Dynamic and consequential LCA aspects in multi-objective optimisation for NZEB design

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Abstract. Multi-objective optimisation coupled with building energy simulation (BES) and life cycle assessment (LCA) models is a promising method to eco-design net-zero energy buildings (NZEBs) in line with sustainable objectives such as UN SDG’s goals 7, 11, 12 and 13. This paper presents a method of building multi-objective optimisation based on NSGA-II coupled with the BES model COMFIE and the building LCA tool EQUER to identify NZEB designs that minimise construction costs and GHG emissions. A dynamic electricity mix model was implemented in LCA to evaluate more precisely time-related impacts of heating and solar photovoltaic production. Three different LCA approaches defining the multi-objective optimisation problem were compared: static LCA (considering an average annual electricity mix), dynamic attributional LCA (average hourly mix) and dynamic consequential LCA (marginal hourly mix). Results show minor differences in optimums quality between static and dynamic attributional approaches but important differences in optimums design parameters between attributional and consequential approaches. The influence of the LCA approach on multi-objective optimisation results emphasises the need to specify guidelines for practitioners about the choice of the LCA approach.

1. Introduction
NZEB is qualitatively defined as “a building that has a very high energy performance […]”. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including sources produced on-site or nearby” [1]. Due to higher energy performance requirements than conventional buildings and specific systems such as photovoltaic panels, there exists a risk of increasing construction costs. Thus, a challenge is to define best practices in eco-design that would synergise with an affordability objective to achieve the development of a building sector that would provide access to affordable and sustainable NZEB in line with UN SDG’s goals 7 “affordable and clean energy”, 11 “sustainable cities and communities”, 12 “responsible consumption and production” and 13 “climate action”.

Eco-design is a design approach with an aim to reach environmentally optimal design helped by modelling tools that simulate energy and environmental performance in order to compare alternative solutions. The evaluation of a sufficiently large number of design variants is required to identify near-optimum solutions and give stakeholders sufficient information to make trade-offs decisions. With recent developments in computing performances, the research of optimal designs according to multiple objectives can now be accomplished with the help of a multiobjective optimisation algorithm coupled with dynamic building energy simulation (DBES) and building life cycle analysis (LCA).
models. This automatic procedure evaluates thousands of relevant designs in order to identify a complete set of optimal design solutions called Pareto front. However, multiobjective optimisation (MOO) results strongly depend on the designer’s choices setting up the optimisation problem: constraints, optimisation parameters, objective functions and, last but not least, models by which those objective functions are evaluated and their related hypotheses.

Energy consumption has an important contribution in standard buildings LCA, while it tends to decrease for low energy buildings. LCA approach (attributionnal or consequential) and time-related hypothesis on the electricity mix (static or dynamic) can greatly influence buildings LCA results [2–4]. A general practice in LCA is to use a yearly average electricity supply mix based on a reference year, but it does not take into account the temporal variability of electricity production within a year related to seasonal and daily peaks implying fossil fuel power plants production. Dynamic electricity mix data is particularly important in NZEB LCA to evaluate avoided impacts from seasonal on-site photovoltaic panels production or innovative control technology such as load shifting [5]. A consequential approach based on dynamic marginal mix would be more relevant in building design or renovation because they imply short-term decisions that have consequences on other systems.

This work intends to explore how these assumptions about LCA approach and electricity mix data can influence the results of a MOO. After a presentation of the methodology in section 2 and of the case study in section 3, results of three different MOO problems are compared, based respectively on annual, hourly and marginal electricity mix. The last section discusses results to help identify good practices in NZEB’s multi-objective optimisation.

