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Building life cycle assessment tools developed in France

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ABSTRACT: In France, LCA began to be applied in the building sector in the 1990s and a common framework was sketched in the European project REGENER in collaboration with German and Dutch partners. Twenty years later, LCA is being integrated in the next regulation planned for 2018. This communication presents the modelling issues addressed, international exchange and comparison of tools, and proposes perspectives for further work. From the beginning of its development, the life cycle simulation model EQUER has been associated with energy simulation. Dynamic simulation was later applied to the electricity system, including production and power grid, in order to account for temporal variation of the production (according to the season, the day of the week, the hour). A consequential approach was compared to attributional LCA, considering marginal instead of average production processes. Due to the long life span of buildings, prospective aspects were also studied.

1 INTRODUCTION

The French research community was very active in the 1960s in the field of solar and bioclimatic architecture. But in 1985 the oil price went down and these activities were not funded anymore. The concept of sustainability appeared soon after this period, in 1987. A common opinion at that time in France was that sustainability was more global than energy related issues, so that the attention should be paid on construction materials rather than on energy efficiency or renewable energy.

A research program was launched in 1992 regarding the evaluation of buildings' environmental quality. Several approaches were proposed: environmental impact assessment, qualitative methods, and life cycle assessment (LCA).

2 FIRST BUILDING LCA TOOLS

The international Research Workshop "Buildings and the Environment" organised in Cambridge by Cole et al. (1992) allowed first exchanges to take place and a first European project was launched: REGENER (Peuportier et al., 1997).

Building LCA tools were developed in Switzerland and Germany (Kohler et al., 1994), and in the Netherlands (Kortman et al., 1998). As shown in Figure 1, the EQUER model developed in France (Polster, 1995 and 1996) was linked to the thermal simulation tool COMFIE (Peuportier & Blanc Sommereux, 1990), allowing to compare design alternatives accounting for their influence on heating/cooling loads.

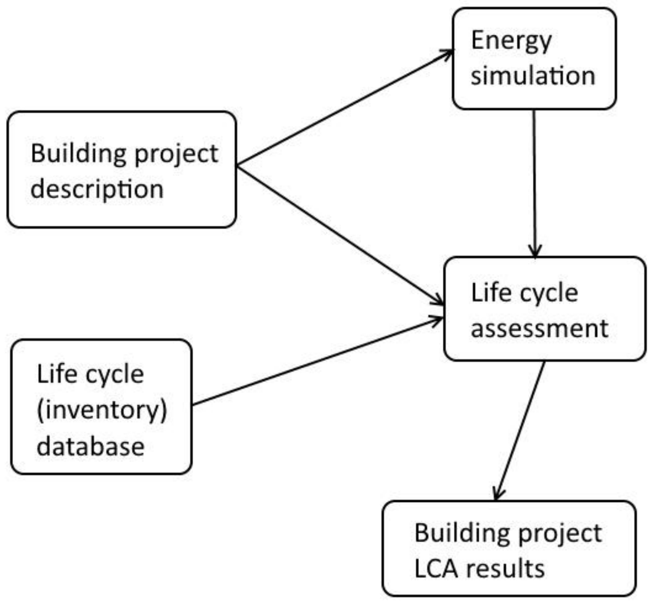

Figure 1. Link between LCA and energy simulation.

LCA specialists are aware of the role of thermal insulation on the energy performance of buildings, but they generally do not perceive the role of thermal mass or optical properties. For instance when comparing concrete versus timber structure, it is not correct to assume an equal energy consumption because the storage of solar gains and therefore heating/cooling load is different as the thermal mass of the concrete structure is higher compared to timber's.

A carpet on a concrete slab reduces the heat flow and the possibility to store solar gains in the slab. Comparing a carpet, a wooden flooring and thinner tiles without accounting for different heating and cooling loads is therefore not accurate. Lighting consumption depends on optical properties of surface materials, which influences the cooling load because artificial lighting creates internal heat gains. Coupling LCA and Building energy simulation (BES) allows such interactions to be accounted for.

This requires an appropriate data structure, defining computer objects which play a role in the thermal behaviour of a building and are as well related to environmental impacts regarding their production, maintenance, replacement and end of life. This may seem complex, but actually the first prototype tool was developed within two years and its structure facilitates the use of LCA in practice because most characteristics of a building project are already included in the energy calculation model, so that LCA can be performed with limited additional effort.

