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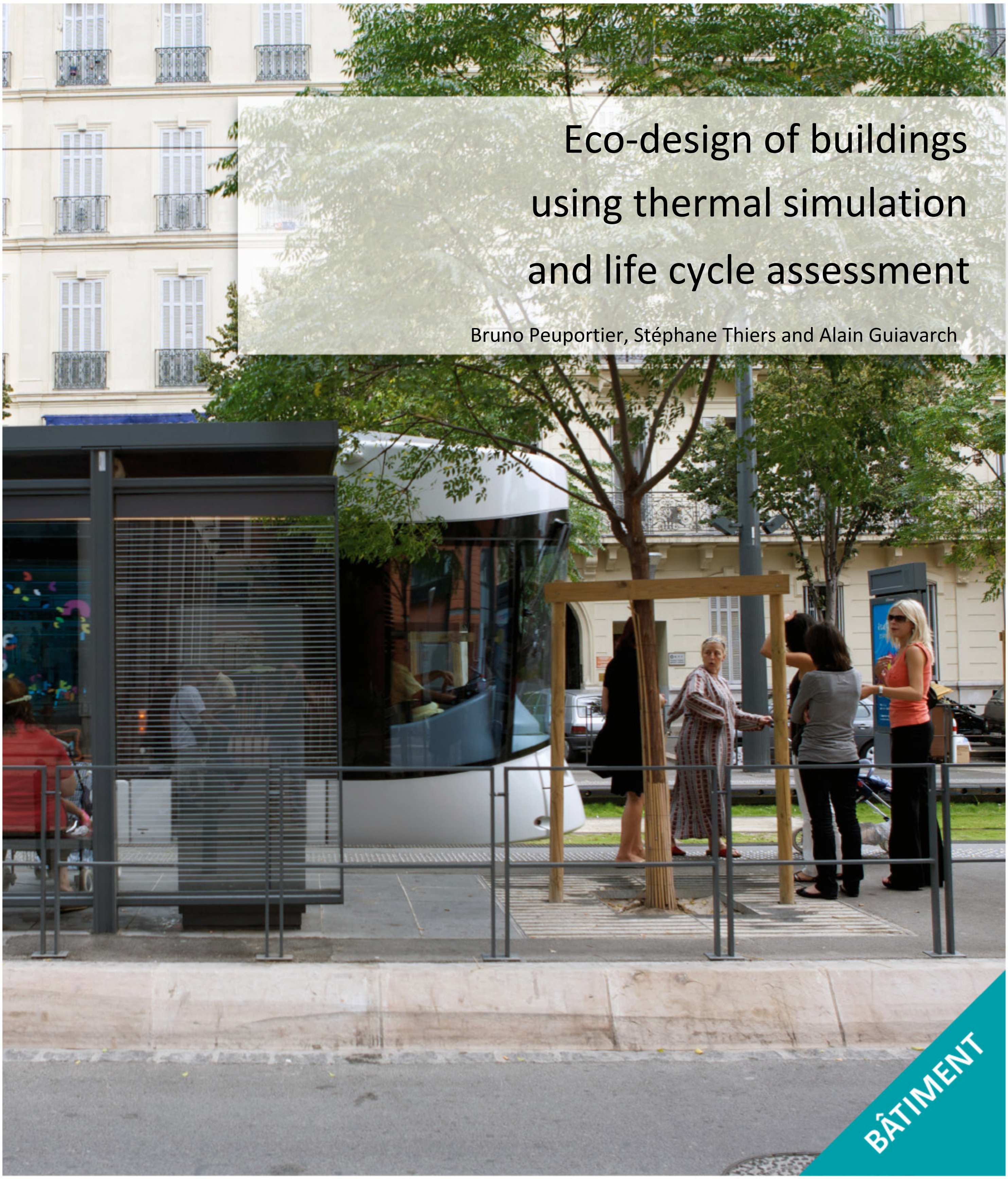

Eco-design of buildings using thermal simulation and life cycle assessment

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BÂTIMENT

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ABSTRACT

Energy efficient building are designed to minimize heating, cooling and lighting energy loads, so that attention is now paid on the energy consumption related to inhabitants (e.g. use of appliances) and life cycle issues: fabrication of materials, construction, maintenance, dismantling and waste treatment.

