a measure of the sum of all interactions of each single parameter with other factors and of all its non-linear effects. Value r is the number of elementary effects that are investigated.

Based on these two index the inputs can be ranked and the type of influence on the final results can be identified.

4.5 Sensitivity analysis applied to the case study

As it was mentioned above, Elementary Effects is selected as the method in this study due to its general approach that can achieve balance between accuracy and efficiency. The analysis development process is able to investigate more than one input at the same time, which can enlarge the possible results of the model in different aspects, and moreover, define macro-parameters properly in the screening phase [41]. Following this way, the initial inputs will be divided into micro-parameters with more details in the next step, which would further explore the model and its sensitivity to different assumptions or features. The literature review on SA shows that the applicability of SA relies on the definition of inputs: two different scales as micro factors (e.g. material properties) and macro factors (e.g. wall properties) existing in one model can bring difficulties in understanding and interpreting the final results. These difficulties can be avoided when only macro parameters are selected to define. This simplification would not modify either the initial inputs or the model.

In the case study presented, the sensitivity analysis is set to better understand the design parameters and their influence on building performance in the contexts of the smart living lab building. The selected outputs are energy demands for heating, consequent primary energy and CO_2 contents of used energy. The parameters are grouped as input families, which are important in describing the physical properties and the energy concept of the building. The sensitivity analysis is also useful to have the first group of "project families", which are a group of models with the same characteristics created by the input matrix of the SA. These families are the basis of the optimization process and able to test what inputs can be correlated together based on the possible effects on the outputs. This is an important step for assessing the deeper investigation, where it is important to group scenarios in which some parameters will stay constant and others will vary in accord to the results of the SA.

The results of the sensitivity analysis are very specific: given certain external conditions, the tool used for assessing, modelling goals, selecting inputs and varying ranges validates the findings indissolubly for the particular project [42].

4.5.1 The six-steps in the smart living lab building

The sensitivity analysis applied to the smart living lab building is developed into six steps. The base of this development is the final aim of the project as to achieve building sustainability in a high level through optimizing the inputs in details in the screening phase.

1. Outputs identification:
   The important outputs of the smart living lab building that should be investigated are the primary energy used for the whole building and the energy demand for heating. The energy concept of the building also includes two aspects: the active systems and the passive strategies corresponding to the ways of energy supplying and demand reduction. Two outputs will be considered as needs of heating and cooling (kWh/m^2) and energy provision (kgCO_2/kWh).
2. Inputs definition:
   In the sensitivity analysis, macro-parameters are selected as design measure and possible energy systems that concur to the final performance

of the building. Firstly the physics of the building, such as the thermal shield and the glazing porosity of the shell are described. Secondly, the macro-parameters are linked to different options that were highlighted in the state of art. According to the selected parameters, the specification of the SA of this project is the mixed approach to both the passive and the active system design.

3. Probability distribution and input value range definition:
   Since the purpose of the SA for the smart living lab building smart is to investigate the effect of each design assumption, the distribution of portability of each value is discrete and uniform. In this way there is no prejudice in the design phase for achieving the expected results.
4. Method selection:
   Morris method is selected as the SA approach in the project. This method is applied by the software Simlab 2.2 designed for Monte Carlo analysis. Based on the available information Morris method is evaluated to be the most interesting one for the sensitivity analysis in the sustainable building design, because of:
   - Its capability of handling a large number of parameters;
   - Its comparatively fewer simulations to the number of parameters;
   - Its easy interpretation and graphic visualization on results; and
   - Its indication on non-linear or mutually correlated parameter variations.

   According to this method the number of required computation is:
   $$N = r \times (k + 1) = 6 \times (12 + 1) = 78$$
5. Output distribution calculation based on the generated input matrix:
   The building energy behaviour is assessed by a dynamic simulation software named Lesosai.
6. Related influential inputs / outputs assessment:
   The elementary effect method associated by Morris approach is used to figure out the correlations between the input matrix and the output array as well as to calculate the sensitivity of the model with different introduced design options.

To conclude the chapter it is possible to say that the Morris approach is the most suitable method for the smart living lab building. It is based on the elementary effect evaluation by the variation of input parameters each time. The aim of this method is to quantify the final influence of each input parameter on the outputs. Regarding the research framework the analysis is used as screening phase to reduce the possible elements and conduct to a deeper optimization process. The aims of doing so is to find all possible combinations and solutions that can reach the 2000 Watt-society goals. In the next chapter the choice of outputs and inputs is presented as well as the explanation of the relative importance on the final target.

5 Parameters

5.1 Outputs

As mentioned in the previous chapter the first step to perform a SA is the identification of the outputs. For the smart living lab research the final values that are important to control are the primary energy used for the supply system and the energy demand for heating. These are two main aspects of the energy concept of the building: the active systems and the passive strategies, corresponding to the way to give energy and the measure undertaken to reduce the demand.

As described, the inputs will be translated into two different main outputs: the primary energy and the energy demand. In this way, it will be possible to control both the passive energy field and the active system choice.

Always regarding the energy it has been chosen to analyse it adding also a third value: the final energy, to better underline the performance of the building energy systems.

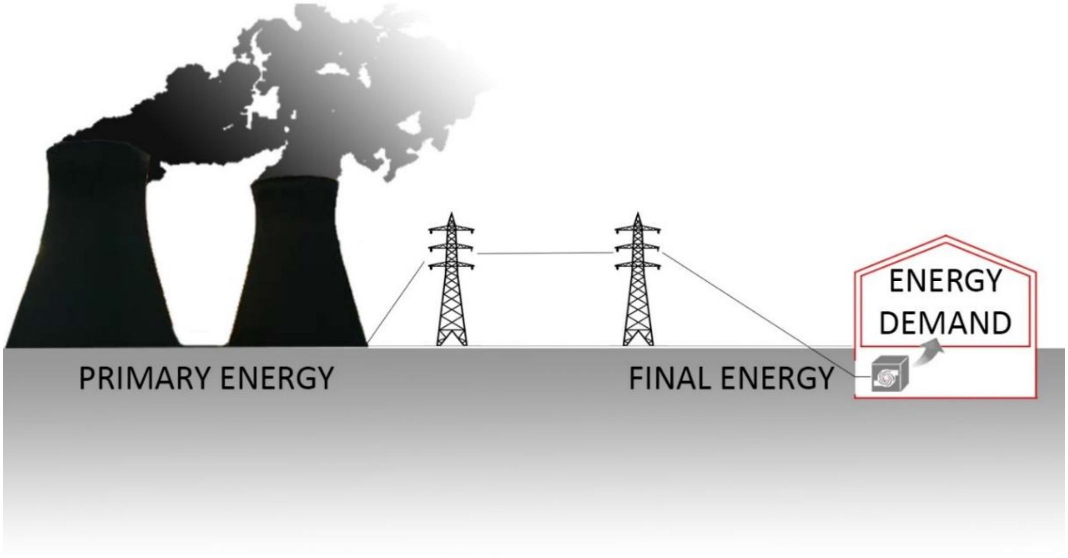


Figure 22: The three different energies considered in the study

As shown in the Figure 22, at the end three different energies have been considered. The energy demand is the quantity of energy that the building needs, is the real demand in terms of space heating. Final energy has been defined as the energy that is delivered to the building. It is the one that, depending on the HVAC system used and its efficiency, will cover the demand. The final energy has been divided into two main elements: the thermal final energy, that is the one used for the SH and DHW, and the electrical final energy, that is the one used for lighting, appliances and other auxiliaries. Finally the primary energy is the one used directly in the power plant to produce the electricity or the one spent to prepare the fuel. With reference at the Figure 6, it is clear as the outputs of this research should consider not only the energy used and with which efficiency is treated, but also the quality of this energy, in terms of CO_2 emissions generated. Therefore it has been decide to look at them in terms of CO_2 emitted by the primary energy used for the whole building. In that way the quantity of gCO_2/kWh contained in the energy it has become $kgCO_2/m^2$, using the dimension of the building [m^2] and the total primary energy used [kWh].
To summarize the five outputs investigated in this analysis are:

1. Heating demand [kWh/m^2]
2. Thermal final energy [kWh/m^2]
3. Electrical final energy [kWh/m^2]
4. Primary energy [kWh/m^2]
5. CO_2 emissions [$kgCO_2/m^2$]

Before to conclude this paragraph it is important to remember that the choice of the inputs for the sensitivity analysis is driven mainly by the outputs factors that are considered, with the purpose to highlight the possible effects of that inputs on the final values. Keeping this in mind it is possible to better understand the choices made in the selection of the input parameters.

5.2 Inputs

The second step to assess the SA is the selection of the inputs. The macro-parameters adopted are chosen as design features and possible supply systems that concur to the final performance of the building. The first describes the buildings physics, such as thermal shield and glazing surface, the second, instead, are related to different supply options highlighted during the state of the art analysis. As already stated the particularity of the SA conducted is the mixed approach to both the passive design and the active systems, given by the parameters chosen.

The twelve macro-parameters analysed, therefore, can be clustered into five different groups:

- Active system: parameters that defined the way in which the energy is supplied to the building and the technical characteristics of the systems.
- Internal: parameters that defined the internal condition of the building and that usually are regulated by norms (like the ventilation ratio of each ambient).
- Transparency: all the parameters used to describe the glazed surface of the building, in terms of quantity and quality.
- Envelopes: parameters that described the physical and thermic properties of the envelope.
- Building's shape: this group it is made just by one parameter, represented the different geometrical solutions proposed for the smart living lab building.

5.2.1 Active system parameters

HVAC

Obviously the first parameter select in this group is the HVAC system. This choice has been done using the information obtained by the state of art, to be as close as possible to the real performance of actual system (with feasible efficiency). With this parameter it is possible to see how different HVAC solutions can answer to the same demand, and how much it affect the result in terms of primary energy. The same system used for the SH it is also used for the DHW, so in each simulation just one system is used.

Four possibilities are given for this parameter:

1. **Natural gas:** a gas boiler with efficiency of 90% has been chosen. As shown in the chapter 3, this kind of solution is the only one applied in new buildings regarding the ones with fossil fuel.

2. **Pellets:** a boiler with efficiency of 92.5% has been used for the pellets solution. Also this one is a result of the case studies analysis that showed clearly how this system is one of the most used.
3. **District heating (waste heat):** this solution has been used to model the waste heat from the nearby industrial area. Using the heating product by a waste plant it has been possible to simulate the waste heat by the productive process of the Villars factory.
4. **Heat pump:** a heat pump with geothermal probes and coefficient of performances of 3.9 has been selected. This system is the most used in the case studies but always with different COP. The choice of 3.9 has been done to keep this system with realistic performance and have reliable results.

PV panels

The second parameter that could describe the active system is the quantity of photovoltaic panels. Efficiency, orientation and inclination are always constant in each scenarios, due to the importance of understanding the relative sensitivity of the implementation of photovoltaic panels on the CO_2 content of the energy supply system. The panel is a polycrystalline one, with an area of 1.58 m^2, oriented at south with a tilt of 40°. An important assumption is that the PV system aims to cover only the demand of lighting and appliances and it is meant as integration to the use of the electricity grid. So the HVAC system and the PV are not linked and it is therefore possible to see how much different percentage of use affect the result of the electrical final energy. The value used to describe this parameter is the percentage of roof surface used for the installation, trying in this way to make a link with the building's geometry. Due to the different size of the building shapes, the number of panels representing the 100% (and the other percentage) it is different in each case, varying from 204 panels to 324 on the bigger solution. To calculate the number of panels not only the roof surface has been used, but also the minimum distance between two rows has been taken in account, always to keep the result as more reliable as possible.