2. Methodology
An optimisation problem is defined by objective functions on fitness values, constraints on quantity of interest and optimisation parameters defined in the decision space. The chosen optimisation algorithm is a popular genetic algorithm NSGA-II. In this paper, the two objective functions are: minimisation of life cycle greenhouse gases (GHG) emissions expressed in kg-CO2-eq. as an overall environmental criterion, and minimisation of construction costs, expressed in euros (€) as a cost difference with the initial design. An inequality constraint was set to allow designs having annual net electricity balance inferior or equal to 0 kWh in case of an all-electric NZEB. The net electricity balance considered in the study was the photovoltaic production minus the sum of heating, domestic hot water (DHW), appliances and auxiliaries’ electricity end-uses. For each solution, the energy simulation was performed with the DBES model COMFIE [6], providing hourly energy consumptions. COMFIE was validated on standard and low-energy buildings by experimental comparison and model inter-comparison [7].

Building LCA was performed with EQUER [8] that had previously been validated by inter-comparison with 8 other LCA tools [9]. The functional unit was defined as: a square-meter (m²) of living area of a NZEB or positive energy house having a lifetime of 100 years for a family of four occupants. Life cycle inventories provided by the ecoinvent v3.4 database were used to assess all products and processes involved in the building life cycle including the twelve electricity production technologies used in the mix [10]. GHG emissions were assessed with the life cycle impact assessment (LCIA) method developed by the Intergovernmental Panel on Climate Change (IPCC) in 2013 [11]. All life cycle stages were considered: construction (including products fabrication, transport and on-site construction), use (including energy and water consumption), renovation, and deconstruction. Use stage impacts were evaluated from dynamic energy simulation of a reference-year. A positive electricity balance (annual or hourly) means an export of photovoltaic production to the grid. Avoided impacts from this export were considered to be equal to the (annual or hourly) average impacts of 1 kWh of electricity consumed from the grid. The current share of intermittent electricity sources in the French hourly mix being low, we considered that all production from photovoltaic system can be efficiently used by the grid [2].

In this paper, three combinations of hypotheses about time precision of electricity mix supply and LCA approach are considered in order to compare their influence on MOO results. The first one
represents common practice: an attributionnal LCA with a yearly average electricity supply mix called static-attributionnal (SA). The second one is a more precise proposition of attributionnal LCA: an hourly average electricity supply mix called dynamic-attributionnal (DA). The last one is a consequential approach: an hourly marginal electricity supply mix called dynamic-consequential (DC). The three optimisation problems are summarised in Table 1. In the SA approach, the annual electricity consumption impact is calculated as product of net annual electricity consumption and yearly average impact of 1 kWh of electricity consumed from the grid. In the DA and DC approaches, the annual impact is the sum of 8760 hourly products of net electricity consumption and the impact of 1 kWh of electricity consumed from the grid.

Influence of using dynamic attributionnal electricity mix data over yearly average mix in building LCA was studied for a low energy building; using a yearly average mix induces differences above 30% for GWP impacts [2]. Attributionnal approach is favoured when the purpose of building LCA is for instance a certification procedure, when allocation of environmental responsibility to the building is evaluated within a fixed existing context. Consequential LCA widens the frontier of the study to integrate markets’ reactions and their effects on environmental impacts after a decision; it is therefore most adapted to assess impacts of new decisions such as building construction or renovation. Marginal electricity supply mix is a key part of the consequential approach by handling the question about electricity consumption: “which power plant satisfies the additional unit of electricity required by a building project?” [5].

| Name | Objective functions | Constraint | LCA approach | Electricity supply mix data |
|------|---------------------|------------|--------------|----------------------------|
| SA   | minimisation of total GHG emission & minimisation of initial investment | $E_f \leq 0 \text{ kW h/yr}$ | static attributionnal | yearly average mix |
| DA   |                       |            | dynamic attributionnal | hourly average mix |
| DC   |                       |            | dynamic consequential | hourly marginal mix |

The three corresponding electricity mix data were generated by a French national electricity equilibrium model developed by Roux et al. [3]. National demand, photovoltaic power and wind power calculations are based on the same reference weather data used in buildings energy simulations to ensure consistency between the behaviours of the electricity mix and the studied building energy consumption. Each submodel was calibrated on 2012 and 2013 historical data and validated with 2014 historical data. For this paper, installed capacities data from 2016 [12] were integrated into the model to generate supply mixes used. Marginal electricity supply mix were obtained from Roux’s GHG-P method which is an adaptation of the GHG protocol methodology [13]. However, the consequential approach used in this study disregards long-term consequences on future power plant capacities as it is not expected that a single building project would influence the whole electricity supply system on the long term.