At that time there was a debate whether using LCA, adding points (e.g. like in BREEAM or LEED certification schemes) or applying environmental performance evaluation. LCA was used to provide decision aid, primarily for design purposes. It took more time until certification bodies adopted this approach (Chevalier et al., 2010).

LCA databases were emerging, and because there was no database in France we used the Oekoinventare data (Frischknecht et al. 1996) in the first tool, and later ecoinvent (Frischknecht et al. 2004).

3 DATA BASES

The Swiss databases Oekoinventare and ecoinvent have been used since 1996. Contextualisation was applied regarding the electricity mix for locally produced materials (e.g. concrete), otherwise European average data was considered.

A French database appeared later, according to a standard published by the French standardisation body (AFNOR, 2001). This standard was cancelled in 2004 and replaced by the European EN 15804 standard. The database, called INIES, provides more than 1,600 datasets (INIES, 2017).

Data is provided by manufacturers, some is verified. Inventories include 168 fluxes: for instance dioxins are considered in a VOCs (Various organic compounds) group which does not allow a precise evaluation of impacts on human health (Herfray & Peuportier, 2010), (Lasvaux et al., 2014). Toxicity and eco-toxicity issues are evaluated using methods based upon critical volumes, which is obsolete.

Each dataset being elaborated independently, there is no matrix relationship so that updating (e.g. modifying the electricity mix) is difficult: it can only be done by the producer of the dataset.

The advantage of the INIES database is the large number of available datasets. But the drawback is a lack of precision and transparency. Because decisions influencing the most environmental impacts of buildings are made during the early design phases, the EQUER model focuses on applying LCA during these phases so that generic data are more appropriate. A complementary calculation module was added recently to integrate INIES datasets in the frame of a study aiming at preparing the future regulation. Improving the INIES database, e.g. developing French datasets in a more general database like ecoinvent, could be a useful perspective.

4 TRAINING MATERIAL

Three European projects were funded by the Programmes "ALTENER" and "Intelligent Energy – Eu-rope". A web site was first created in order to help teachers in Architecture integrating energy and environment issues into courses, including a section on Buildings life cycle assessment (Peuportier et al., 1996). A few years later, this material was upgraded during a second project, and tested in several countries (Brophy et al., 2000).

The third project, Training for renovated energy efficient social housing, included presentations and corresponding texts, and is still available on the internet (Peuportier et al., 2007). It covered technical aspects (e.g. insulation, glazing, renewable energy systems...), methodological issues (LCA, energy and cost calculations...), and case studies in the participating countries (Sweden, Hungary, The Netherlands, Germany, Norway and France).

5 VALIDATION

Empirical model validation is possible regarding measurable output like energy or water consumption, but e.g. greenhouse gases emissions (GHG) can only be measured for elementary processes and not over the whole life cycle of a building. Therefore in the case of LCA, inter-comparison of models has been used, including sensitivity studies.

The first inter-comparison exercises were conducted in the European project REGENER and in a working group of the International Energy Agency (IEA Annex 31, 2005). But the hypotheses and results of the different tools were not analysed in detail.

The experience gained in these first activities allowed to plan a more precise protocol for the intercomparison performed in the frame of the PRESCO European network (Peuportier et al., 2004). In a first step, the tools were compared in the case of a very simple "cube" building, and the main hypotheses were listed and analysed. A real case study was considered in a second phase: a single family house with a rather simple geometry. This exchange aimed at helping the participating tool developers identifying some good practice and improving their tools.

The considered tools were: ECO-QUANTUM (W/E Sustainable Building, The Netherlands), LEGEP (ASCONA, Germany), OGIP (EMPA, Switzerland), EQUER (ARMINES, France), ENVEST (BRE, United Kingdom), Eco-Soft (IBO, Austria), BeCost (VTT, Finland), SIMA-PRO (BDA Milieu, The Netherlands), and ESCALE (CSTB, France). In general, the input data include a description of the studied building (geometry, techniques…) and its context (e.g. electricity production mix). The output is a multi-indicator comparison of design alternatives, supporting decision making.

A detailed description of the building was provided to all tools developers, who performed a life cycle assessment considering an 80 years operation period. The FUTURA house is a single family house with two levels (210 m^2 heated area), well insulated, with a high solar aperture. The energy for space heating and domestic hot water is gas, and the heating demand corresponds to a Swiss climate. The European electricity mix is considered. Three alternatives were compared: wooden, brick and concrete structure.

