Environmental life cycle assessment and optimization of buildings

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Abstract The work aims to present initial efforts to the development of an integrated user friendly (architect-oriented) tool for the environmental assessment and optimization of buildings. The tool will focus on the preliminary design phase, where improvements, having a major influence on the building lifecycle, are still possible. A software tool for dynamic simulation of the building lifecycle will be coupled to an open source framework for Life Cycle Assessment (LCA) calculations. In order to evaluate building design alternatives according to environmental, economic and comfort criteria, the development of an optimal solution selection strategy approach will be tackled. Also the economically optimal combination of energy saving measures and a hierarchy of energy savings investments will be taken into account. In a further step, the developed approach will then be applied to a concrete case study.

1 Introduction

In 2009, buildings were responsible for 40% of the world's primary energy consumption and caused about 30% of global greenhouse gas (GHG) emissions [1]. Along these lines, Sustainable United Nations (SUN) and United Environment Program - Sustainable Buildings and Climate Initiative (UNEP-SBCI) addressed 6 Key Messages for the international agreement which were negotiated in Copenhagen in December 2009, in the framework of the 2009 United Nations Climate Change Conference, commonly known as the Copenhagen Summit [1]:

1) *The building sector has the most potential for delivering significant and cost-effective GHG emission reductions;*
2) *Countries will not meet emission reduction targets without supporting energy efficiency gains in the building sector;*
3) *The building industry is committed to action and in many countries is already playing a leading role;*

4) *Significant co-benefits including employment will be created by policies that encourage energy efficient and low-emission building activity;*
5) *Failure to encourage energy-efficiency and low-carbon when building new or retrofitting will lock countries into the disadvantages of poor performing buildings for decades.*

After the Summit, on December 2009 the Copenhagen Accord was drafted by the US, China, India, Brazil and South Africa. The document stated that climate change is one of the greatest challenges of the present day and that actions should be taken to keep any temperature increases below 2°C. The document, however, is not legally binding and does not contain any legally binding commitments for reducing CO_2 emissions. According to the IPCC's Fourth Assessment Report [2], buildings have the largest potential for greenhouse gas reductions. With proven and commercially available technologies, CO_2 emissions reductions from about 30% to 80% can be achieved, with potential net profit during the building life-span. This report [2] also draws attention to the three most important principals to reduce greenhouse gas (GHG) emissions from buildings: reducing energy consumption and embodied energy in buildings, switching to low-carbon fuels including a higher share of renewable energy, or controlling the emissions of GHGs different that CO_2.

An extensive set of interrelated factors influences the energy consumption during the operational phase of a building, such as climate and location; demand profile, supply (gas, electricity, vapour, etc.), and source of energy (solar energy, geothermal, etc.); function and use of the building; building design and construction materials; and the level of income and behaviour of its occupants. Seppo [3, 4] reports that during the building's operational phase the greatest proportion of energy is used, suggesting that more than 80% of GHGs emissions arise during this phase (energy demands such as HVAC, water heating, lighting, entertainment and telecommunications). Achieving a design that takes into account each of these factors represents a challenge because of the number of parameters and possible optimization strategies involved. Classical approaches based on rules of thumb or on trial-and-error processes may be able to generate acceptable solutions; however they are extremely time-demanding if the possible set of parameter cannot be limited beforehand and if one wants to achieve near optimal designs. At this purpose, global optimization techniques such as genetic algorithms are especially suitable to estimate the optimized mix of measures to reduce the energy consumption while maintaining a comfortable indoor environment [5, 6].

The main research challenges to address are: the linkage of building design and thermal analysis to Life Cycle Assessment (LCA) calculation considering dynamic[1] LCIs [7]; the definition and utilization of an harmonized set of Life Cycle Impact Assessment (LCIA) and comfort criteria; the definition of a flexible and consistent set of methodological assumptions. One of the most complicated phases in this process is the accomplishment of a complete and reliable LCA in combination with building design and analysis and targeting the preliminary design phase. This should not be limited to the consideration of environmental scores or CO_2 emissions as an additional database to be used to evaluate the building use phase and materials, as it has commonly been done in literature, but should result in a full LCA (even with some necessary simplifications).