1. **None:** any panel is used in this case.
2. **30% of roof surface:** the number of panels can be 61 or 97.
3. **60% of roof surface:** the number of panels can be 122 or 194.
4. **100% of roof surface:** the number of panels can be 204 or 324.

Solar thermal collectors

Exactly like in the case of the PV panels, also this time the efficiency, the orientation and inclination of the collectors are constant in each scenarios. A vacuum collector is used (model DRC 10 – AMK-COLLECTOR AG) with a surface of 2 m^2, oriented at south with a tilt angle of 35°. In this case the collectors are used only to cover the hot water demand, in fact, this is an implementation of the HVAC system chosen that is already providing heating and hot water. Since that solar collectors alone are not feasible to supply the entire demand for DHW and SH, it becomes important to understand how the integration of this system can influence the final energy used for the thermal part.

The value used to describe this parameters is so the percentage of covering of the hot water demand during the whole year. To calculate the latter, the SIA norms has been used: the demand of water for the housing zone is 40 l/day per person, in the offices is 10 l/day and 0 l/day for the others destination of use. The maximum value of covering is 60% of the demand, as the highest value founded in the case studies was 55%. Also in this case due to the different size of the different destination of use in each building shape, the number of person and the hot water demand is always different, and as consequence the number of collectors to cover the same percentage is always different.

1. **None:** any collector is used in this case.
2. **20% of the hot water demand:** the number of collectors vary between 8 and 15.
3. **40% of the hot water demand:** the number of collectors vary between 20 and 33.
4. **60% of the hot water demand:** the number of collectors vary between 29 and 49.

Heating distribution

To conclude this cluster of active parameters the heating distribution system has been chosen. As known from the literature, the effect on the thermal final energy is very variable, ranging from great effects to negligible ones. It is clear why a deeper investigation on the specific case of smart living lab is essential to quantify the impact on the outputs.

Also this time the different options for this parameters are from the case studies analysis, where only this four solutions are used:

1. **Radiators**
2. **Floor heating**
3. **Ceiling heating**
4. **Air heating**

5.2.2 Internal parameters

Ventilation ratio

Little changes of the flow in the ventilation system can bring to important difference in the thermal performance of the building. According to Swiss norms, mechanical ventilation system is mandatory in all new buildings and it is, therefore, important to understand the extent of its influence on the energy consumption. Moreover, this strategy can be used for different purpose beyond the air quality one, for example higher values can help in dissipating extra internal gains. Lower value are now not aligned with the norms, but can be implemented in the future when requirements may change. Since that for each distinct zone of the building it is defined a different ventilation ratio, in this study has been used the SIA value as reference and the relative percentage of difference; in this way there is not an absolute reference for each room but it will be changed according to the real requirements indicated. The norm used for reference is the SIA 382/1 - Ventilation and air conditioning systems; general guidelines and performance requirements.

Always following the norm also the working time of the system has been set, that for the rooms of the houses is 7/7 days and working at full capacity during the day and at half of the capacity during the night. For the offices, the meeting rooms and the experimental area only two options has been generated: full capacity during the working time and turn off all the rest of the period. Since the high flow of hot air moved by the mechanical ventilation, a heat recovery system has been applied, with a recovery index of 60%. This values, as the specific fan power set like 0.095 W/ (m^3/h), have been left fixed in all the three scenarios, in order to understand how much exclusively the increase or the decrease of the ventilation ratio used, in m^3/h, affect the result. For this reason just three possible scenarios are given, that are:

1. **As SIA 382/1:** in this case the minimum flow given by the norm is used.
2. **As 120% of SIA 382/1:** here the air flow used is bigger than the one given by norm.
3. **As 80% of SIA 382/1:** in the last case the air flow used is smaller than the one given by norm.

Lighting + appliances

One of the main result provided by the analysis of the building stock and of the case studies is the importance, nowadays and in the future, of the electrical consumption for lighting and appliances. Therefore it has been created this input to assess the relevance of the electrical consumption on the primary energy used, and validate in this way the results of the case studies. The quantification of this value has been made through the creation of four possible scenarios, obtained by SIA and other norms. Starting from the value given by SIA 380/4 - Electricity in buildings, a discrete variation in term of percentage is given. The upper limits is represented by the normative SIA 2024 - Standard conditions for the energy and the installations of a building. The lowest level, instead, is weighted on the possible technical implementation given by the new technology available.

For both this values, lighting and appliances, the norms provide a limit in terms of power, defined in W/m^2, which must be respected, for example using the SIA 380/4 for the offices the power for appliances is 7 W/m^2 and the one for lighting is 12 W/m^2. Then using the usage time it is possible to define the quantity of energy consumed. For the appliances the usage time is settle by some curves of people distribution, divided on days, weeks and months. With this data it is possible, for each destination of use, to know the quantity of people in one room and consequently the appliances used by them. On the contrary for the lighting another system to define the usage time has been used. Indeed to turn on and off the lights it has been applied a type of regulation with automatic daylighting stop and manual switch on. In this way when the natural light it is enough any kind of energy will be used for the artificial light. Since that SIA refers to the destination of use of each room, the scenarios are not defined by an absolute number but by a percentage.

1. **Lighting as SIA 380/4 normal + appliances as SIA 380/4:** in this proposal both the parameters are following the SIA 380/4, so this are the maximum values request by norm.
2. **Lighting as SIA 380/4 target + appliances as 73 % of SIA 380/4:** in this case it is always followed the SIA 380/4, but using the target values, or rather the ones that in the future are going to be the maximum allowed by law. This values are almost the 73% of the previous, and this scenario is the one with the minimal consumption.
3. **Lighting as Minergie + appliances as 82% of SIA 380/4:** here the values Minergie are used, that are the ones request to reach the Minergie label. As it is clear they are smallest than the first one (the 82%) and bigger that the previous, but are values that are already accessible today, with existing technologies.
4. **Lighting as SIA 2024 + appliances as 110% of SIA 380/4:** the last scenario is the one referred at the SIA 2024, therefore is the building stock. So this values are larger than the first one (110%) because old and not efficient technologies are used.

5.2.3 Transparency parameters

Windows to wall ratio

The transparent components implemented into the construction are responsible of considerable thermal losses: the relative low transmittance, respect to the walls value, represents a thermal bridges on the facades. However, the extent of the influence of the windows dimension on heating demand and the correlation with other design parameters must be investigated deeply in relation to the specific case. External context, weather file and architecture can, in fact, affect the impacts and the magnitude of the interactions. The assessment of this features is essential in order to take in consideration the variation of the balance between solar gains and thermal losses through the windows, which have a great influence on the final performances and thermal needs of the building. The physical meaning of this input is related to the porosity of the envelope on the outdoor environment, seen as the quantity of transparent surfaces on the facades. The variation is free inside the construction, and it is implemented as percentage of glazing surfaces on the total external portion of façade related to each internal room. The ratio is changed in the same way on each facades, without any consideration on the orientation and the destination of use of the relative indoor space. Three different solutions are proposed, from 25% to 75% of the external surface on which the window is applied.

1. **25% of the surface**
2. **50% of the surface**
3. **75% of the surface**

Windows type

The second main features that characterize the transparent component is the quality of the windows, expressed by thermal and visual properties. The physical properties analysed are the global thermal transmittance (frame and glasses) and the solar factor, which directly influences the solar energy transmittance meant as the ratio of radiation passing through the glazing element. In order to implement the parameter in a reliable way, it has been chosen to consider technical elements already available on the market, taken by the software database. The elements considered are representative of three different type of windows corresponding to three different type of construction: the average, the efficient and the passive one. The proportion between the frame and the panes is fix to 30%, representing an average value for office windows. The variation is made on the whole constructions, without any difference regarding the orientation and the use of internal spaces.

1. ***S*tandard double glazing (U: 2.7 W/m^{2}K, g: 0.77)**
2. **Low-E double glazing (U: 1.3 W/m^{2}K, g: 0.64)**
3. **Low-E triple glazing (U: 0.7 W/m^{2}K, g: 0.5)**

Shading system

Another important parameter that must be considered in this group is the shading system used for the transparent elements. Internal gains can play an important role in reducing the heating needs, but, on the other hand, could easily bring to overheating during the summer season. As commonly used in high performant buildings, the protective screen for solar gains and glare are separated into two different system: the first is on the outside and the second instead in the internal part. In this way it is possible to minimize the users interactions with the activation of shading screen, that are mostly used to protect from glare, interfering with the thermal behaviour of the building. The input has been implemented as a total sliding curtain, with different levels of solar and lighting transmission, representing the percentage of solar radiation and lighting passing through the element. In order to avoid the activation of the shading system when it is not needed, a control system is modelled. The threshold is fixed as solar radiation greater than 150 W/m^2 and external temperature higher than 16°C. These conditions are taken from the weather file for Fribourg to assure that during wintertime the positive effects of gains are not avoided by a wrong use of the curtains.

1. **20% of radiation pass-through**
2. **50% of radiation pass-through**
3. **70% of radiation pass-through**
4. **90% of radiation pass-through**

5.2.4 Envelope parameters

Thermal transmittance

The most important parameter to describe the thermal behaviour of an opaque envelope is the thermal transmittance of its elements. This feature is also called thermal shield due to its function of protection from external temperatures variations, blocking or smoothing the thermal flows between the outdoor and the indoor environment. Therefore, the importance of this parameters is related to the ability of the buildings envelope to improve the heating efficiency. The thermal shield is, in this case, meant as the total transmittance of the shell to the external, signing a global buildings performance more than the local ones related to each components. In this first phase, in fact, the accuracy of the local properties effects is not so much important as the one of the general value.

Four different values are assigned to this parameter, according to the technological definition of the factor inside the building: the thermal transmittance is changed varying the thickness of the insulation layer of walls and roof, changing in this way only the thermal properties of the stratigraphies.

1. **0.10 W/m²K**
2. **0.15 W/m²K**
3. **0.20 W/m²K**
4. **0.25 W/m²K**

Internal inertia

Second parameter of this cluster is the inertia. It is a key driver for comfort, acting as heat tank to store gains, influencing also the energy consumption of the building. The extent of this influence is, however, very related to the specificity of the project: weather conditions, construction technology, internal environment and solar gains are the key drivers for the inertial behaviour of a building. For this reason it is important to understand how the smart living lab is sensitive to this factor, investigating the importance of inertia's implementation inside the design. As physical properties, however, inertia is very difficult to control because there are more than just one way to consider it: through its effects (as time lag), through envelope's features (as admittance), through materials properties (as mass) or through the whole system (as thermal capacity of the room). In this study, since that it is a preliminary analysis, it has been chosen to regulate it in a very simple way: considering three different type of constructions, associated to three different level of inertia. The options are considered as for the thermal transmittance: fixing a kind of component, the massive layer is implemented through the thickness of the concrete inside the element. For quantifying the quantities, the French Thermal Regulation is used as reference, applying the simplify method for the constructions typologies classification; due to its easiness of application is suitable for a preliminary analysis.
Inertia has been dissociated from the thermal transmittance applying the inertia's properties only at the internal walls and at the slabs, in order to change them in different step.