Regarding GHG emissions over the whole life cycle of the house, the results were similar: there was a +/- 10% discrepancy between the tools. Concerning the comparison between wood, brick and concrete structures, the global warming indicator was lower for wood in all the tools except Envest. In all the tools, the highest CO_2 emissions corresponded to the operation phase.

Different other indicators can be considered, depending on each tool: acidification, smog, waste (possibly indicating also radioactive waste), primary energy consumption, water consumption, exhaust of resources, eutrophication, ozone depletion, toxicity, eco-toxicity, cost, and global indicators like ecopoints or eco-scarcity. Therefore it was difficult to compare the ranking of the three alternatives considered (wood, brick and concrete).

6 EXTENSION TO URBAN PROJECTS

A first PhD applied LCA to urban projects (Popovici, 2006), in relation with the European project e-co-housing (Peuportier; 2005). A settlement model was created (see Figure 2) including: several building types, infrastructure (street, networks), collective equipment and processes (e.g. waste treatment, district heating). The tool was tested in three projects in Norway, Hungary and France.

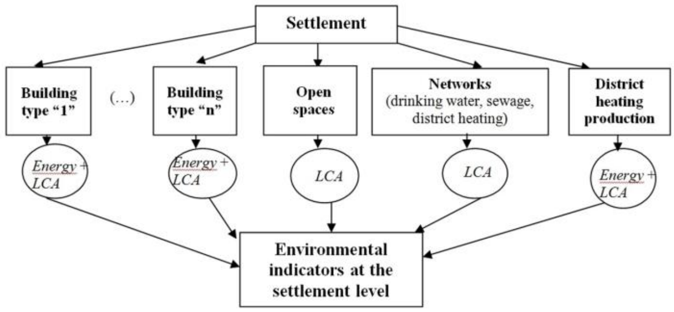

Figure 2. LCA model of urban projects.

The Norwegian case study in Trondheim (Svartlamon) was suitable for testing the settlement model because it included various components:

- a building for private dwelling (House A): 5 floors, 590m², 24 residents,
- a common building for leisure activities (House B): 2 floors, 110m², no permanent resident,
- extensive common facilities: parking area (150 m²), alleys (50m²), permeable yard (350m²) and a green area (500m²),
- and also a public infrastructure section: a road (500m²) and a small street (125m²).

Several alternative designs were compared: heat recovery on ventilation air, solar domestic hot water, reducing the wood thickness in walls (2 cm, instead of 14 cm proposed by the designer). Impact indicators were reduced up to 20% compared to the initial design.

The tool has later been improved and applied to larger projects in Lyon (Peuportier, 2016) and Greater Paris Area (Herfray et al., 2011). In Lyon, three urban blocks were studied which corresponds to 60,000 m^2 dwelling, 15,000 m^2 offices and 70,000 m^2 outdoor spaces. The project performs between a standard level corresponding to the regulation threshold and a "best practice" level corresponding to the Passivhaus label. The LCA results show the influence, particularly on a human health indicator, of using wood fuel in the district heating system.

In Greater Paris Area, the development includes 25 buildings with 45,000 m^2 offices, 33,000 m^2 dwelling, 4000 m^2 shops, and 24,000 m^2 external spaces. The project proposed by the urban designer was compared to both a best practice alternative based upon the Passivhaus label, and a plus energy alternative including PV modules. This alternative leads to significantly lower impacts on energy related issues (energy resources and radioactive waste), with limited transfer of impacts to other environmental aspects (Peuportier et al., 2016).

7 LINK WITH THE ENERGY SYSTEM

In France, buildings consume two thirds of the electricity. The building and energy sectors interact increasingly due to local electricity production (e.g. using photovoltaic systems) and the use of thermodynamic systems. The concepts of smart building and smart cities aim at better integration by taking the grid constraints into account in the operation of local energy systems (e.g. reducing peak demand by appropriate control). It is therefore important to model this interaction when evaluating the environmental impacts of such systems. In this context, the fact that the LCA model is combined with thermal dynamic simulation of buildings allows a comprehensive evaluation of the environmental benefit from smart buildings and onsite renewable energy production.