3. Case study
As part of the EU Horizon 2020 A-ZEB project focusing on the affordability of NZEB, the case study is a passive house initially located in Bulgaria. For the purpose of this study the house was virtually located in France. Relocation hypotheses concern French electricity supply system, Trappes’ regional climate zone and French construction costs data. This passive house has 206 m² of living area. Its envelope is composed of concrete, with an exterior insulation of 25 cm of expanded polystyrene (EPS) in facades and attic, 25 cm of extruded polystyrene (XPS) in floors upon ground and crawl spaces and 10 cm of EPS in garage exterior wall. Windows are triple glazing in all facades. Heating and DHW are provided by an electric air/water heat pump. Ventilation has a heat recovery system. Roof is equipped
with 4.5 \( m^2 \) of thermal panels for DHW production and 33.3 \( m^2 \) of poly-Si PV panels. Summer comfort is handled by night ventilation and shadow devices on south façade; no cooling system is installed.

Four thermal zones were defined in the dynamic energy simulation model: living area used during the day, bedrooms, unheated insulated technical spaces, unheated non-insulated technical spaces (see Figure 1). Occupation scenarios were generated by a stochastic occupancy model based on French sociological data [14,15] with settings corresponding to an average family of four people. Living areas were heated at around 20.3°C in the “day” thermal zone and at 18.5°C in the “night” thermal zone. The initial design had heating loads of 10.4 kWh/m²/year (Passive House requirements).

The LCA hypotheses are: lifetime of systems and PV panels of 25 years, lifetime of windows and door of 20 years, lifetime of building and other components of 100 years. When reaching its end of life a component is identically replaced. Metals and PV panels are recycled, windows, doors, woods, and plastics are incinerated with heat recovery and other materials are landfilled.

The optimisation parameters concern insulation thickness in attic, facades and floors, type of glazing, windows surface depending on the facade orientation, and PV panel surface. The decision space is detailed in Table 2.

### Table 2. Research space of the optimisation problems

| Parameters                               | Elements                        | Levels (initial) | Unit | Nb. elements | Nb. levels |
|------------------------------------------|---------------------------------|------------------|------|--------------|------------|
| EPS thickness                            | External wall on crawl space, internal wall, ceiling, terrace roof, external attic wall | 6, 7, 8, 10, 12, 14, 16, 20, 25, 32, 40 cm | 6 | 11 |
| EPS thickness                            | Ext. garage wall                | 0, 6, 7, 8, 10 cm | 1 | 5 |
| XPS thickness                            | Floor on ground, floor on crawl space North South East West | 3, 4, 5, 6, 7, 8, 10, 12, 14, 16, 20, 25, 32, 40 cm | 2 | 14 |
| Glazing type                             | Double glazing, Triple glazing | -                | 4   | 2            |
| Glazing surface (difference with initial design) | South East West North South East West | -30\%, -20\%, -10\%, +0\%, +10\%, +20\%, +30\% | 4 | 7 |
| PV panels area                           | PV panels                       | from 29.9 to 66.5 with 1.6 m² steps, initial: 33.3 m² | 1 | 11 |

4. Results and discussion
The three MOO problems presented in section 2 are computed with the following algorithm parameters: 200 individuals and 40 generations. The initial population is sampled from the research space with a non-random Sobol sampling method, ensuring the same starting point for the three procedures. One MOO procedure takes 9 hours and 40 minutes with an Intel i7 processor and parallel computing.