1.1 Multi-criteria decision-making approaches

Regarding the wide range of parameters influencing energy consumption in buildings and the broad set of criteria that need to be taken into account to achieve a more sustainable solution, multi-criteria decision-making approaches taking into account dynamic simulation of the building lifecycle and/or LCA and/or economic issues have gained attention in recent years. [8] employed a multi-criteria genetic algorithm in the search for a non-dominated (Pareto) set of solutions to trade-off between energy cost and occupants' discomfort. Their outcomes revealed that the multi-criteria genetic algorithm is able to find the compensation between daily energy cost and zone thermal discomfort, showing rapid evolution towards the Pareto optimal solutions. In particular, it is possible to find feasible solutions within very few trial solutions. [9] combines a genetic algorithm with a dynamic thermal model in order to find large numbers of distinctly different low-energy designs. [10] proposed three-step optimization methodology for the building design stage that would lead to environmentally optimal buildings: (1) design variable grouping (4 main groups: production and construction; operational energy; maintenance to demolition; and an Integrated Group relevant to several life cycle stages), (2) generation of the intra-group optimization methodology, and (3) integration. [11] presented a multi-objective optimization model to assist green building design including: (1) parameters determined at the conceptual design stage that have critical influence on building performance, (2) life cycle analysis to evaluate design alternatives for both economic and environmental criteria. A number of Pareto optimal solutions for green building design are presented for a

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[1] In this context, dynamic does not necessarily mean that the development of the product and background system is modelled continuously, but rather it means that a future state of the system is modelled considering the future characteristics of the background and the modelled system.

particular case study. [5] presented a simulation-based Artificial Neural Network (ANN) to characterize building behaviour, and then combined this ANN with a multi-objective Genetic Algorithm (NSGA-II) for optimization. The authors emphasize that by integrating ANN into optimization, the total simulation time was considerably reduced compared to classical optimization methodology. The results showed significant reduction in terms of energy consumption as well as improvement in thermal comfort. [12] analysed the life cycle inventory of four typical Belgian residential buildings showing the relative slight importance of the embodied energy of a building compared to the energy consumption during the usage phase.

1.2 Thermal comfort

Bedford’s study [13] can be considered as the pioneer investigation on people’s thermal comfort in everyday conditions. Since then, many researchers have collected data from a variety of climates and countries, from people in buildings that are heated or cooled or ventilated mechanically, and from buildings operating without either heating or cooling. Basically, two different approaches for the definition of thermal comfort are available: the rational or heat-balance approach and the adaptive approach [14].

Regarding approach for the assessment of building performance with respect to thermal indoor climate, in the 1980's, the weighted temperature excess hours (WTEH) method was developed by the Dutch Government Building Agency [15],[16]. Subsequently, a new method based on the studies of de Dear and Brager [17] supplanted the WTEH method [18]; namely, the adaptive temperature limit method (ATL).

1.3 Life Cycle Assessment optimization

The LCA issues specific to buildings and constructions come basically from the following specificities [19]:

- *The functional output has to be regarded as a service rather than a product;*
- *The system behind the services (as well as the environment context associated with it) is dynamic;*

- *The provided service has a defined service life, while utilised building facilities, building products, etc. have their own life cycles and service lives;*
- *Actions taken in the building sector also influence other sectors, not only on the margin, which makes margin markets an area of special interest;*
- *In the ordinary design process, different aspects are put forward as performance requirements. This application of LCA emphasises the need to improve the utilisation in practice to be able to assess functions.*

According to [20], the approach for incorporating LCA into system optimisation comprises three main steps:

1) Implementing a Life Cycle Assessment study;
2) Formulating the multi-objective optimization problem in the LCA context;
3) Solving the multi-objective optimization problem and choosing of the best tread-off solution.