A first dynamic LCA model was developed to account for the seasonal, weekly and hourly variation of the electricity production mix (Herfray & Peuportier, 2012). The objective was to evaluate more precisely, compared to the usual static approach, the environmental impacts of electricity consumption and production in buildings, which is useful to compare e.g. plus energy and standard alternatives.

The French electric power grid operator (RTE) provides hourly production values for nuclear, hydro-electricity, gas, coal and fuel thermal plants, and other types of power plants. Based upon these data, the model evaluates the production mix in terms of an average outdoor temperature in France (due to a high electricity use for heating), and several periodic functions corresponding to variation frequencies identified by a Fourier analysis. In a second step, specific production mixes are derived for different uses: heating, cooling, domestic hot water, domestic appliances and office appliances.

This method was applied on a case study, showing 30% discrepancy on GHG emissions between such a dynamic model and the standard LCA practice corresponding to the use of a yearly average production mix (Herfray & Peuportier, 2012). The model required hourly energy consumption data which were provided by the EQUER LCA tool, linked to dynamic thermal simulation.

Another study was based upon data provided by the electric power grid operator, without modeling the electric system (Fouquet, 2013). But due to the absence of model, it was not possible to consider the typical climatic years used to evaluate the energy needs for heating, cooling and lighting, which is more relevant than using real years because it provides a statistical average (generally over 20 years). Another limit of using real years is the impossibility of performing consequential LCA and to integrate prospective aspects.

A second model was developed based upon simulation, in order to study more precisely how temporal variation of the buildings' consumption and production influence the electric power grid system (Roux et al., 2016a). The model follows four calculation steps, modeling both electricity demand and production:

- The national hourly electricity demand is evaluated as a function of an average national outdoor temperature (average temperature of climatic zones weighted by their population),
- The non-dispatchable production (corresponding to cogeneration, intermittent renewable and run-of-river hydraulic) is evaluated from weather data or from average historical load factors (i.e. production power divided by installed capacity),
- Pumped storage and export are considered as additional electricity demand on the system,
- Dispatchable production is evaluated using an optimisation model (minimising the electricity production cost while matching the demand).

The principle of the model, using the demand and installed capacities as input in order to derive the hourly production mix as output, is shown in Figure 3.

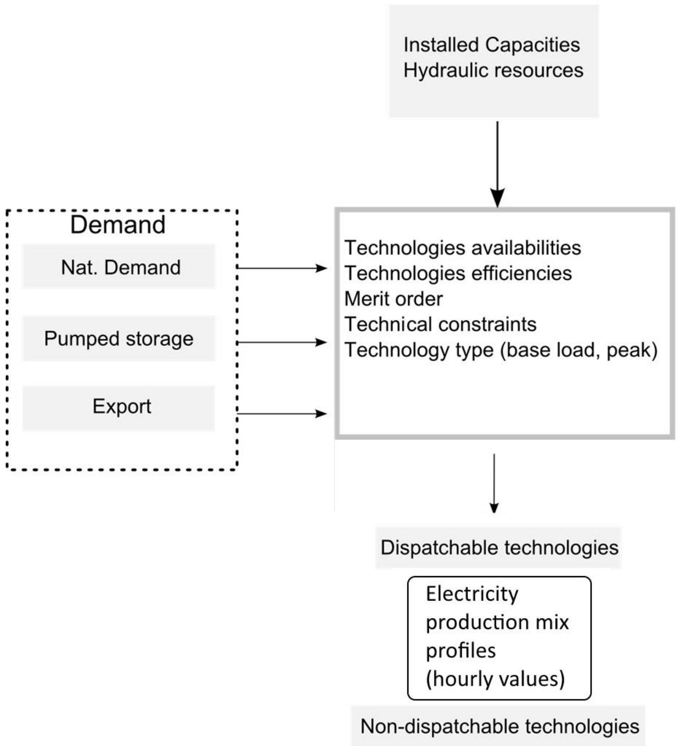

Figure 3. Electric system model.

Models were developed for each group of technologies thanks to system identification followed by calibration and validation of observed data for 2012, 2013 and 2014. Example GHG emissions per kWh electricity are shown on Figure 4. They were derived from RTE data (hourly amount of electricity produced by nuclear, thermal plants, hydroelectricity etc.) using the GHG emissions provided by ecoinvent (v2.2) for each technology.

