Stochastic comparative LCA of smart buildings

Marie-Lise Pannier[1*], *Thomas* Remoué[2], and *David* Bigaud[1]

[1]Univ Angers, LARIS, SFR MATHSTIC, F-49000 Angers, France
[2]Department Sustainable Building Engineering, Polytech Annecy Chambéry, 2 Avenue du Lac d'Annecy, 73370, Le-Bourget-du-Lac, France

Abstract. Driven by the energy and digital transitions, the concept of smart buildings is gaining importance. In most cases, these buildings are designed with the aim of reducing the consumption of energy resources during the operation phase, while improving the occupants' comfort and safety. However, smart sensors and actuators themselves have impacts on other environmental indicators and life cycle stages. In this work, the environmental performances of a smart multifamily house and of a standard one are compared using both dynamic building energy simulations and life cycle assessments (LCA). Two insulation levels are possible for the building and the alternatives' comparison includes uncertainties and variabilities related to occupancy. It turns out that smart building has less impacts than conventional one over their entire life cycle, but their benefit decreases when the level of insulation increases.

1 Introduction

1.1 Context

In recent years, there was an increasing research interest in the concepts of Smart Building and Internet of Things. Buildings are more and more equipped with connected devices and it is expected that these buildings have an optimised energy and comfort management. Several studies have shown the benefits of combining connected sensors and actuators integrating for instance predictive control and machine learning algorithms to decrease the energy consumption during the operation phase [1]. In these studies, the emphasis was on:
- building monitoring: use of smart sensors such as intelligent assistant to give feedback or advice to users regarding the use of equipment;
- building management: use of smart sensors and actuators to control energy equipment;
- building commissioning: detection of faults at the early stage of the building use phase;
- or building renovation: understanding of the actual building operation and adaptation of the renovation strategies accordingly.

However, smart sensors and actuators themselves consume energy. In addition, beyond their energy consumption during the use phase, they may also cause other problems or damages to the environment for their production, use or end-of-life. In this article, we propose to extend the scope to assess the overall performances of Smart Buildings and to include an

* Corresponding author: marie-lise.pannier@univ-angers.fr

uncertainty analysis of the results. Following a life cycle approach, smart and conventional buildings are statistically compared considering several environmental indicators.

1.2 State of the art

A few studies focused on the environmental impact assessment of smart buildings over their entire life cycle. The articles identified assessed residential buildings [2–4], offices [5] or metro stations [6]. Smart devices were installed to monitor or manage the lighting consumptions [5,6], other electricity consumptions [2,4,6], or heating consumptions [3].

The sensors included in the scope of these studies were ambient sensors [3,4], motion sensors [5] and electricity or gas meters [2,4,6]. Smart actuators were also investigated such as smart plugs [2,4], thermostats [3], valves [3] or control units [3]. In addition, the studied buildings were equipped with user interfaces [2,4].

Energy consumption was investigated using the cumulative energy demand indicator [2], by calculating the energy payback time [5,6] or by calculating environmental impacts per kWh of energy saved [3]. Some studies framed in a multicriteria context and a life cycle assessment (LCA) was performed [2–4].

Most of the studies were comparative. The authors compared different smart systems [2–4] or lifespan for the smart devices [6]. They also studied the effect of the source of electricity [3] or the effect of the number of inhabitants [4]. Prospective LCA (with future scenarios) [3] and dynamic LCA (with time-varying factors) [4] were performed in some cases.

In previous studies, the smart version of the building was not always the best alternative [4,5]. In addition, the authors pointed out that the savings could vary over time because of behavioural [2] or technological changes such as a transition in the electricity mix [3].

Based on previous work, the present study intends to further analyse the potential benefits of a smart multifamily house compared to a conventional one following an LCA approach. In order to complement existing works, the effect of the energy standard is studied as well as the effect of uncertainties and variabilities due to the behaviour of occupants.