Similarly to the aim of our work, [21] presented a LCI model combining advanced optimisation techniques, LCI and cost-benefit assessment to optimise low energy buildings simultaneously for energy, environmental impact and costs taking into account boundary conditions for thermal comfort, indoor air quality and legal requirements for energy performance.

2 EAVES project

Hence, an important research issue is the development elaboration of a tool which could combine state of the art LCA approaches with comprehensive building design software, allowing a dynamic simulation of the lifecycle of a building.

The project EAVES (Environmental life cycle assessment and optimization of buildings), funded by the National Research Fund Luxembourg (FNR), aims to develop an integrated tool for the environmental assessment and optimization of buildings focusing on the preliminary design phase. The tool (conceived to be endowed with a user-friendly interface, particularly tailored for architects' use) will avail itself of the graphical user interface (GUI) of Google SketchUp®, of the buildings dynamic thermal performance simulation tool - TRNSYS®, and of an open source framework for Life Cycle Assessment (OpenLCA).

Four phases are foreseen in the project, namely:

1) Definition of a set of indicators: to define a set of environmental and (as far as possible) comfort indicators to be further used as assessment and optimization criteria;

2) Combination of TRNSYS and OpenLCA: to have an effective data and information exchange between the two working environments;
3) Lifecycle optimization based on environmental, economic and indoor comfort criteria: to develop and implement a framework for the lifecycle optimization of preliminary building design;
4) Case study: application of the developed tool to the assessment and optimization of a real building design.

2.1 Definition of a set of indicators (phase 1)

The present project reflects the existing knowledge available in Europe on building assessment methodologies. Hence, the assessment of the performance of buildings should be consistent with indicators which are broadly accepted by the European stakeholders involved in sustainable construction. At this aim, pertinent environmental, social or economic sustainability issues (Tab. 1) were excerpted from the project LEnSE - Methodology Development towards a Label for Environmental, Social and Economic Buildings [22] and adapted to this work. A set of indicators will be elaborated and applied in the project EAVES, in order to tackle these issues.

Tab. 1: List of selected issues representing environmental, social or economic sustainability themes (adapted from: [22]).

Category	**Issue**
Environmental impacts	• Reduce Greenhouse Gas Emissions and Acidification
Resource use and Waste	• Minimise Primary Energy Consumption (embodied, operational and renewability) • Limit Raw Material Use and Source renewable/recycled/responsibly sourced materials • Minimise Water Consumption (reduce use and maximise reuse)
Occupants' Well Being	• Improve Visual Comfort (internal and external lighting provision) • Improve Thermal Comfort • Improve Indoor Air Quality (odours, ventilation and humidity)
Financing and	• Improve Economic Feasibility

Management	• Reduce Construction and Financing Costs • Reduce Life Cycle Costs

2.2 Approach outline (phases 2 and 3)

The proposed computational procedure will start with a 3D building draft in Google SketchUp® where thermal zones, fenestration objects, shading objects matching walls, roofs and floors and building position are to be defined.

These data are saved in a standard file format. In the next step, the required detailed building data have to be entered, such as location (weather data), function, structure (U-Value, internal heat gains, ground insulation, etc.), doors, windows and openings, MPE/HVAC systems. Based on the information therein, it is possible to generate a building description file and a TRNSYS Project File. At this stage a fully functional TRNSYS simulation is set up and the required links are generated. The tool has now to be fed with the optimization as well as the LCA parameters. Then, parameters and combined variation domains that are determined by the model of the building are outlined for the optimization problem. Here objectives and genetic algorithm settings have to be chosen and one or more objectives can be followed concurrently. In this way, the definition of the optimization problem can be done through the description of the building and the choice of parameters, objectives and algorithm settings. The genetic algorithm is able to accomplish the calculation process. The first generation of individuals is randomly selected. Each given population consists of individuals representing buildings configurations. Each configuration resulted from the preliminary selection accomplished through the application of energy saving strategies (for instance: Trias Energetica[2], [23]). Afterwards these alternatives will be assessed further, consistently with previously chosen objectives employing tools and databases assisted by an interface liking TRNSYS, OpenLCA and economic approaches. The parents for the next generation are selected taking into account the calculation outcomes successively. After a pre-set number of generations, the optimization process stops. Subsequently the results, i.e. categories of optimized scenarios for buildings design, are displayed. A simplificative description of the process is depicted in Fig. 1.