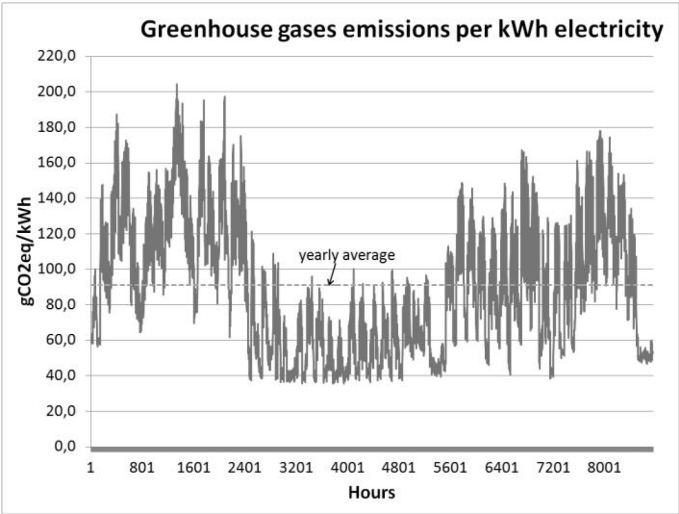

Figure 4. Temporal variation of GHG emissions (derived from hourly RTE data, year 2013).

According to LCA results on a case study, using an annual average mix instead of hourly mix data can lead to an underestimation of potential impacts up to 39 % for Abiotic Depletion and 36 % for Global warming when combining all end-uses. The increase of impacts when using hourly mix data is mainly explained by a higher share of coal and gas power plants in the electricity mix in winter. This coincides with a higher electricity consumption of the studied house in this season due to space heating, electric back-up of the solar water heating system and a lower onsite production (photovoltaic system).

Another advantage of the simulation model presented above is that it allows an attributional dynamic approach (AD) and a consequential approach (marginal dynamic, MD) to be compared (Roux et al., 2016b). To derive the marginal electricity production associated with the studied building project, the model runs two times: once using the reference electricity demand and once adding the hourly electricity load of the studied project to the reference electricity demand. The electricity production difference between the two calculations is allocated to the studied project.

Depending on the chosen approach to evaluate electricity related impacts, the carbon footprint of the electric space heating option for the evaluated low-energy house can be 84 g CO_2eq / kWh (annual average), 146 g CO_2eq / kWh (AD) or 1179 g CO_2eq / kWh (MD). Compared to a wood or a gas boiler, 86 gCO2eq / kWh and 253 gCO2eq / kWh respectively, the ranking between the different technical options for space heating depends on the chosen approach.

The dynamic LCA model was complemented by integrating prospective aspects (Roux et al., 2016c). The objective is to account for climate change scenarios (IPCC, 2014) and evolution of the energy mix on the long term (at 2050). The two methodological approaches -attributional and consequential- were illustrated using the same case study: a low-energy single family house located in France. Two design options were evaluated using life cycle assessment: the choice of a heating system and the integration of photovoltaic (PV) modules on the roof.

Using an attributional approach compared to a static LCA considering no prospective parameters, the carbon footprint of the house (total life cycle) varies from +21 % to +43 % for the electric heating alternative, -7 % to +4 % for the gas boiler alternative, - 6 % to +15 % for the PV alternative depending on climate change intensity and evolution of the energy mix (Roux et al., 2016c). Accounting for climate change and the evolution of the energy system has therefore a large influence on LCA results over the long life span of a building, which induces a large uncertainty.

8 OPTIMISATION

Designing buildings at lower environmental impact and lower cost, is a complex optimisation problem. A multicriteria optimisation procedure has been developed (Rivallain et al., 2012) and linked to LCA (Recht et al., 2016). It uses a genetic algorithm in order to find a set of solutions as close as possible to the theoretical Pareto front (obtained by calculating all possible combinations of input parameters), corresponding to the best compromises for the formulated problem. The solutions' performance was evaluated using the dynamic building energy and life cycle analysis models presented above, and a construction cost database. In order to study the solutions' robustness, the diversity of occupants' behaviour was stochastically modelled.

In a first case study corresponding to the design of a plus energy house, 11 design variables were considered in the optimisation problem. This search space was established in collaboration with the architect in order to integrate constraints and degrees of freedom of the project. These variables are the glazing area on different facades, the type of glazing (double or triple), the thickness of insulation (walls, floors and roof), the ventilation system (with or without heat recovery), the implementation of heat recovery on grey water, and the number of photovoltaic modules.