1. **Massive walls, light concrete (average)**
2. **Light walls, no concrete (low)**
3. **Very massive walls, concrete (high)**

5.2.5 Building shape

The last parameter selected is the building geometry, its shape. It is important to assess the sensitivity of the final energy performance to this factor due to the related significance during the design stage. The first step to design the smart living lab, but more in general all the buildings, is represented by an architectural study about the feasibility of different shapes according to the context requirements. It is therefore a central point to understand how much a change in the geometry can influence the thermal behaviour of the building. To underline this thermal properties the compactness ratio, defined as the ratio between the external surface and the volume (C = S/V), is used. Another feature linked with the shape that has been investigated is the variation of percentage of each destination of use in each case. As explained in the first chapter, the smart living lab is going to host dwellings, offices, meeting rooms and an experimental space. Obviously the relative percentage of each spaces is different in each shapes, according to the specific architectural study made. So ad example the experimental area in one case is covering the 21.2% of the surface, in another case it is only the 15.9%. This variation are changing not only the SH demand, but also the DHW demand and the electricity consumption, that are strictly related with the destination of use.
The three shapes are taken by the architectural feasibility study of smart living lab and are here presented:

1. **Shape 1**: this variant is the one with the dimension of each destination of use like in the project requirements. The geometrical dimension are:
    - C = 0.22
    - V = 16935 m^3
    - S envelope = 3691 m^2
    - S flooring = 1218 m^2

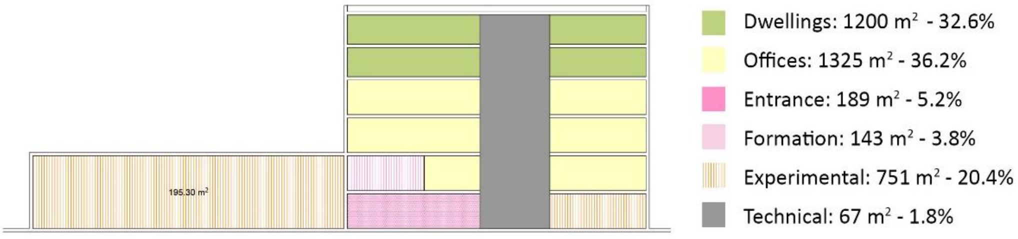


Figure 23: Shape 1, variante COMPACTE

2. **Shape 2:** in this proposal all the space available for the building is used, but then just one area is heated while the other part is built but not used. The data regarding the heated zone are:
   - C = 0.26
   - V = 13883 m^3
   - S envelope = 3574 m^2
   - S flooring = 765 m^2

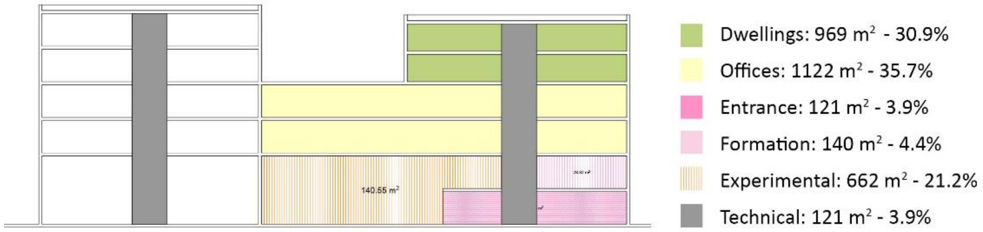


Figure 24: Shape 2, variante RESERVE BATIE

3. **Shape 3:** this last option is using all the available space with the maximum volume that can be developed. There are important variation in the distribution of the surface compared to the previous shapes.
   - C = 0.21
   - V = 23973 m^3
   - S envelope = 4944 m^2
   - S flooring = 1218 m^2

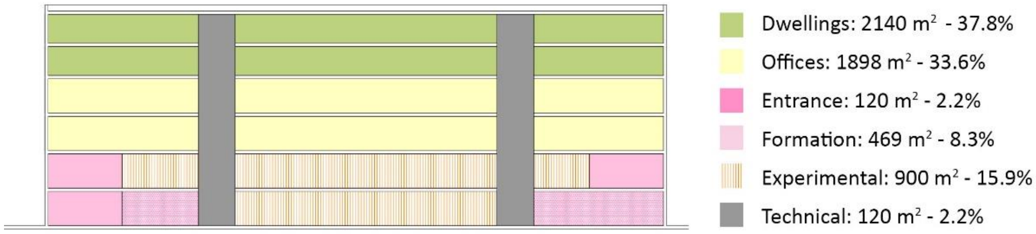


Figure 25: Shape 3, variante 100%

5.3 Definition of the probability distribution

After the definition of outputs and inputs, the third step to perform the SA is to give to all inputs a probability distribution. For the smart living lab case this has been done giving to all of them a discrete distribution with each step of the same weight, so the values related to each input can vary only between the ones that has been selected above. Moreover each input is independent from the others, so they are free to change without any correlation between them. This has been done with the intention of not create any relationship a priori in the inputs (for example window ratio and window type), to be able to identify the real weight of each parameter in the final output. To summarize, all the parameter used and the range of values for the inputs are reported in the Table 11.

Parameter	***Input***			
Shape	1	2	3	-
Window to wall ratio	25%	50%	75%	-
U value	0.10 W/m^{2}K	0.15 W/m^{2}K	0.20 W/m^{2}K	0.25 W/m^{2}K
Window type	U: 2.7 W/m^{2}K g: 0.77	U: 1.3 W/m^{2}K g: 0.64	U: 0.7 W/m^{2}K g: 0.5	-
Inertia	Light wall	Average	Massive wall	-
Shading system	20%	50%	70%	90%
Ventilation ratio	SIA	120% SIA	80% SIA	-
Lighting + appliances	Light SIA App SIA	Light SIA target App 73% SIA	Light Minergie App 82% SIA	Light SIA 2024 App 110% SIA
Hvac system	Pellets	Natural gas	District heating	Heat pump
Photovoltaic panels	None	30%	60%	100%
Solar collectors	None	20%	40%	60%
Heating distribution	Radiators	Floor H.	Ceiling H.	Air H.

Table 11: Input distribution

5.4 The samples matrix

Fourth step of the SA is the generation of the matrix that for this case has been done using the Morris approach. To set up all this analysis the software SimLab 2.2 has been used. SimLab is a professional tool designed for Monte Carlo (MC) - based uncertainty and sensitivity analysis (37). MC-based uncertainty and sensitivity analyses are based on performing multiple model evaluations with probabilistically selected model input, and then using the results of these evaluations to determine the input variables that gave rise to the uncertainty of the output. This software has been chosen because is composed of three modules that are able to cover all the steps of the sensitivity analysis. So for first the Statistical Pre Processor module has been used, to apply the inputs in the software. Then the Model Execution module accomplishes the creation of the matrix and it is able to provide a list of conditions to reach the output desired. This section is the one that has been used in this phase to generate the set of simulations for the smart living lab case. The last module, used to obtain the results of the SA, is the Statistical Post Processor one that is in charge to provide the final results.

As it has been showed in the previous chapter the Morris approach generate N simulations to run, defined by the formula:

$$N = r \times (k + 1) = 6 \times (12 + 1) = 78$$

where r is the number of trajectories (successions of points starting from a random base vector in which two consecutive elements differ only for one component) and k the number of model input factors. In this study 12 parameters has been identified and a r equal to 6 has been adopted. This bring the number of simulations to 78. In the Table 12 it is possible to see a frame of the input matrix generated, with the simulations between 55 and 60. All the matrix is available in the Annex I.

Simulation number	Shape	Windows ratio	U value	Windows type	Inertia	Shading	Ventilation ratio	Lighting + Appliances	HVAC	PV panels	Solar thermal	Heating distribution
55	1	75	0.1	1	Low	70	80	2	Pellets	30	20	Floor
56	1	75	0.1	1	Low	70	100	2	Pellets	30	20	Floor
57	1	75	0.1	2	Low	70	100	2	Pellets	30	20	Floor
58	1	75	0.1	2	Low	70	100	2	HP	30	20	Floor
59	1	25	0.1	2	Low	70	100	2	HP	30	20	Floor
60	1	25	0.1	2	Low	70	100	2	HP	100	20	Floor

Table 12: Frame of the input matrix used

As it is clear from the Table 12, in each case just one or two parameters are changing in each row. This generate 78 simulations with always different combinations, perfect to underline the importance of each input on the outputs.

6 Results

6.1 The software: Lesosai

The fifth step of the SA is to calculate the output distribution given by the generated input matrix. For the smart living lab case the outputs are related to the energy performance of the building, so to calculate the outputs a software for dynamic thermal simulation has been used. Nowadays there are a lot of programs that are able to make such a kind of work, all with different characteristics and features. A long work of selection has been done to find the most suitable for this project and at the end it has been identified in the software Lesosai [43].
Lesosai is a Swiss software, developed with the support of the Solar Energy and Building Physics Laboratory of EPFL, for the certification and thermal balance calculation of buildings containing one or more heated zones. It has been chosen for two main reasons:

1. It allows easy verification of building performance by the Swiss standard SIA 380/1 and by the labels Minergie® and Minergie®-P.
2. It allows the calculation of environmental impacts of the energy consumption, taking into account the energy used in the building, but also the building's construction materials (Life Cycle Impacts Analysis).

This features are very important for this case, because the principal objective is to investigate the environmental impact of a highly performing building, like those Minergie® verified. The software it is designed primarily for building engineers, HVAC engineers and architects and it contain all the properties to model the inputs that has been chosen and descibed in the previous chapter. For example to calculate the heat transfer coefficient (U-value), the integrated software *USai* has been used, which allows the creation of constructions and materials while controlling condensation. To implement all the active parameters the Polysun Inside® Module has been adopted, perfect to perform the simulation of solar thermal, photovoltaic and geothermal systems. Moreover, as already said, Lesosai is very well indicated also regarding the outputs that can provide. It is able to perform the LCA evaluation, based on a *building life cycle* approach, with the list of impacts maintained by KBOB database and the methodology conforming to Swiss Draft Standard SIA-2032. This feature has been used to obtain the output connected to the CO_2 emissions.