The hypervolume is the area enclosed in the Pareto front. It is computed at each generation. On Figure 2, the hypervolume evolution is normalised by its last respective value. In the three optimisations, the hypervolume reach a steady state after about 32 generations. In the last 5 generations before 40, the hypervolume is improved by 0.005% in SA, 0.009% in DA, and 0.002% in DC. Satisfying levels of algorithm’s convergence are obtained with 40 generations.

Revised SA represent the SA solutions re-evaluated with the reference hourly electricity mix to allow relevant comparisons with DA solutions. Figure 3 shows Pareto front solutions of SA, Revised SA and DA. Revised SA solutions have +6 % to +10 % more GHG emissions than SA solutions. This gap is relatively low because a change of precision in the electricity mix influences use stage’s emissions that only represent 2% to 7% of total GHG emissions in this case because of the relatively high PV production. Figure 3 (left) shows that Revised SA and DA’s Pareto front leads to similar improvements in terms of GHG emissions and investment costs reduction of the initial design. When zooming in the fronts (figure 3 right), DA’s solutions show slightly further reduction of GHG emissions. Most dominating solutions over both fronts are filtered and squared in brown. DA’s front represents 70% of domination over Revised SA and dominates mainly the most expensive solutions.

DC solutions and consequential LCA evaluation of the initial design are shown in Figure 4. The GHG emissions range is larger than for the previous results because of the marginal electricity mix higher carbon footprint than the average electricity mix. DA front solutions have been re-evaluated with the marginal electricity to allow a comparison. Fitness values are close but DC solutions dominate the most. DC front has a higher number of more spread optimal solutions (174) than in other approaches that allows more choices to the decision maker.

On Figure 5 and Figure 6, PV areas and heating loads are shown with respect to reduction of investment costs compared to the initial design. A common global trend in all approaches is lower heating loads and higher PV area as investment increases. In the price range -510€/m² to -490€/m², DA solutions dominate the most with lower heating needs and less solar PV area than SA. However, below -510€/m², going left in both figures, most of DA solutions are dominated by SA and show strange increase in solar PV panel that could be related to the decreasing quality of those solutions. An important observation is that heating needs in both SA and DA solutions doesn’t go below 30 kWh/m², but DC provides solutions to 10 kWh/m². This difference can be explained by the very low carbon footprint of the French average electricity mix that, in the context of these optimisation problems, is not incentive to further consumption reduction.
Figure 3. Revised SA and DA Pareto fronts compared to initial design (left) and zoomed in (right).

Figure 4. DC Pareto front compared to initial design

Figure 5. Heating loads among SA, DA and DC Pareto optimal solutions

Figure 6. PV system area among Revised SA, DA and DC Pareto optimal solutions
5. Conclusion

In this study, three LCA approaches regarding electricity impacts, and their influence in MOO of NZEB were compared in the French context: attributionnal with a static mix, attributionnal with a dynamic mix and consequential with a dynamic mix. In all cases, multiobjective optimisation provides NZEB solutions cheaper and with less GHG emissions than the initial design. Main improvements concern optimal balance between heating needs and production with better insulation and glazing distribution in the envelope and increasing the PV system area. First comparison between SA and DA show that a dynamic electricity supply mix in LCA can slightly enhance quality of MOO’s results. In this case, they tend to lower heating needs and PV area. However, the consequential LCA approach based on a marginal electricity supply shows similar improvements of initial design while providing a wider range of NZEB solutions that goes further low in heating loads compared the attributionnal solutions. It shows that LCA hypothesis can not only influence quality of MOO’s results but also influence the range of possible solutions provided to the decision maker. While these results are specific to its context, decision makers should be aware of the variability in MOO’s results that can be led by attributionnal and consequential approach to make a well-informed decision. Furthermore, consequential LCA is methodologically more appropriate in building design or renovation decisions than attributionnal LCA.

Similar comparisons of MOO approaches would be interesting in other regional contexts to draw more general rules. Another perspective would be to assess DA and DC’s solutions’ robustness towards future weather and electricity supply mix in order to conclude which approach is more robust.

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