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[2] *The 3 elements of Trias Energetica are: 1. Reduce the demand for energy by avoiding waste and implementing energy-saving measures; 2. Use sustainable sources of energy like wind, solar power and water; 3. Use fossil fuel energy as efficiently as possible and only if sustainable sources of energy are unavailable.*

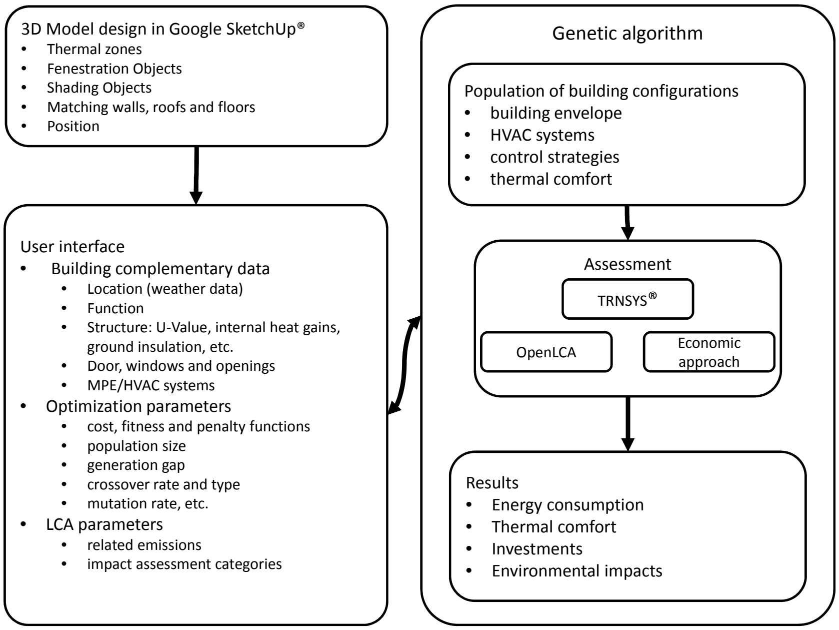

Fig. 1: Schematic structure of the tool.

2.3 Case study: Assessment and optimization of CRTE building (phases 4)

In order to assess the EAVES tool, it will be tested on the design of a real building whose construction is foreseen in the next years in Belval, Luxembourg (the so-called "maison de l'Innovation" building). Furthermore, reliable develops by using EAVES tool are expected to be disseminated widely in Luxembourg.

3 Final considerations

In this work, the first concepts and the overall logic flow of the software tool foreseen within the EAVES project is presented. Targeting the entire lifecycle of a building simulation under dynamic conditions, involves the development and employment of a consistent and comprehensive LCA methodology which has not been developed so far in such an integrated and comprehensive way. Challenging and demanding is the consideration of energy and environmental criteria, as well as economic constraints and optimal target configurations of HVAC and lighting elements in order to achieve indoor comfort conditions for the occupants in the preliminary building design phase.

Further actions regarding close relationship with the architectural offices and other stakeholders in charge of building projects development will also allow the EAVES project fine adjustment. As a final objective, the tool will support Luxembourg to design more efficiently the real estate assets contributing to reduce carbon foot print.

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