An example result, the Pareto front considering GHG emissions and construction costs, is shown in Figure 5. More than 4 million simulations were needed to obtain the theoretical Pareto front, whereas 20 generations (i.e. 8,000 runs) were enough to provide a similar curve using the genetic algorithm.

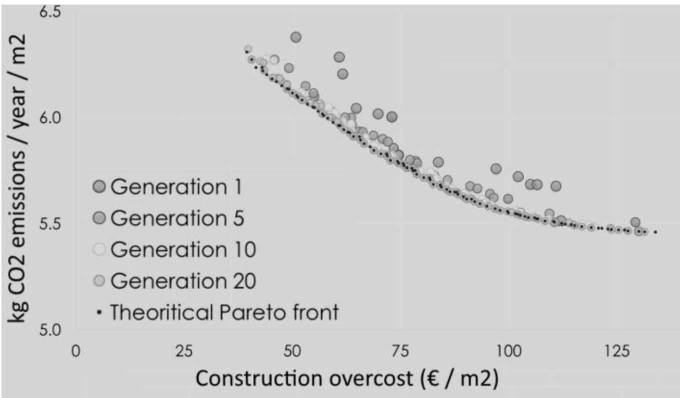

Figure 5. Example multi-criteria optimisation result.

The relatively small computation time (a few seconds per run) was achieved thanks to model reduction. This proved to be very useful to perform a large number of calculations with a reasonable total computation time without compromising accuracy.

9 UNCERTAINTIES

The reliability of an LCA tool is essential to guide the decision maker towards sustainability. A methodology has been elaborated in order to investigate the most uncertain input parameters and evaluate uncertainties on the calculated environmental impacts.

Five uncertainty sources were identified in building LCA:

- Hypotheses about the building, concerning the building envelope and systems, occupant's behaviour or the lifetime of the building and its components.
- Long term evolution: buildings have a long lifetime and the long term evolution of the context is largely unknown (e.g. change in the electricity production, materials end of life processes etc.).
- Modeling methodology: some aspect may be modeled in different ways in LCA. For instance regarding recycling, two allocation methods can be used: the cut-off or the avoided burden method. In the avoided burden approach, an environmental benefit is considered because recycling avoids a standard production. This benefit is split between the construction stage and the end of life. In the cut-off approach, the benefit is only accounted for in the construction phase whereas no avoided impact is allocated to end of life, supposed to be in a far future so that the benefit is too uncertain.
- Life cycle inventory (LCI): the way to inventory all substances emitted to and extracted from the environment corresponding to building materials' production and other processes also leads to uncertainty. The choice of marginal or average data for the inventory does not give the same results. Additionally, simplifications of the inventory are sometimes conducted, e.g. gathering many substances in a single VOC (volatile organic compounds) group, which leads to the reduction of some substance effects (e.g. dioxins are more toxic than the average of VOCs).
- Life cycle impact assessment (LCIA): the aggregation of substances into environmental impact categories is uncertain. Indeed, effects of substances alone or of interactions between substances are not always well known. And the effect of substances may vary with the time and the emission location.

Uncertainty and sensitivity assessment (UA, respectively SA) requires a large number of simulations to ensure convergence of the results. At least one thousand simulations are required in UA and thousands of simulations in global SA. The Morris method (Morris, 1991), which belongs to the screening techniques, has the advantage to be quick and simple. The aim is to rank the input factors according to their influence. It also gives information about the linearity and the presence of interactions (Pannier, 2017). In the considered case study, the uncertain parameters influencing the most GHG emissions are the time horizon of the IPCC global warming indicator, the electricity mix and the building lifetime (see Figure 6).