6.1.1 Boundaries of the analysis

To use the software some assumptions has been done, in order to have reliable and coherent results. It is important to be clear on this hypothesis for understand the boundaries of this research. The simulations has been run all in the same context (city center) and also with the same weather file (the one for Fribourg), exposition of the building, altitude (630 m) and wind exposition (low). Then in each shape has been applied some differences, but in all of them six thermal zone has always been created:

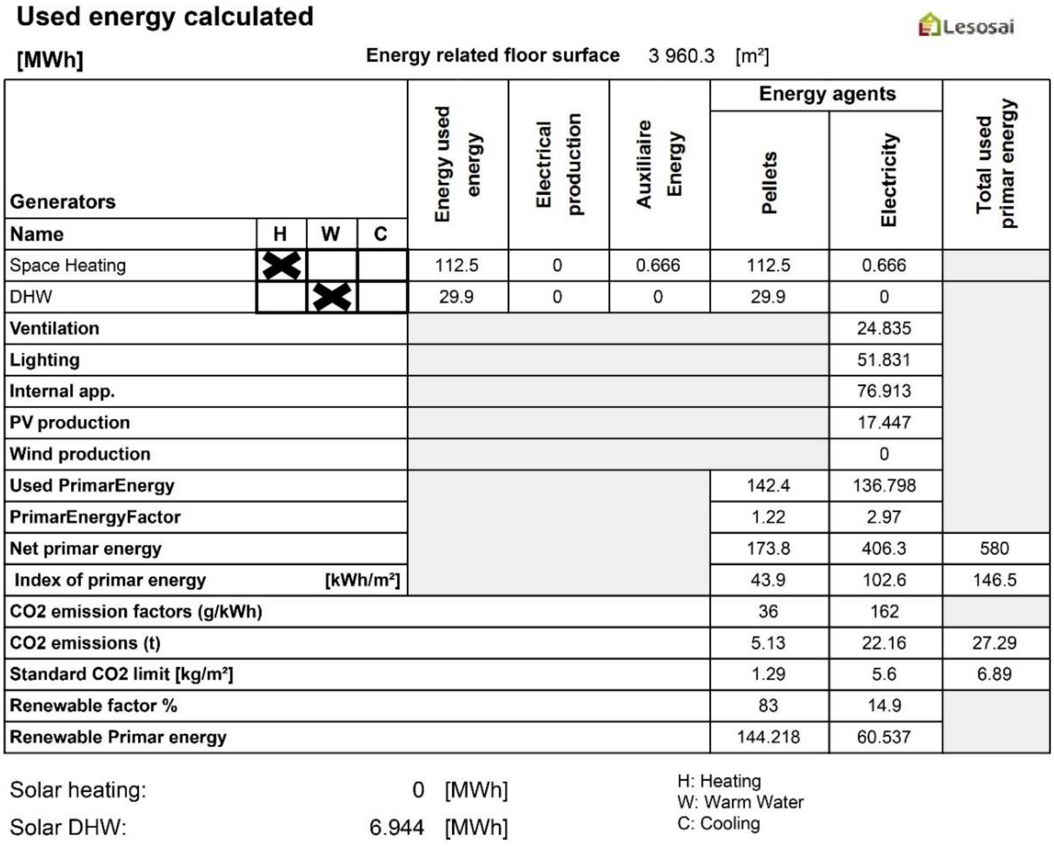
- The houses zone, located at the last 2 floors, which includes several different rooms, like bathroom, kitchen, bedroom and living room. Each of this room has been linked to the model provided by norms for each destination of use, in terms of lighting and appliances consumptions, for the air changes and for the quantity of people.
- The office one, placed at the third and fourth floor that consist of all the offices and the WC related to this area. All the offices has been created as open space, without any internal partition or walls.
- The meeting area, including only the 2/4 rooms that in each shape are defined for that scope. It has been possible with the software to link this rooms with a model exactly defined for meeting room.
- The experimental hall, one of the most difficult zone to model because the electrical consumptions and the thermal needs can be very different depending on the real destination of use of this area. For this first draft it has been decided to define it like a production area for precision work, trying in this way to simulate the equipment that are going to be used.
- Extra, this area contains the entrance, corridors, halls and all the locals without a destination of use yet. For all of them only the consumption for lighting has been calculated.

- Not heated zone, which includes all the areas where the heating is not required, like stairs and technical rooms.

6.2 Simulations

Several outputs has been obtained for each simulation. As explained before the software can provide numerous results, nevertheless the attention has been focus only on the ones useful for the sensitivity analysis as it has been already presented before. Every simulation has been run in an independent way, changing in each case the parameters as suggested by the input matrix. Afterwards the results has been saved and treated in order to be analysed.

In the Figure 26 it is possible to see a typical sample of the results generated by Lesosai. All this results for each simulation has been placed in the Annex II, in order to be consulted and compared.



Used energy calculated

Lesosai

[MWh] **Energy related floor surface** 3 960.3 [m²]

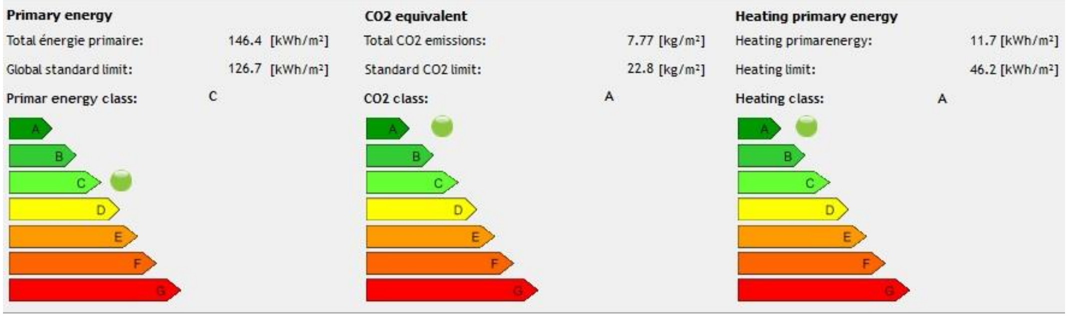
Generators							**Energy agents**		
Name	**H**	**W**	**C**	**Energy used energy**	**Electrical production**	**Auxiliaire Energy**	**Pellets**	**Electricity**	**Total used primar energy**
Space Heating	☒			112.5	0	0.666	112.5	0.666	
DHW		☒		29.9	0	0	29.9	0	
Ventilation								24.835	
Lighting								51.831	
Internal app.								76.913	
PV production								17.447	
Wind production								0	
Used PrimarEnergy							142.4	136.798	
PrimarEnergyFactor							1.22	2.97	
Net primar energy							173.8	406.3	580
Index of primar energy [kWh/m²]							43.9	102.6	146.5
CO2 emission factors (g/kWh)							36	162	
CO2 emissions (t)							5.13	22.16	27.29
Standard CO2 limit [kg/m²]							1.29	5.6	6.89
Renewable factor %							83	14.9	
Renewable Primar energy							144.218	60.537	

Solar heating: 0 [MWh]
Solar DHW: 6.944 [MWh]

H: Heating
W: Warm Water
C: Cooling

Figure 26: Model of the results of one simulation on Lesosai

As it is clear from the picture this values are in MWh, used for the whole building: the results have been normalized in kWh/m^2 to be comparted between different shapes. Then for each case the *Used PrimarEnergy* (called in the previous chapter Final energy) for SH, DHW and electricity (where are visible the different contributions of ventilation, lighting, appliances and PV production) has been acquired. Directly linked to this value, with a correlation that derive from the energy system used (e.g. in the picture a pellets boiler for the thermal part and electricity from the grid for the electrical requirements), it has been identified the *Primary Energy* used. Then, using the quantity of gCO$_2$/kWh, it has been possible to define the emissions for m^2. For each case also a fast and easy description in terms of "quality" has been produced, in order to quickly understand the energy performance of the building simulated. This is represented in the Figure 27.



Primary energy
Total énergie primaire: 146.4 [kWh/m²]
Global standard limit: 126.7 [kWh/m²]
Primar energy class: C

CO2 equivalent
Total CO2 emissions: 7.77 [kg/m²]
Standard CO2 limit: 22.8 [kg/m²]
CO2 class: A

Heating primary energy
Heating primarenergy: 11.7 [kWh/m²]
Heating limit: 46.2 [kWh/m²]
Heating class: A

Figure 27: Quality indicators

It is important to remember that the objective of this thesis it was not to create, with this set of simulations, a low consumption building. The goal was to understand, in the frame of sustainable buildings, which are the technical and architectural parameters that affect the energy performance. However it was interesting to analyse this results in order to understand if exclusively with the right combination of modern technology and solutions it was possible to reach the target values fixed for the 2000 Watt-society. From the results have been clear that this objectives are still far, but they also suggested in which field put attention in order to achieve the goal.

These results are briefly shown and commented. In the Figure 28 the demand for SH, DHW and cooling is represented.

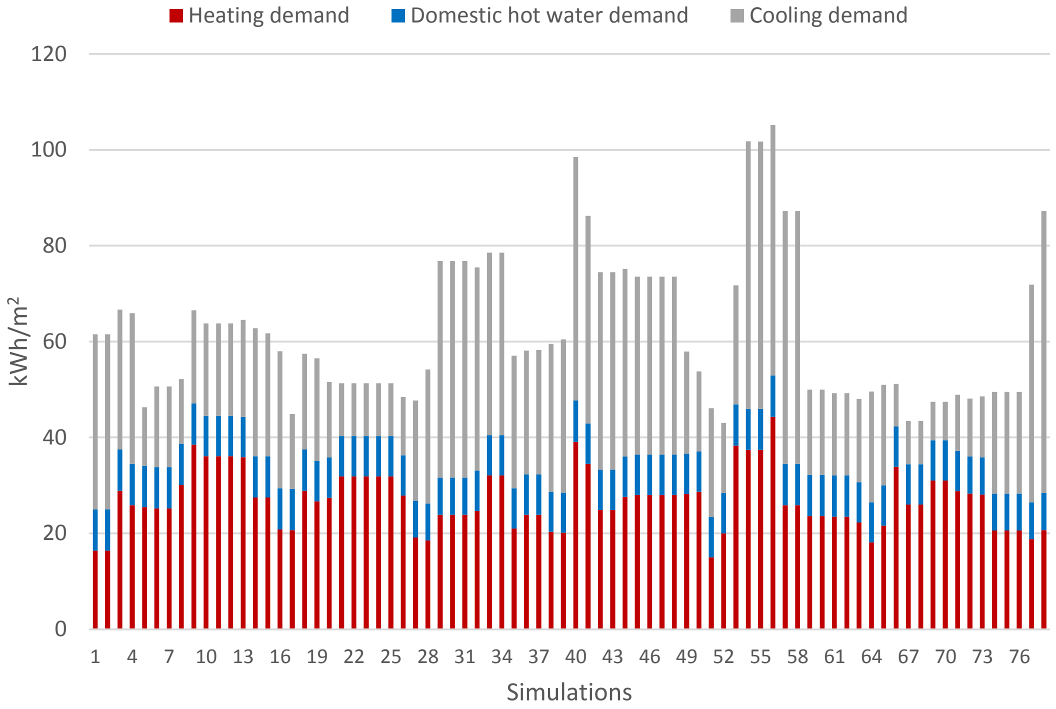


Figure 28: Energy demand of the 78 simulations

Clearly the demand for DHW it is almost the same for each case (it is only function of the shape), but what is very variable is the SH and cooling demand. Actually the cooling has not been part of the analysis, since that in Switzerland air conditioning is not allowed if not for very exceptional case (like the hospitals). Also from the case studies analysis was clear that no one of the building analysed was equipped with cooling system, but was still interested understand how large it was this cooling demand. Although from the picture it is evident a cooling issue, it has been decided to do not provide this demand, in order to set up the results as close as possible to the real Swiss conditions.

This thermal demand has been supplied with different HVAC systems, while the electricity for lighting and appliances has been provided only by the grid (minus the local PV production). In the Figure 29 the final energy for each case is reported, in order to show where has been localized the main consumptions.