2 Case study and methodology

2.1 Case study

The case study is a multifamily house located in Angers, France. It consists of six dwellings spread over three storeys. Each dwelling has two to three main rooms. The building area reaches 380 m² and it is electrically heated.

Two energy performance levels are possible, corresponding to two designs. In the first one, referring to building built in France in the 90s, the orientation is not optimal, and the building is poorly insulated (R_{wall}=1.52 m².K/W). The second one is closed to a passive design. The house is well insulated (R_{wall}=5.18 m².K/W), well oriented, and has a heat pump.

Three smart alternatives are compared (see Table 1). The first one serves as a baseline. It is a conventional building without sensors nor actuators, for which no energy saving is possible. In the second alternative, the building is monitored with ambient sensors (such as temperature or CO_2 sensors) and energy meters. A user interface informs occupants about the building performances and consumptions and gives personalised advice to reduce consumption. Occupants can follow or ignore the advice. Energy savings may therefore vary. We assume that the savings on heating and electricity are normally distributed with 4 % savings as a mean value and 1.5 % as a standard deviation. The third option is a building energy management system. Based on data collected by the smart sensors, the smart actuators act on building systems without involving occupants. As occupants can still manually change

https://doi.org/10.1051/e3sconf/202234904012

the regulation set by the actuators, energy savings remain variable. We assume that the heating and electricity savings are normally distributed with 20 % savings as a mean value and 1.5 % as a standard deviation. The assumed savings for the second and third alternatives are based on data from the literature [2,3,7–9]. Beside energy savings, the life cycle environmental impacts of the smart devices is included in the scope.

Table 1. Smart Buildings' alternatives.

Alternative		**Energy savings**	**Smart devices**
1.	Without sensor	No energy savings	No smart equipment
2.	Building monitoring	Savings : random samplings in N(μ = 4% ; σ= 1,5 %)	Ambient sensors in main rooms, energy counters User interface
3.	Building management	Savings : random samplings in N(μ = 20% ; σ= 5 %)	Ambient sensors, thermostats, energy counters, actuators (radiators, smart plugs) Control unit and user interface

Finally, different family types with different equipment levels can live in a same dwelling. For that reason, instead of considering a deterministic occupancy scenario (for the heating setpoint, the presence of occupants, or the internal loads), many simulations with different realistic occupancy scenarios are performed, to take the variability of occupancy into account.

2.2 Methodology

In order to compare the smart and conventional buildings, simulations are performed with the dynamic building energy simulation and building LCA software Pléiades[†]. The methodological steps are summarised in Fig. 1.

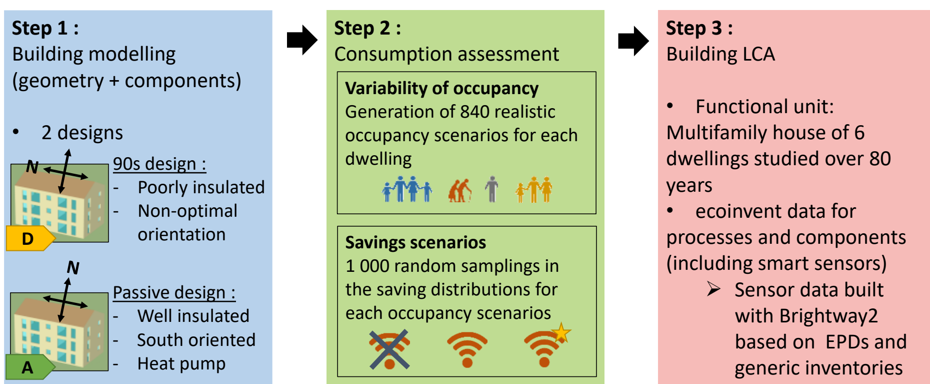

Fig. 1. Methodological steps.