In order to study these aspects, both in new construction and renovation projects, thermal simulation has been linked to life cycle assessment. Such a global environmental balance of a building allows for comparison of alternatives, constituting an eco-design tool. This methodology is presented, as well as validation elements from model inter-comparison. Application of this method is illustrated by a case study: two attached passive houses built in France. The results show the contribution of different life cycle stages in the environmental impact indicators (e.g. energy demand, global warming potential, water consumption, waste production…) as well as the influence of occupants on the performance.

INTRODUCTION

Sustainability is on the agenda of most organisations, and particularly cities [1]. Meeting the needs of the present without compromising the ability of future generations to meet their own needs is such a broad objective that many ways are proposed to achieve it. Accounting for environmental issues in the building and urban sectors is presently based upon rather subjective approaches. Yet the severity and planetary extent, long duration and possible irreversibility of environmental impacts like global warming, nuclear risk, dispersion of toxic substances, biodiversity loss and resource depletion, justifies more precise tools to be used in the decision making process. The building sector is a major contributor to environmental burden, representing e.g. nearly half of the total energy consumption in Europe.

The first generation of green building certification schemes has been elaborated in the 90's, generally by organizations gathering policy makers and professional representatives. In parallel, scientists developed tools, mostly based upon life cycle assessment (LCA), aiming at a better understanding of how environmental impacts are generated, and proposing some aid to designers. LCA has long been regarded as too complex by building professionals, but the development of user friendly interfaces makes the use of this method much easier so that it is increasingly applied for different purposes: eco-design is the main application, but LCA can also be used to compare various possible building sites, different projects in an architectural competition, architectural and technical solutions for retrofit, end of life processes etc.

Since the beginning of tool development towards green buildings, there has been little relationship between LCA experts and researchers in the field of energy efficiency so that the priority has been to develop data bases providing life cycle inventories of building products. In fact, energy related impacts are essential in the global environmental balance of buildings due to the long life span of these systems compared to most industrial products, and the importance of the operation stage and associated energy consumption for heating, cooling, lighting etc. Linking thermal simulation and LCA is therefore relevant in order to assess and possibly improve the performance of a building project on a global basis.

For instance, the energy experts community promotes concepts like "passive houses" [2], while the LCA experts are questioning these concepts because of the energy consumed for the fabrication of insulation, triple glazing and equipment implemented in such houses. Linking energy and life cycle assessment allows balancing embodied and operation energy when choosing e.g. insulation thickness or window type. Energy saving is one of the objectives of eco-design, which also addresses issues like climate change, human health, biodiversity etc.

Another specificity of the building sector is the influence of occupants on the performance. Measurements performed on 18 identical passive houses [3] have shown that the actual energy consumption for space heating varies from 5 to 30 kWh/m2, the 14 kWh/m2 average corresponding rather well to the calculated value: 15 kWh/m2. A sensitivity study is presented here regarding the influence of occupants on energy use but also other environmental issues, in the case of passive houses that have been built in France in 2007.

DEVELOPMENT OF MODELS ADAPTED TO THE DESIGN PROCESS

The objective being eco-design, i.e. accounting for environmental issues in the design of buildings and urban neighbourhoods, models are developed according to criteria like sensitivity to design parameters, accuracy of the results, and adaptation to professional practice (regarding particularly data input, computation time and interpretation of results). These different criteria may seem contradicting, though appropriate model reduction techniques and user-friendly interfacing help solving such contradictions.

A first step is to elaborate a set of environmental issues to be studied. An example set of sustainability objectives has been defined in the European project Eco-housing [4], see Table 1.

Table 1. Example list of considered sustainability issues

Dimensions	Main goals	Objectives
1 Ecological	1 Preserve resources	1 Preserve material resources
		2 Save energy
		3 Save water
		4 Reduce land use/transformation
	2 Protect the ecosystems	1 Limit toxic emissions
		2 Protect the climate
		3 Protect the forests
		4 Protect rivers and lakes
		5 Improve outdoor air quality
		6 Protect fauna and flora
		7 Reduce waste
		8 Reduce radioactive waste
		9 Preserve the ozone layer
		10 Limit floods