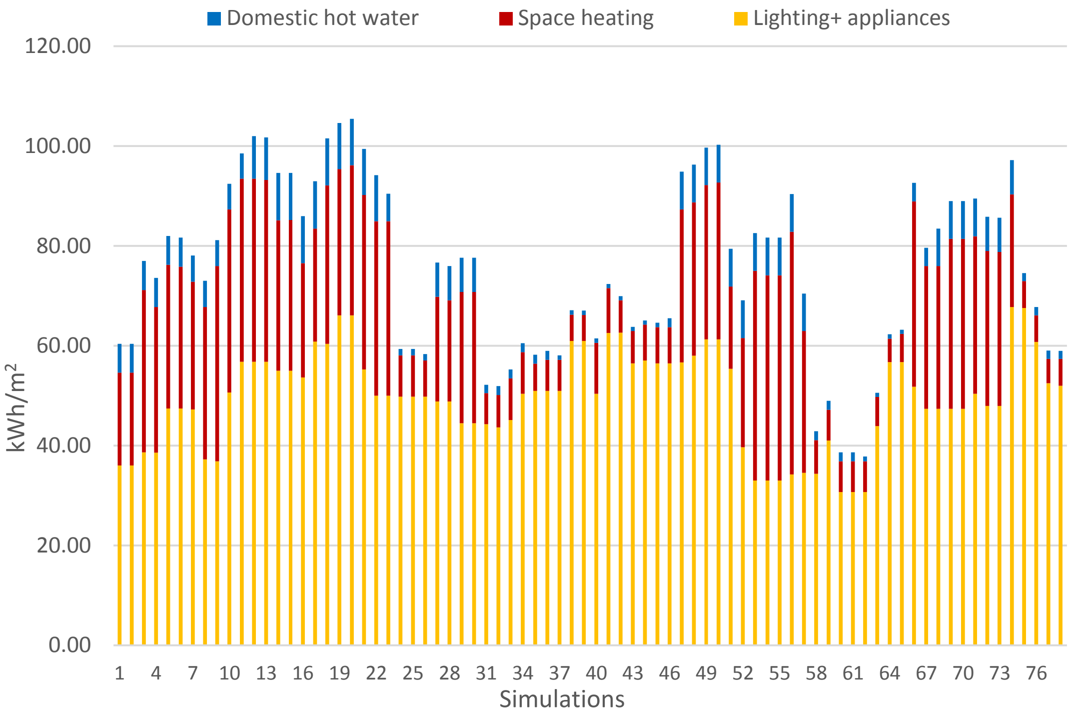


Figure 29: Final energy of the 78 simulations

It is evident as the main consumption for each case is the one related to the lighting and appliances, totally respecting the assumptions done during the case studies analysis. In addition the Figure 29 shows that the electrical consumption is also the one with the greatest potential to be reduced, while SH and DHW in same case are already at very low level, which makes the further reduction of them very difficult. To conclude this overview on the simulation's results, the primary energy and the CO_2 emission for each case are shown in the Figure 30 and in the Figure 31.

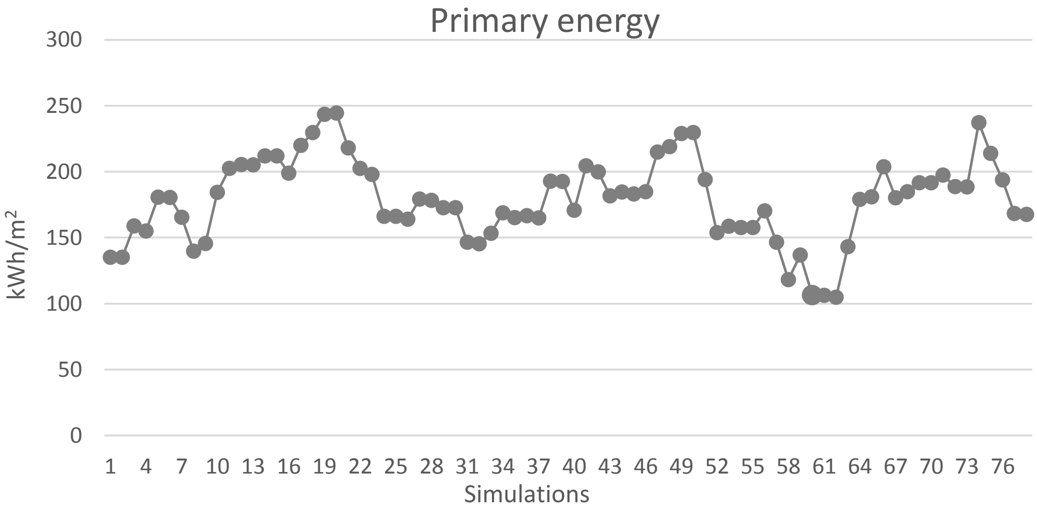


Figure 30: Primary energy of the 78 simulations

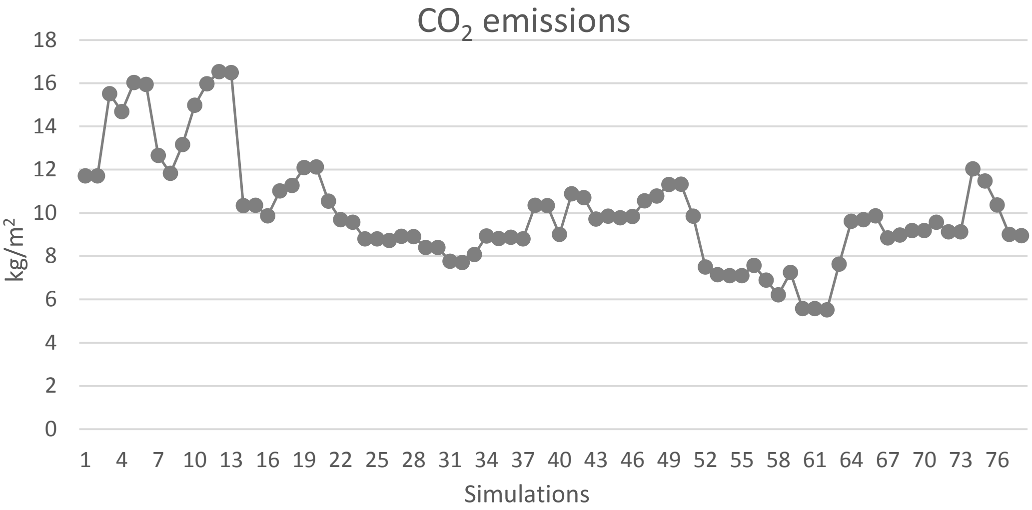


Figure 31: CO_2 emissions of the 78 simulations

These results have been presented to show how much this values can be reduced (primary energy from 250 to 100 kWh/m^2 and CO_2 from 16 to 6 kg/m^2) only changing some key parameters but without adding any kind of real innovation.

To understand which are the parameters that have led to this big variation, a further step it is necessary: the sixth one of the SA or rather assessing the relative influence of the inputs on the outputs.

6.3 Sensitivity analysis outcomes

With the results of all the 78 simulations it has been possible to obtain also the final outcome of the sensitivity analysis. As explained before, the main purpose of the Morris method is to determine the authority of each input defined on the outputs. It is possible to have only three kind of correlations between them, which are:

- Negligible (low average, low standard deviation).
- Linear and additive (high average, low standard deviation).
- Non-linear or involved in interactions with other input parameters (high standard deviation).

So this result has been used to understand which are the main contributors in the energy performance, and in which way they are correlated with the output.

6.3.1 Energy demand

The heating demand has been calculated for first, to be able since the beginning to understand how to minimize it, that seems very variable looking at the simulations results. The results are reported in the Figure 32.

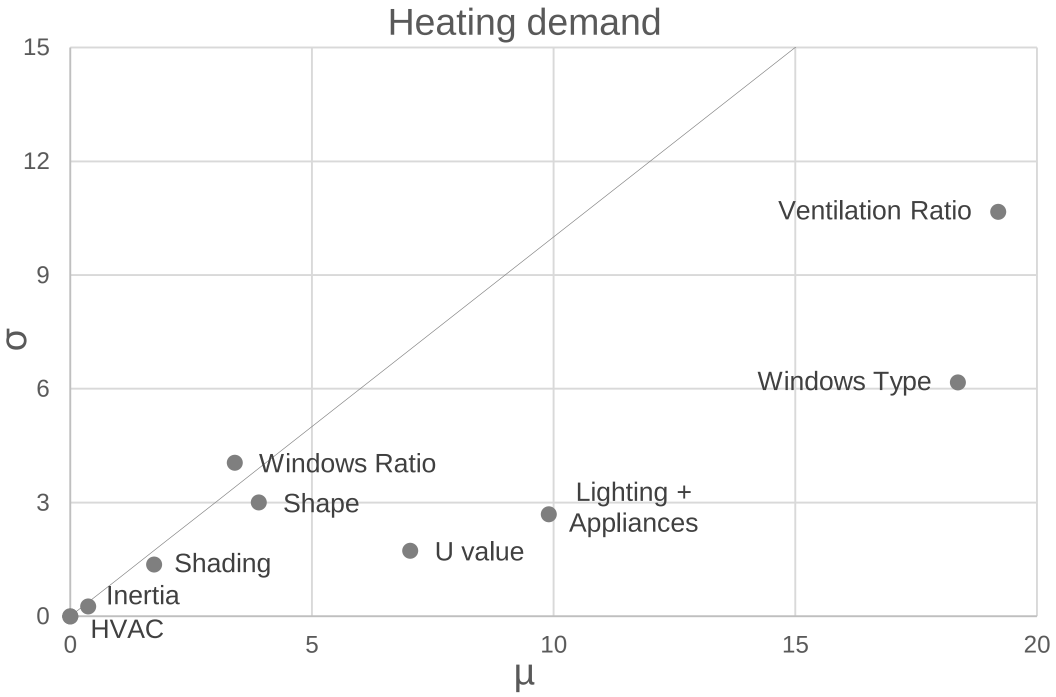


Figure 32: Results SA for the heating demand

Before to go deeper in the results, it can be useful to explain this figure, in order to be able to understand it and to use it in the proper way. As said above three possible values can be identified:

- The values with a high average and low standard deviation, like *Windows Type*, are related to the output in a linear way, so an alteration of the *Windows Type* is directly impacting the heating demand.
- The values with a standard deviation at the same magnitude of the average like *Windows Ratio*, so close to the line of the figure, are in a non-linear relations with the output or involved in interactions with other input parameters. Therefore ad example *Windows Ratio* could be linked with *Shape*, because both of them are close to the line.
- The values with low average and low standard deviation, like *Shading*, that are irrelevant in the course of the output.

Therefore the main outcome of this analysis has been a ranking of the twelve inputs, different for each output, based on their influence on the output selected. In the Table 13 is presented the ranking for the heating demand.

Heating demand	
Ventilation Ratio	19.2
Windows Type	18.3667
Lighting + Appliances	9.9
Thermal Transmittance	7.0333
Shape	3.9
Windows Ratio	3.4
Shading	1.7333
Inertia	0.3667
HVAC	0
PV panels	0
Solar Thermal	0
Heating Distribution	0

Table 13: Input ranking for the heating demand

As expected, in the demand, the parameters related to the active system are not influent, so the average value is 0. Instead of the most important parameters are *ventilation ratio* and *windows type,* which almost have the same importance.

VENTILATION RATIO: although the air exchange has been modelled with a heat recovery system of 60%, the losses introduced by the mechanical ventilation (mandatory in Switzerland) are still very important for the heating demand. To a decrement of the value of 40% corresponds a decrease in heating demand of almost 40%. From the heating point of view, cutting this losses increase exponentially the performance, while, despite the bigger influence in term of percentage of variation, for cooling it is not the most influent parameter.

WINDOWS TYPE: it has been implemented in the simulations using three different type of windows with different thermal properties. The influence of more performant windows is in heating in one direction: improving the glazed thermal properties from the type 1 (low performance) to the type 3 (high performance triple glazing) decrease the needs of almost 35%. This parameters becomes more important if watched also together with the *windows ratio* because the glazing surface is threaten in the same way on all the facades, increasing in this way also the losses on the north façade and increasing the gains of the south façade. It is clear that high performance windows can compensate the losses but can't block the solar gains, with big effects on the cooling demand.