Firstly, the two design alternatives (90s and passive design) are modelled in the software. Secondly, the energy consumption is assessed for the two designs. In order to take into account the diversity of families that can live in the six dwellings as well as the various set of domestic equipment that a family owns, the generator of realistic occupancy scenarios of the module Amapola of the software Pléiades is run. 840 occupancy scenarios are obtained for each dwelling. Then, for each possible family, a saving scenario is randomly sampled in the savings distribution presented in 2.1 for the "monitoring" and "management" alternatives. Thirdly, building LCA calculations are performed for all cases assuming a building lifetime of 80 years and a replacement of smart devices every 10 years. The inventory data for the

[†] Software Pléiades: https://www.izuba.fr

sensors come from EPDs of different manufacturers or from generic data from ecoinvent database[‡]. The Brightway2 framework is used for the impact assessment of the smart devices. Four environmental indicators are assessed: the climate change (CC) from Intergovernmental Panel on Climate Change (GWP_{100}), the cumulative energy demand (CED), and the short-term damages to ecosystem quality and the human health from ImpactWorld+.

3 Results

3.1 "Without sensor" alternative

Usual results are obtained for the LCA of the conventional building ("without sensor") for the mean occupancy scenarios (Fig. 2). The use is the most significant life cycle stage for the 90s design, and the impacts are considerably reduced for passive design.

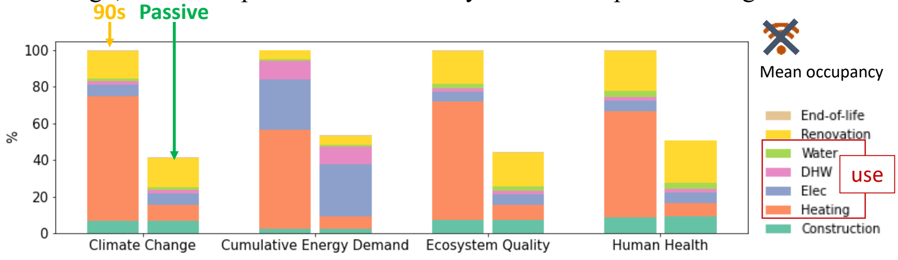

Fig. 2. Contribution analysis for the "without sensor" alternative and the mean occupancy.

The effect of the variability of occupancy on the "without sensor" alternative is shown in Fig. 3. The overlap between the distributions for the two building designs is very small for each indicator, meaning that the passive design remains a better option, whatever the behaviour of the occupants living in the building.

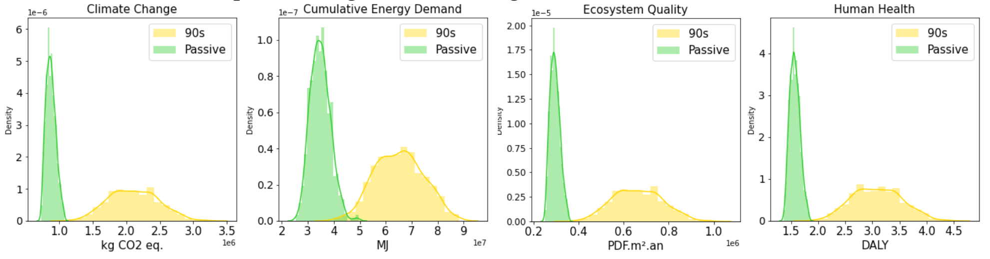

Fig. 3. Effect of the variability of occupancy for the "without sensor" alternative.

3.2 Comparison of smart and conventional buildings

The comparisons of the three alternatives are given in Fig. 4 using three distributions: one distribution for the "without sensor" case, another for the "monitoring" case and a last one for the "management" case. For the "building monitoring" and "building management" alternatives, the uncertainties on the energy savings are included in the distributions. The alternative comparison is performed for the two designs (90s design in shade of orange, and passive design in shade of green) and for the four environmental indicators.