2 Economic	1 Reduce life cycle cost	1 Reduce construction cost 2 Reduce operation cost 3 Reduce maintenance cost 4 Reduce renovation cost 5 Reduce demolition cost
	2 Add value	1 Ease space modification 2 Ease use modification
3 Social	1 Preserve residents health	1 Improve indoor air quality 2 Improve water quality 3 Reduce radiation risk 4 Reduce risks (fire, explosion…)
	2 Improve comfort	1 Improve visual comfort 2 Improve thermal comfort 3 Reduce noise 4 Reduce odours 5 Improve well being
	3 Add social value	1 Improve quality of use 2 Increase social and gender equity 3 Integrate the disability issues 4 Ease social relationships 5 Improve participation
4 Cultural	1 Develop creativity	1 Improve architecture and image 2 Improve site integration 3 Support cultural activities
	2 Conserve cultural heritage	1 Conserve historical sites 2 Consider conserving or transforming existing buildings 3 Conserve local regional materials

For each environmental issue, an indicator has been selected, mostly from CML [5] or Eco-indicator [6], see Table 2 hereunder. Social and economic aspects are addressed in other projects, e.g. LEnSE (Methodology development towards a label for environmental, social and economic buildings, see www.lensebuildings.com). The EQUER model developed earlier [7] has been adapted to evaluate these indicators. This model simulates the life cycle of a building using a one-year time step and object-oriented programming. Each object includes data (e.g. a life span) and methods (e.g. impact assessment for its fabrication, assembly, use, dismantling) allowing impacts to be evaluated for the whole building.

A user-friendly interface is also essential to a professional use of software. In the building sector, drawing a plan or sketching a volume are the preferred ways for geometry input. A 3D geometry model is necessary for a precise quantification of material volumes. It is also needed to perform lighting calculations by ray-tracing, in order to evaluate the related energy consumption. But geometry is not sufficient to describe a building. Physical properties of materials are needed to perform energy calculations, as well as environmental data for LCA. The object-oriented approach has been helpful to link a graphical modeller, a thermal simulation model and an LCA tool.

Table 2. List of the impact indicators computed by EQUER

Impact indicator	Unit	Legend
Cumulative Energy Demand	GJ	ENERGY
Water consumption	m^3	WATER
Abiotic Depletion Potential	kg Sb-eq	RESOURCE
Non-radioactive waste creation	t eq	WASTE
Radioactive waste creation	dm^3	RADWASTE
Global Warming Potential at 100 years (GWP_{100})	t CO_2-eq	GWP_{100}
Acidification Potential	kg SO_2-eq	ACIDIF.
Eutrophication Potential	kg PO_4^{3-}-eq	EUTROPH.
Damage caused by the ecotoxic emissions to ecosystems	PDF.m^2.yr	BIODIVERSITY
Damage to human health	DALY	HUMAN HEALTH
Photochemical Oxidant Formation Potential (Smog)	kg C_2H_4-eq	O_3-SMOG
Odour	Mm^3	ODOUR

Decisions having the largest influence on building performance are made in early design. An eco-design tool should therefore be usable in this phase, which seems in contradiction with the accuracy and sensitivity criteria mentioned above because these criteria imply the use of a detailed model, which requires a lot of data on a building.

But in fact, a detailed model can be used in early phases of a project thanks to default values and generic data. For instance, the materials producers are not yet selected at early design phases. Generic data, corresponding to average or typical impacts for a certain material can be used for the fabrication impacts, e.g. generic impacts for glass wool corresponding to an average of specific data for different producers and products. Such life cycle inventory and impact assessment data are provided e.g. by the Ecoinvent database [8] (and further versions on www.ecoinvent.ch). Contextualisation is applied for local production processes (e.g. fabrication of concrete blocks), e.g. by adapting the electricity production mix according to a national or regional context.

A default value can also be considered for the transport distance from each product factory to the building site. Fortunately this parameter has a rather low influence on the global performance because transport related impacts are lower than those related to fabrication and operation (assuming typical distances, even using trucks). For instance according to the Ecoinvent database, the amount of CO_2 emitted by the transport by truck of one ton over 100 km is only 12% (resp. 1%) of the emissions corresponding to the fabrication of one ton of concrete (resp. of steel).