LIGHTING AND APPLIANCES: in the simulations are considered as electrical and thermal gains. Both on cooling and heating demand it is quite important, but it influences them in the opposite way: heavier gains contribute to warming the spaces but it could easily bring to a problem of overheating. The great effect of this parameters is probably due to the SIA profiles, defined as continuous during the day and varying just in intensity.

U VALUE: the relative importance is high on heating demand and watching at the numerical results the influence is around the 20%. This is due to the fact that the values assigned are representative of a medium - high situation, ranging from 0.25 to 0.1 W/m^{2}K, so not the most performing conditions. This is the reason way the result is so affected by this parameter.

6.3.2 Final energy

The second output that has been analyzed it was the final energy, divided between the one used for SH and DHW, and the one used only for electrical requirements. In the Figure 33 are shown the results for the thermal part.

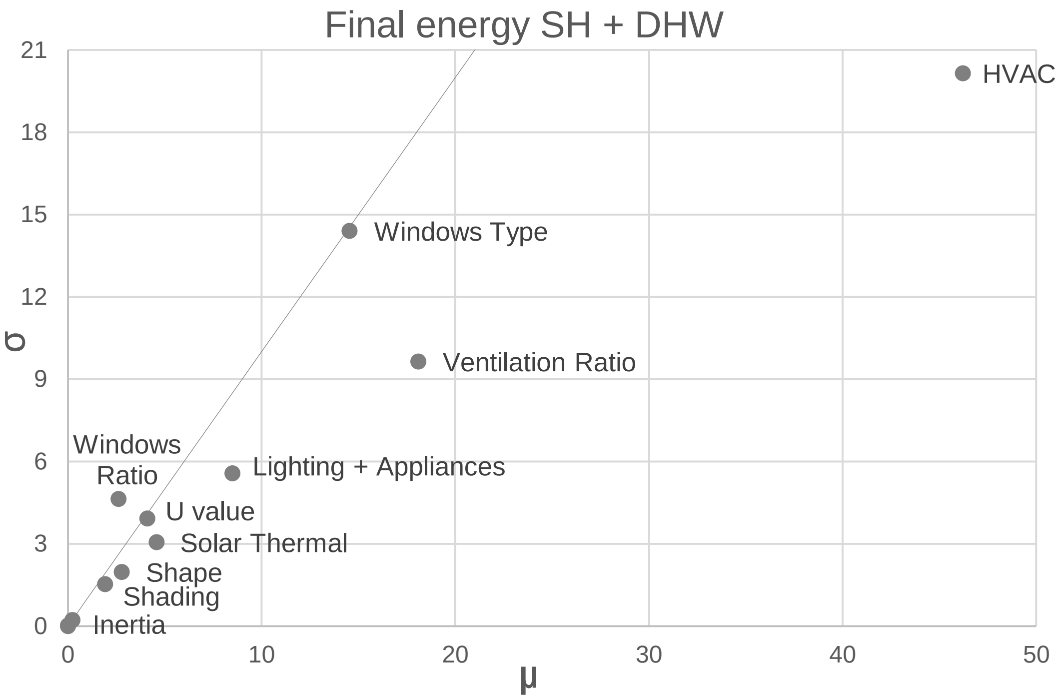


Figure 33: Results SA for the final energy SH + DHW

Final Energy SH + DHW	
HVAC	46.2167
Ventilation Ratio	18.1
Windows Type	14.5467
Lighting + Appliances	8.5033
Solar Thermal	4.5767
Thermal Transmittance	4.1
Shape	2.78
Windows Ratio	2.6167
Shading	1.9167
Inertia	0.2267
Heating Distribution	0.0067
PV panels	0

Table 14: Input ranking for the final energy SH + DHW

Compared to the heating demand it is clear that in this case the system used to supply to the needs become basic on the final results. As expected the ranking between the factors that affect mostly the needs is still the same, but implemented with the active parts. The relative importance is re-assessed accordingly to these. However two conclusions can be made: first of all that the first parameter, the *HVAC,* has an absolute value of influence which is almost 2.5 times bigger than the second one. It is clear that the efficiency of the system adopted is the most influent factor in the final energy and this lead to the finding that providing energy in a clean way is much more important than saving energy. Secondly that *Solar thermal*, in fifth position, before the *Thermal transmittance,* have a strong and positive effect to reduce the energy used for the DHW.

On the contrary, for the electrical final energy the thermal parameters are the less important, since that their effects on the consumption of electricity is not directly correlated, as it is shown in the Figure 34.

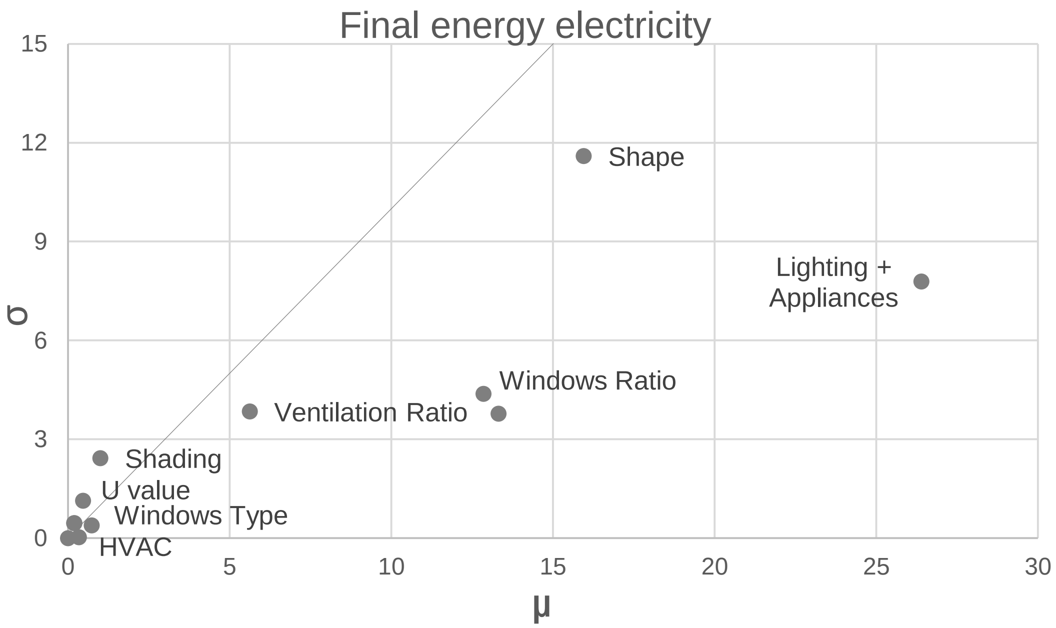


Figure 34: Results SA for the final energy electricity

Final Energy Electricity	
Lighting + Appliances	26.4
Shape	15.9533
PV panels	13.3133
Windows Ratio	12.85
Ventilation Ratio	5.62
Shading	1
Windows Type	0.7367
Heating Distribution	0.4633
HVAC	0.3333
Thermal Transmittance	0.1967
Inertia	0.19
Solar Thermal	0

Table 15: Input ranking for the final energy electricity

Three groups of parameters can be defined from the Table 15: the first one, which includes all the factors directly related to the electrical final energy used (absolute value more than 10), the second that contains the parameters correlated to the relationship between lighting and daylight (absolute value more than 1), and the third with all the thermal parameters which have weak influence with the output/other inputs (absolute value less than 1).

LIGHTING AND APPLIANCES: it is the most influent parameters, since that the weight is very heavy and, due to the high electrical requirements of the working spaces, the request is very high. As it is clear the correlation is strongly linear, so a variation on this input is evident on the output. Varying the input value from the one with the highest consumption to the most performant one, it is has been found a reduction for the energy used of almost 35%, without any link with the others input parameters.

SHAPE: it is representative of the proportion between each destination of use, more than the compactness of the volume. It is very influent because the surface for each usage space requires different electrical power, driving then the consumption for electrical appliances and, consequently, impacting on the final output through the correlation with the first ranked input. The relation with the output is non-linear, as is strongly related to the *lighting and appliances,* so regarding to the value of this parameter the influence of the shape on the finale energy can vary between 10 and 40%.

PV PANELS: it is clearly very influent due to the final balance on the electrical consumption. Related to the way it has been implemented into the simulation, it is strictly connected to the *shape* as the surface available is always different.

WINDOWS RATIO: defined as the percentage of glazing surface on the façade, it represents the dimensions of the windows implemented. It is therefore clear that the effects are mainly related to the lighting system: in the simulations the lights are implemented with a regulation system that considers also the natural daylighting level and calibrate the switching on of the artificial lamp based on that. Enlarging the glazing surface, therefore, brings to higher daylight availability, decreasing the lighting consumption. The same principle is applicable to the *shading*, which influence is related to the quantity of illuminance that the system let enter into the room. Since that it functions only during the summer period, then the relative weight in the output is smaller.

6.3.3 Primary energy

The primary energy ranking is a perfect mix between the electrical and thermal one. As it is shown in the Table 16 the first two parameters are the main contributor of the other outputs.

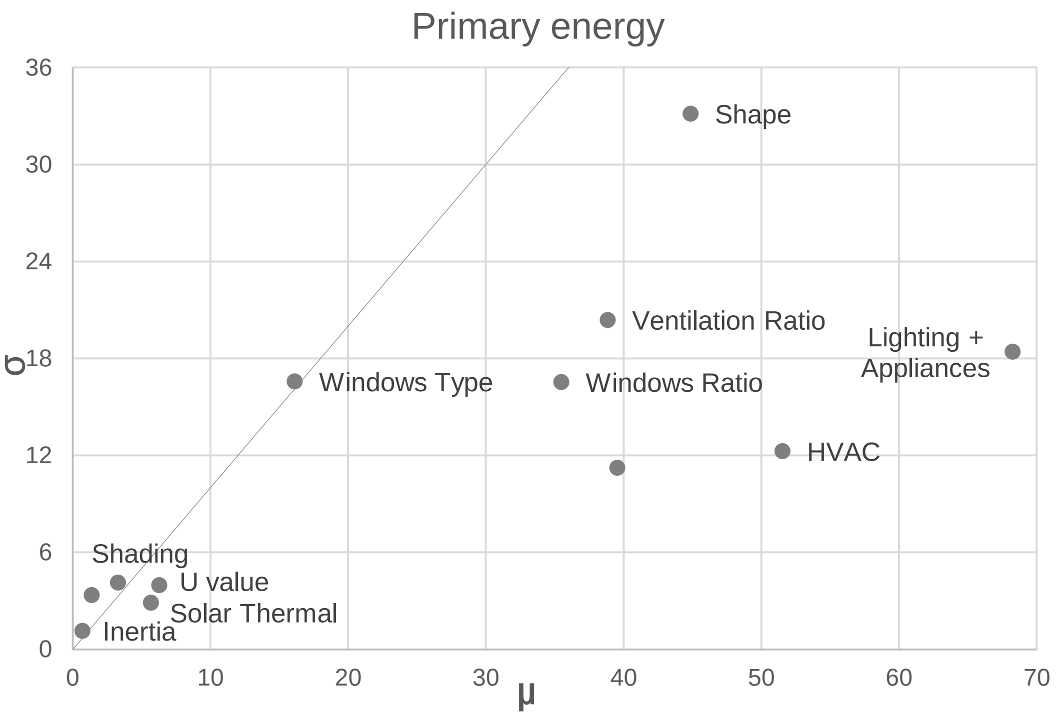


Figure 35: Results SA for the primary energy

Primary Energy	
Lighting + Appliances	68.2633
HVAC	51.5433
Shape	44.8733
PV panels	39.5467
Ventilation Ratio	38.86
Windows Ratio	35.4767
Windows Type	16.1067
Thermal Transmittance	6.28
Solar Thermal	5.6833
Shading	3.2933
Heating Distribution	1.3867
Inertia	0.71

Table 16: Input ranking for the primary energy

From the results it is possible to notice that the absolute value of the main parameters is much bigger than on the other outputs, this is due to great influence that they have on the primary energy and it means that there is a great potential in each of them to improve the final consumption. It is also clear that the electrical part due to *appliances and lighting* is the strongest, followed by the thermal part due to the *HVAC* chosen. Then *shape* and *PV panels* preserve their position with a strong influence on the output but also a strong relation between them and other parameters. Also on the primary energy the most important part of the envelope is represented by the glazing surface *windows ratio* and *windows type*, more than the thermal shield.