For all environmental indicators and building designs, there is a large overlap between the distributions of the "without sensor" and the "monitoring" alternatives. As the

‡ ecoinvent database: https://ecoinvent.org/

 https://doi.org/10.1051/e3sconf/202234904012

"management" alternative leads to highest energy savings, this option seems to perform better than the two others even when considering the impacts of smart devices and all life cycle stages. Note that the overall environmental impacts of the sensors are equivalent to 1 to 3 % of the construction impacts.

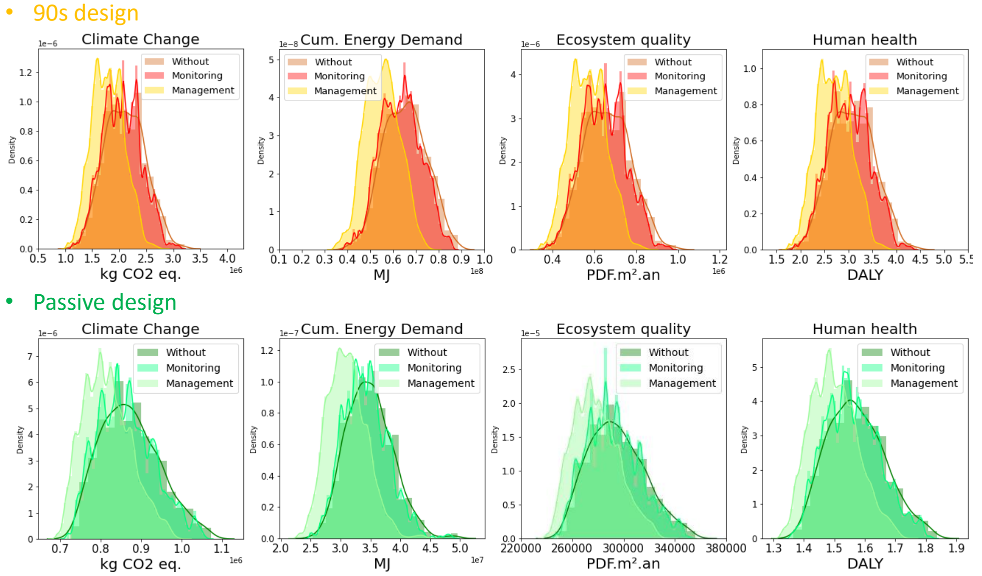

Fig. 4. Comparison of smart and conventional building alternatives, for the 90s design (graphs on the top) and the passive design (graphs on the bottom).

It is difficult to conclude on the benefits of smart buildings from these distributions only, as the overlap does not inform on the dependencies between alternatives. In order to extract more information from the comparison of alternatives in presence of uncertainties, the relative differences between alternatives are computed as suggest in [10]. For each simulation (840 sets of possible families * 1,000 savings scenarios), the differences between the impacts of the "smart" and the "without sensor" alternatives are calculated. This value is then divided by the impacts of the non-smart option, as in equation (1):

$$\boldsymbol{RD_i} = \frac{\boldsymbol{I_{without,i}} - \boldsymbol{I_{smart,i}}}{\boldsymbol{I_{without,i}}} \quad (1)$$

where $\boldsymbol{RD_i}$ is the vector of the relative differences for the environmental indicator i; $\boldsymbol{I_{without,i}}$ is the vector of impacts of the "without sensor" alternative and $\boldsymbol{I_{smart,i}}$ is the vector of impacts of a smart alternative (either "monitoring" or "management"). $\boldsymbol{RD}$ and the vectors of impacts $\boldsymbol{I}$ consist of 840,000 elements corresponding to every simulation.