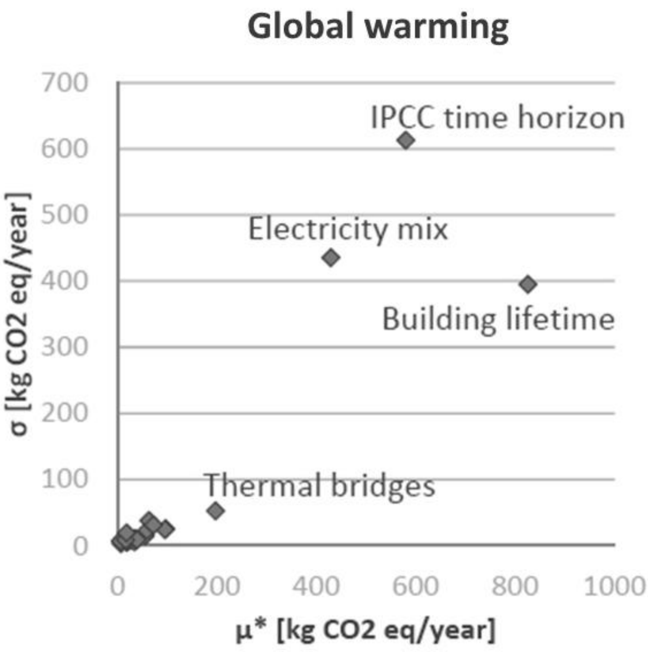

Figure 6. example result of a sensitivity analysis.

Probability distribution functions are defined for each influential parameter. Using Monte-Carlo based methods allows probability distributions to be obtained on calculated impact differences when comparing alternatives. When performing such uncertainty analysis, it is important to calculate impacts considering the same set of uncertain parameters for all compared alternatives. For each set of uncertain parameters, the impacts difference between alternative A and B is calculated, and a statistical distribution can be derived.

An example result is shown in Figure 7: electric and gas heating are compared, the relative difference between impacts being represented by boxplots indicating average, minimum, maximum, first and third quartiles.

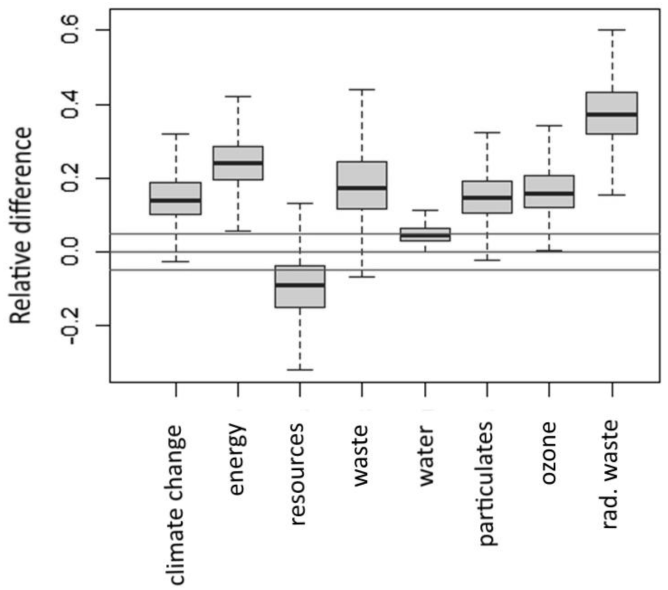

Figure 7. Example of an uncertainty analysis, relative impacts difference between electricity and gas heating.

Some design alternatives may lead to lower uncertainties: e.g. even with an identical annual energy balance, lower electricity consumption and production reduce uncertainties related e.g. to climate change and to the evolution of the electricity production techniques.

Focusing on the first life cycle stages, i.e. the fabrication of building elements and the construction process, is sometimes proposed in order to reduce environmental impacts in the near future, therefore with less uncertainty than addressing the whole life cycle. But the impacts during the operation phase are still high even in low energy buildings, due to a large electricity consumption for appliances. Rejecting renewable energy systems, e.g. photovoltaic, due to the high impacts related to their fabrication, induces the risk of transferring impacts to the operation phase. Robust optimisation could be useful to search for relevant compromises between performance and uncertainty.

10 CONCLUSIONS AND PERSPECTIVES

A software platform has been developed including dynamic energy simulation of buildings and national electric system, life cycle assessment, occupants' behaviour models, uncertainty calculations and multi-criteria optimisation. Attributional and consequential LCA can be performed, and prospective aspects have been integrated regarding the electric system.

The long life span of buildings induces large uncertainties regarding e.g. the effect of climate change on heating and cooling loads, the long term evolution of the electric system, waste treatment processes etc. But sociological issues regarding the evolution of occupants' way of life would probably deserve much attention.

It would also be useful to improve the LCA methodology on several aspects like the assessment of human health and biodiversity related impacts, including spatial (e.g. indoor emissions) and temporal (e.g. biogenic carbon) modelling.

Uncertainty evaluation and robust optimisation could increase the reliability of LCA, which would be useful for a wider dissemination of this method among decision makers.

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