6.3.4 CO_2 emissions

The last output analyzed has been the CO_2 emissions, to understand which are the main contributors related to this issue and to identify a strategy to reduce them. The results are shown in the Figure 36 and in the Table 17.

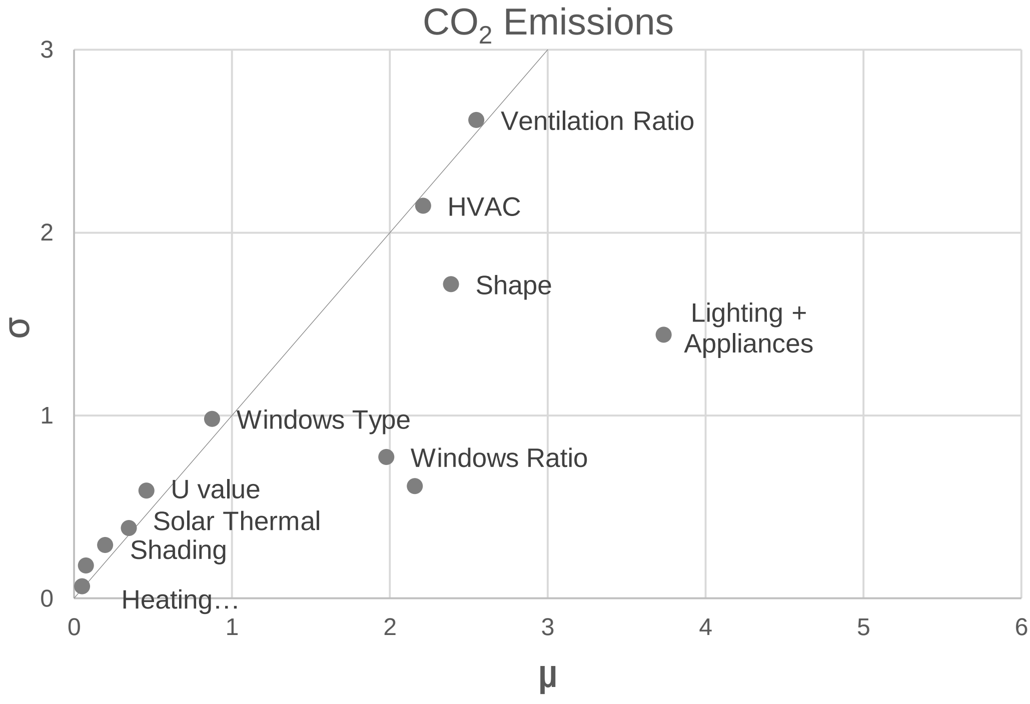


Figure 36: Results SA for the CO_2 emissions

CO_2 Emissions	
Lighting + Appliances	3.7333
Ventilation Ratio	2.5467
Shape	2.3867
HVAC	2.21
PV panels	2.1567
Windows Ratio	1.9767
Windows Type	0.8733
Thermal Transmittance	0.4567
Solar Thermal	0.3467
Shading	0.1967
Heating Distribution	0.0733
Inertia	0.05

Table 17: Input ranking for the CO_2 emissions

As always *lighting and appliances* is the parameter with the biggest influence, and as always is not very related with the others but it is the only one with a linear correlations with the emissions. It is also clear as in absolute value the average is lowest than in the previous case (Primary energy), this because there are not inputs with an independent association with the output. *Ventilation Ratio, Shape, HVAC, PV panels, Windows Ratio, Windows Type* are all parameters that can affect the CO_2 emissions, but that must be balanced between them to find the most suitable solution. Just to make an example, there is no point to improve the *thermal transmittance* in order to reduce the energy used for heating, if this energy is provided by a not efficient *HVAC* system. In this way only the heating demand will be reduced, but the CO_2 emissions will not be touched by this change.

Conclusions

The aim of this thesis was to set a methodology to optimize the energy concept of the smart living building, in order to reach the environmental objectives given by the 2000 Watt-society. Sensitivity analysis on building energy behaviour and assessment of interdependence between the main design parameters unveil the potential of this approach to lead a clearer and definite point of view on the performance of the building. This methodology has made it possible to identify the major technical and architectural macro-parameters contributors on the reduction of the main energy indicators of the building: heating demand, final energy, primary energy [kWh/m^2] and CO_2 emissions [kgCO_2/m^2]. The results have been processed for each output, in order to understand the correlations between the inputs and between the different outputs.

The main findings have been obtained for the final and primary energy. The analysis performed for the thermal final energy has shown how decisive is the choice of the *HVAC* system regarding all the other design strategies. For the space heating it is consequently possible to conclude that providing energy in an efficient way is much more effective than reducing energy demand. The parameter *lighting and appliances* was the most important for the final energy used for electricity. Likewise, this result was expected because the importance of this parameter was already revealed during the case study analysis. However, the wide impact of this value on the primary energy used for the whole building was not foreseeable. The analysis done for the primary energy has shown that *lighting and appliances* is again the most effective one, but also that many other parameters, like *HVAC, shape, PV panels, ventilation ratio* and *windows ratio,* are strongly related with this output. This means that an independent variation of one of these parameters can directly change the primary energy which is used. The opposite results have been found for the last output analyzed, the CO_2 emissions. Once again *lighting and appliances* is the parameter that lead the ranking, with a linear relation with the emissions. In this case all the other values are strictly correlated, demonstrating how difficult it

is to reduce the CO_2 emissions of the whole building without taking into account all the involved parameters.
Thanks to the results obtained it will be possible to specify better the macro-parameters used as input into micro-parameters. A more accurate sensitivity analysis will then be performed on the detailed micro-parameters, to further investigate the detected issue.

Before concluding, it is worth remembering that this analysis represented the cornerstone to build the energy concept of the *smart living lab*. However it is clear that a great effort must be done to reduce and optimize the consumption of appliances and lighting. This field is responsible of the highest energy consumption and of the greater impact on the CO_2 emissions. Accordingly the next research phase will focus on new and innovative solutions to provide this energy, using other technology to avoid the power grid beyond the PV panels.

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ANNEX I

Sample matrix

Matrix generated by the statistical approach to the sensitivity analysis. It includes all the simulations that must be run to assess the influence of each design parameters on the final output. Each line represents a case study: it identifies the combination of inputs that describes the building features.

Nr.	*Shape*	*Windows Ratio*	*U value*	*Windows Type*	*Inertia*	*Shading*	*Vent Ratio*	*Lighting Applian*	*HVAC*	*PV panels*	*Solar Thermal*	*Heating Distribution*
1	1	75	0.25	3	Low	50	80	1	Natural gas	100	40	Air heating
2	1	75	0.25	3	Low	50	80	1	Natural gas	100	40	Floor heating
3	1	75	0.25	3	Low	50	120	1	Natural gas	100	40	Floor heating
4	1	75	0.15	3	Low	50	120	1	Natural gas	100	40	Floor heating
5	1	25	0.15	3	Low	50	120	1	Natural gas	100	40	Floor heating
6	1	25	0.15	3	Low	90	120	1	Natural gas	100	40	Floor heating
7	1	25	0.15	3	Low	90	120	1	District heating	100	40	Floor heating
8	1	25	0.15	3	Low	90	120	3	District heating	100	40	Floor heating
9	1	25	0.15	1	Low	90	120	3	District heating	100	40	Floor heating
10	3	25	0.15	1	Low	90	120	3	District heating	100	40	Floor heating
11	3	25	0.15	1	Low	90	120	3	District heating	30	40	Floor heating
12	3	25	0.15	1	Low	90	120	3	District heating	30	0	Floor heating
13	3	25	0.15	1	High	90	120	3	District heating	30	0	Floor heating
14	1	50	0.2	3	Average	70	120	1	Pellets	0	0	Floor heating
15	1	50	0.2	3	Low	70	120	1	Pellets	0	0	Floor heating
16	1	50	0.2	3	Low	70	100	1	Pellets	0	0	Floor heating
17	1	25	0.2	3	Low	70	100	1	Pellets	0	0	Floor heating
18	1	25	0.2	1	Low	70	100	1	Pellets	0	0	Floor heating
19	3	25	0.2	1	Low	70	100	1	Pellets	0	0	Floor heating
20	3	25	0.2	1	Low	20	100	1	Pellets	0	0	Floor heating
21	3	25	0.2	1	Low	20	100	3	Pellets	0	0	Floor heating
22	3	25	0.2	1	Low	20	100	3	Pellets	60	0	Floor heating
23	3	25	0.2	1	Low	20	100	3	Pellets	60	40	Floor heating
24	3	25	0.2	1	Low	20	100	3	Heat pump	60	40	Floor heating

25	3	25	0.2	1	Low	20	100	3	Heat pump	60	40	Air heating
26	3	25	0.1	1	Low	20	100	3	Heat pump	60	40	Air heating
27	2	25	0.1	1	Low	50	80	3	Pellets	60	20	Air heating
28	2	25	0.1	1	Low	90	80	3	Pellets	60	20	Air heating
29	2	50	0.1	1	Low	90	80	3	Pellets	60	20	Air heating
30	2	50	0.1	1	Low	90	80	3	Pellets	60	20	Floor heating
31	2	50	0.1	1	Low	90	80	3	Heat pump	60	20	Floor heating
32	3	50	0.1	1	Low	90	80	3	Heat pump	60	20	Floor heating
33	3	50	0.1	1	Low	90	100	3	Heat pump	60	20	Floor heating
34	3	50	0.1	1	Low	90	100	3	Heat pump	0	20	Floor heating
35	3	50	0.1	3	Low	90	100	3	Heat pump	0	20	Floor heating
36	3	50	0.2	3	Low	90	100	3	Heat pump	0	20	Floor heating
37	3	50	0.2	3	Low	90	100	3	Heat pump	0	60	Floor heating
38	3	50	0.2	3	Low	90	100	1	Heat pump	0	60	Floor heating
39	3	50	0.2	3	Average	90	100	1	Heat pump	0	60	Floor heating
40	1	50	0.1	1	High	90	120	4	Heat pump	30	60	Ceiling heating
41	3	50	0.1	1	High	90	120	4	Heat pump	30	60	Ceiling heating
42	3	50	0.1	2	High	90	120	4	Heat pump	30	60	Ceiling heating
43	3	50	0.1	2	High	90	120	4	Heat pump	100	60	Ceiling heating
44	3	50	0.2	2	High	90	120	4	Heat pump	100	60	Ceiling heating
45	3	50	0.2	2	Low	90	120	4	Heat pump	100	60	Ceiling heating
46	3	50	0.2	2	Low	90	120	4	Heat pump	100	20	Ceiling heating
47	3	50	0.2	2	Low	90	120	4	Pellets	100	20	Ceiling heating
48	3	50	0.2	2	Low	90	120	4	Pellets	100	20	Radiators
49	3	25	0.2	2	Low	90	120	4	Pellets	100	20	Radiators
50	3	25	0.2	2	Low	50	120	4	Pellets	100	20	Radiators