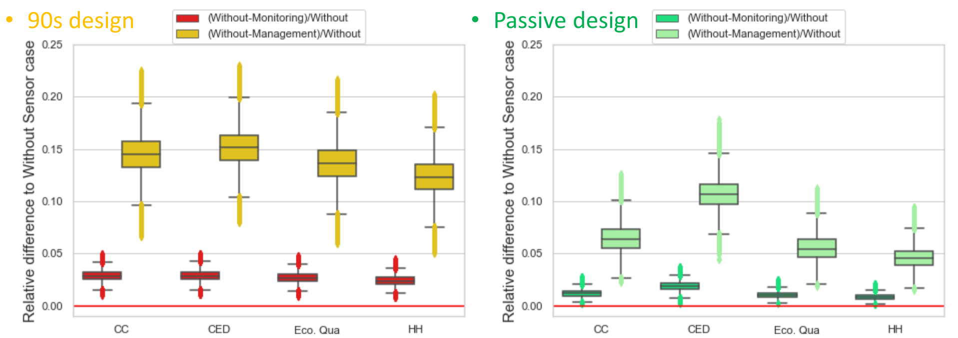

Fig. 5. Relative difference between the conventional and smart alternatives.

The relative differences are shown in Fig. 5. For the 90s design, the relative difference is always positive, meaning that the smart alternative (either "monitoring" or "management") performs better than the "without sensor" option for each environmental indicator.

For the passive design, the relative differences are lower than for the 90s design. Thus, the benefits of the smart building decrease with an improved building design. In addition, in few cases, the "without sensor" alternative performs better than the "monitoring" option, as the relative difference is negative. In these few cases, the sampled energy savings are so small that they are counterbalanced by the impacts of the smart devices.

4 Conclusions and perspectives

In this study, different versions of a multifamily house were compared using LCA to understand if smart building performs better than classical ones considering several environmental indicators and all building life cycle stages. Uncertainties regarding energy savings and variabilities due to occupancy were considered. In almost all studied cases, smart building performed better than conventional ones in our case study. However, the interest of smart building decreases when performing monitoring instead of management, as well as when the building design is improved.

In future work, other sources of uncertainties (such as uncertainties related to the life cycle inventory of smart devices) and other environmental indicators will be included. Then, the performance will be assessed for a real energy strategy applied in a smart building with an energy management system.

This research has been performed within the frame of the BEBAC project, funded by the French region Pays de la Loire and the Université d'Angers through the Pulsar Programm.

References

1. Y. Yao and D. K. Shekhar, Build. Environ. **200**, 107952 (2021), https://doi.org/10.1016/j.buildenv.2021.107952
2. S. S. van Dam, C. A. Bakker, and J. C. Buiter, Energy Policy **63**, 398 (2013), https://doi.org/10.1016/j.enpol.2013.09.041
3. S. Beucker, J. D. Bergesen, and T. Gibon, J. Ind. Ecol. **20**, 223 (2016), https://doi.org/10.1111/jiec.12378
4. J.-N. Louis and E. Pongrácz, Environ. Impact Assess. Rev. **67**, 109 (2017), https://doi.org/10.1016/j.eiar.2017.08.009
5. T. Kumar and M. Mani, in *Res. Des. Communities Vol. 2*, pp. 105–116, https://doi.org/10.1007/978-981-10-3521-0_9
6. M. Gangolells, M. Casals, N. Forcada, M. Macarulla, and A. Giretti, Renew. Sustain. Energy Rev. **55**, 662 (2016), https://doi.org/10.1016/j.rser.2015.11.006
7. S. S. van Dam, C. A. Bakker, and J. D. M. van Hal, Build. Res. Inf. **38**, 458 (2010), https://doi.org/10.1080/09613218.2010.494832
8. J. Reynolds, Y. Rezgui, A. Kwan, and S. Piriou, Energy **151**, 729 (2018), https://doi.org/10.1016/j.energy.2018.03.113
9. J. Walzberg, T. Dandres, N. Merveille, M. Cheriet, and R. Samson, Renew. Sustain. Energy Rev. **125**, 109798 (2020), https://doi.org/10.1016/j.rser.2020.109798
10. M.-L. Pannier, P. Schalbart, and B. Peuportier, in *Eco-Des. Build. Infrastruct.* (CRC Press, 2020), http://dx.doi.org/10.1201/9781003095071-3