51	3	25	0.2	2	Low	50	80	4	Pellets	100	20	Radiators
52	3	25	0.2	2	Low	50	80	2	Pellets	100	20	Radiators
53	1	75	0.1	1	Low	20	80	2	Pellets	30	20	Air heating
54	1	75	0.1	1	Low	70	80	2	Pellets	30	20	Air heating
55	1	75	0.1	1	Low	70	80	2	Pellets	30	20	Floor heating
56	1	75	0.1	1	Low	70	100	2	Pellets	30	20	Floor heating
57	1	75	0.1	2	Low	70	100	2	Pellets	30	20	Floor heating
58	1	75	0.1	2	Low	70	100	2	Heat pump	30	20	Floor heating
59	1	25	0.1	2	Low	70	100	2	Heat pump	30	20	Floor heating
60	1	25	0.1	2	Low	70	100	2	Heat pump	100	20	Floor heating
61	1	25	0.1	2	High	70	100	2	Heat pump	100	20	Floor heating
62	1	25	0.1	2	High	70	100	2	Heat pump	100	60	Floor heating
63	3	25	0.1	2	High	70	100	2	Heat pump	100	60	Floor heating
64	3	25	0.1	2	High	70	100	4	Heat pump	100	60	Floor heating
65	3	25	0.2	2	High	70	100	4	Heat pump	100	60	Floor heating
66	3	25	0.15	3	Low	20	120	2	Pellets	30	60	Air heating
67	3	25	0.15	3	Low	20	100	2	Pellets	30	60	Air heating
68	3	25	0.15	3	Low	20	100	2	Pellets	30	20	Air heating
69	3	25	0.25	3	Low	20	100	2	Pellets	30	20	Air heating
70	3	25	0.25	3	Low	20	100	2	Pellets	30	20	Floor heating
71	3	25	0.25	3	Low	70	100	2	Pellets	30	20	Floor heating
72	2	25	0.25	3	Low	70	100	2	Pellets	30	20	Floor heating
73	2	25	0.25	3	High	70	100	2	Pellets	30	20	Floor heating
74	2	25	0.25	3	High	70	100	4	Pellets	30	20	Floor heating
75	2	25	0.25	3	High	70	100	4	Heat pump	30	20	Floor heating
76	2	25	0.25	3	High	70	100	4	Heat pump	100	20	Floor heating

77	2	75	0.25	3	High	70	100	4	Heat pump	100	20	Floor heating
78	2	75	0.25	2	High	70	100	4	Heat pump	100	20	Floor heating

ANNEX II

Output arrays

Table of the several outputs used for the sensitivity analysis. Each column represents an output array on which the assessment of inputs influence is made; the results of the analysis are independent from one output to the other.

Nr.	*Final energy HEATING kWh/m^2*	*Final energy DHW kWh/m^2*	*Final SH + DHW kWh/m^2*	*Energy PRIMARY kWh/m^2*	*CO2 SH+DHW kg/m^2*	*CO2 ELECTRICITY kg/m^2*	*CO2 Total kg/m^2*	*Demand HEATING kWh/m^2*	*Demand COOLING kWh/m^2*	*Final energy ELECTRICITY kWh/m^2*
1	18.53	5.81	24.34	135.12	5.87	5.84	11.71	16.40	36.53	36.07
2	18.53	5.81	24.34	135.12	5.87	5.84	11.71	16.40	36.53	36.07
3	32.55	5.81	38.36	158.88	9.25	6.26	15.51	28.90	29.18	38.64
4	29.16	5.81	34.97	154.94	8.43	6.26	14.69	25.90	31.43	38.63
5	28.76	5.81	34.57	180.72	8.34	7.69	16.03	25.50	12.17	47.46
6	28.41	5.81	34.21	180.29	8.25	7.69	15.94	25.20	16.87	47.45
7	25.55	5.23	30.78	165.39	4.99	7.66	12.65	25.20	16.87	47.29
8	30.53	5.23	35.75	139.61	5.79	6.04	11.83	30.10	13.47	37.26
9	39.06	5.23	44.29	145.44	7.18	5.98	13.16	38.50	19.44	36.89
10	36.68	5.10	41.78	184.28	6.77	8.21	14.98	36.10	19.30	50.65
11	36.68	5.10	41.78	202.53	6.77	9.20	15.97	36.10	19.30	56.80
12	36.68	8.55	45.23	205.33	7.33	9.20	16.53	36.10	19.30	56.80
13	36.40	8.55	44.96	205.10	7.28	9.20	16.48	35.90	20.21	56.80
14	30.12	9.44	39.57	211.78	1.42	8.92	10.34	27.50	26.68	55.04
15	30.15	9.44	39.59	211.80	1.43	8.92	10.35	27.50	25.60	55.04
16	22.85	9.44	32.30	198.87	1.16	8.70	9.86	20.80	28.56	53.69
17	22.68	9.44	32.12	219.83	1.16	9.85	11.01	20.70	15.60	60.82
18	31.74	9.44	41.18	229.68	1.48	9.79	11.27	28.90	19.94	60.41
19	29.33	9.24	38.57	243.37	1.39	10.71	12.10	26.70	21.43	66.10
20	30.10	9.24	39.34	244.31	1.42	10.71	12.13	27.40	15.77	66.10
21	34.97	9.24	44.22	218.03	1.59	8.95	10.54	31.90	11.04	55.24
22	34.97	9.24	44.22	202.42	1.59	8.10	9.69	31.90	11.04	49.99

23	34.97	5.51	40.48	197.87	1.46	8.10	9.56	31.90	11.04	49.99
24	8.30	1.31	9.61	165.96	0.73	8.07	8.80	31.90	11.04	49.80
25	8.30	1.31	9.61	165.96	0.73	8.07	8.80	31.90	11.04	49.80
26	7.26	1.31	8.57	164.00	0.65	8.07	8.72	27.90	12.13	49.80
27	20.97	6.85	27.82	179.11	1.00	7.92	8.92	19.10	20.92	48.87
28	20.26	6.85	27.11	178.20	0.98	7.92	8.90	18.50	27.98	48.87
29	26.28	6.85	33.13	172.52	1.19	7.21	8.40	23.90	45.20	44.48
30	26.28	6.85	33.13	172.52	1.19	7.21	8.40	23.90	45.20	44.48
31	6.24	1.62	7.86	146.42	0.59	7.18	7.77	23.90	45.20	44.32
32	6.43	1.79	8.22	145.26	0.62	7.08	7.70	24.70	42.37	43.70
33	8.34	1.79	10.13	153.13	0.77	7.31	8.08	32.10	38.04	45.14
34	8.34	1.79	10.13	168.73	0.77	8.16	8.93	32.10	38.04	50.40
35	5.45	1.79	7.24	165.10	0.55	8.26	8.81	21.00	27.66	51.00
36	6.22	1.79	8.01	166.54	0.61	8.26	8.87	23.90	25.83	51.00
37	6.22	0.87	7.09	164.83	0.54	8.26	8.80	23.90	25.95	51.00
38	5.28	0.87	6.16	192.70	0.47	9.88	10.35	20.30	30.80	60.98
39	5.22	0.87	6.10	192.59	0.46	9.88	10.34	20.10	31.96	60.98
40	10.18	0.93	11.11	170.59	0.84	8.17	9.01	39.10	50.82	50.41
41	8.97	0.87	9.85	204.38	0.75	10.14	10.89	34.50	43.33	62.57
42	6.47	0.87	7.35	199.82	0.56	10.15	10.71	24.90	41.22	62.62
43	6.47	0.87	7.35	181.55	0.56	9.15	9.71	24.90	41.22	56.48
44	7.18	0.87	8.05	184.57	0.61	9.24	9.85	27.60	39.18	57.04
45	7.29	0.87	8.16	183.07	0.62	9.15	9.77	28.00	37.16	56.48
46	7.29	1.79	9.08	184.79	0.69	9.15	9.84	28.00	37.16	56.48
47	30.70	7.54	38.24	214.92	1.38	9.18	10.56	28.00	37.16	56.65
48	30.70	7.54	38.24	219.03	1.38	9.40	10.78	28.00	37.16	58.04

49	30.89	7.54	38.44	228.92	1.38	9.93	11.31	28.20	21.29	61.29
50	31.45	7.54	38.99	229.60	1.40	9.93	11.33	28.70	16.72	61.29
51	16.49	7.54	24.03	193.93	0.87	8.98	9.85	15.00	22.72	55.42
52	21.91	7.54	29.45	153.75	1.06	6.43	7.49	20.00	14.65	39.67
53	41.97	7.55	49.52	158.60	1.78	5.36	7.14	38.30	24.88	33.06
54	41.08	7.55	48.63	157.51	1.75	5.35	7.10	37.40	55.79	33.05
55	41.06	7.55	48.61	157.46	1.75	5.35	7.10	37.40	55.70	33.05
56	48.58	7.55	56.13	170.26	2.02	5.55	7.57	44.30	52.27	34.28
57	28.41	7.55	35.96	146.45	1.29	5.60	6.89	25.90	52.77	34.54
58	6.74	1.79	8.53	118.12	0.64	5.57	6.21	25.90	52.77	34.37
59	6.14	1.79	7.93	136.83	0.60	6.65	7.25	23.60	17.75	41.06
60	6.14	1.79	7.93	106.20	0.60	4.98	5.58	23.60	17.75	30.75
61	6.14	1.79	7.93	106.20	0.60	4.98	5.58	23.50	17.15	30.75
62	6.14	0.93	7.07	104.61	0.53	4.98	5.51	23.50	17.15	30.75
63	5.81	0.87	6.68	143.06	0.51	7.12	7.63	22.30	17.32	43.94
64	4.70	0.87	5.57	178.99	0.42	9.19	9.61	18.10	23.10	56.74
65	5.63	0.87	6.50	180.74	0.49	9.19	9.68	21.60	21.00	56.74
66	37.16	3.70	40.86	203.69	1.47	8.39	9.86	33.90	8.86	51.80
67	28.56	3.70	32.26	180.14	1.16	7.68	8.84	26.00	9.03	47.40
68	28.56	7.54	36.10	184.82	1.30	7.68	8.98	26.00	9.03	47.40
69	34.03	7.54	41.57	191.55	1.50	7.68	9.18	31.00	8.05	47.42
70	34.03	7.54	41.57	191.55	1.50	7.68	9.18	31.00	8.05	47.42
71	31.56	7.54	39.10	197.38	1.41	8.16	9.57	28.80	11.69	50.40
72	31.04	6.85	37.89	188.69	1.36	7.77	9.13	28.30	12.14	47.96
73	30.82	6.85	37.67	188.42	1.36	7.77	9.13	28.10	12.77	47.97
74	22.62	6.85	29.47	237.17	1.06	10.97	12.03	20.60	21.24	67.75

75	5.36	1.62	6.98	213.91	0.53	10.95	11.48	20.60	21.24	67.60
76	5.36	1.62	6.98	193.63	0.53	9.84	10.37	20.60	21.24	60.77
77	4.91	1.62	6.53	168.22	0.49	8.51	9.00	18.80	45.40	52.51
78	5.39	1.62	7.01	167.58	0.53	8.42	8.95	20.70	58.84	51.99