Generic data can also be used for end of life processes, e.g. regarding environmental impacts due to incineration of plastics and wooden products, landfill of inert materials, recycling of metals. Again, default values can be used for transport distances. In a later design phase, when selecting material producers, specific data and more precise transport distances can be used to compare products.

MODEL VALIDATION

The objective being eco-design, i.e. accounting for environmental issues in the design of a building, it is essential to check the sensitivity of the tool when varying architectural and technical characteristics.

Regarding energy calculations, a benchmark procedure has been developed in the frame of the International energy agency task 12 of the Solar Heating and Cooling Programme [9]. This benchmark includes around 30 cases, in which insulation, solar gains, thermal mass, thermostat set point (with possible intermittent heating/cooling), ventilation and other parameters are varied. The results obtained using the dynamic thermal simulation tool COMFIE developed at CEP [10] are consistent with the benchmark values derived from international reference models.

Environmental impact indicators have also been compared, first in the frame of the European project REGENER, then in another programme of the International Energy Agency and finally, in the European thematic network PRESCO (Practical Recommendations for Sustainable Construction). For instance in the case of a Swiss wooden frame house studied in the inter-comparison, the CO2 emissions over 80 years evaluated by the 8 participating tools differ from +/- 10% from the average value [11].

EXAMPLE CASE STUDY

The building under study is a group of two attached houses built in 2007 in Picardy region, France (Figure 1). These houses are the first certified “Passive-House” buildings in France.

Figure 1. General view of the two houses (Arch.: En Act architecture, contractor: les Airelles)

Each house is two-storied, with an inhabitable area of 132 m^2, a garage, a terrace, a balcony and a garden. Both include a hall, an office, a living-room and a kitchen downstairs, and a sitting room, a bathroom and three bedrooms upstairs. Only the situation of the garage differs. These dwellings are designed for a family of four persons.

Wooden frame external walls are insulated by cellulose (22 cm) and polystyrene (15 cm), the slab by polystyrene (20 cm) and the attic by cellulose (40 cm). Triple-glazed windows and insulated external doors provide high insulation and air-tightness[1]. External venetian blinds provide solar protection during summer and mid-season. Thermal bridges are very low, supposed to be limited to 0.1 $W.m^{-1}.K^{-1}$ around the slab and the attic.

Both houses are equipped with a 30 m-long earth-to-air heat exchanger for summer cooling, with a heat recovery ventilation (average efficiency: 70%), with 5 m^2 of solar panels for solar water heating (solar fraction: 50%), and with a compact electric heat pump for the air heating and the water heating backup (average annual coefficient of performance: 3).

[1] The houses fulfill the Passivhaus label criterion: the air infiltration rate is inferior to 0.6 $vol.h^{-1}$ at 50 Pa pressure difference between inside and outside.

In order to evaluate the energy and environmental benefit of the passive house concept, a reference house has been defined, keeping the same geometry but considering technologies corresponding to the French thermal regulation level: 13 cm insulation in the walls, 14 cm in the ground slab and 22.5 cm in the roof, low emissivity double glazed windows, no heat recovery on ventilation, standard air tightness (total 0.6 ach ventilation + infiltration), no earth-to-air heat exchanger, no solar hot water system, standard boiler (87% annual efficiency) instead of a heat pump.

SIMULATION RESULTS

The meteorological data used for the simulation correspond to the local climatic zone (oceanic climate). Ventilation, occupancy and internal heat gains are modelled by scenarios, considering two types of occupants' behaviour: economical, and spendthrift (see Table 3).

Table 3. Assumption regarding two types of occupants' behaviour

	Economical behaviour	Spendthrift behaviour
Heating set point	19°C	22°C
Air infiltration including window opening	0.1 ach	0.5 ach
Annual internal gains due to electricity consumption (appliances ...) per dwelling	1,500 kWh	2,600 kWh
Cold water consumption	80 l/day/person	120 l/day/person
Domestic Hot Water (DHW) consumption	20 l/day/person	50 l/day/person

Thanks to the implemented energy saving solutions described above, the heating load is very low if the occupants' behaviour is reasonable, see Table 4. The DHW load is also limited due to the solar system. On the other hand a spendthrift behaviour, increasing the temperature set point, hot water consumption and air exchange rate, reduces the performance of the house. The heat recovery and earth-air heat exchanger increase the electricity consumption for ventilation compared to the reference house.

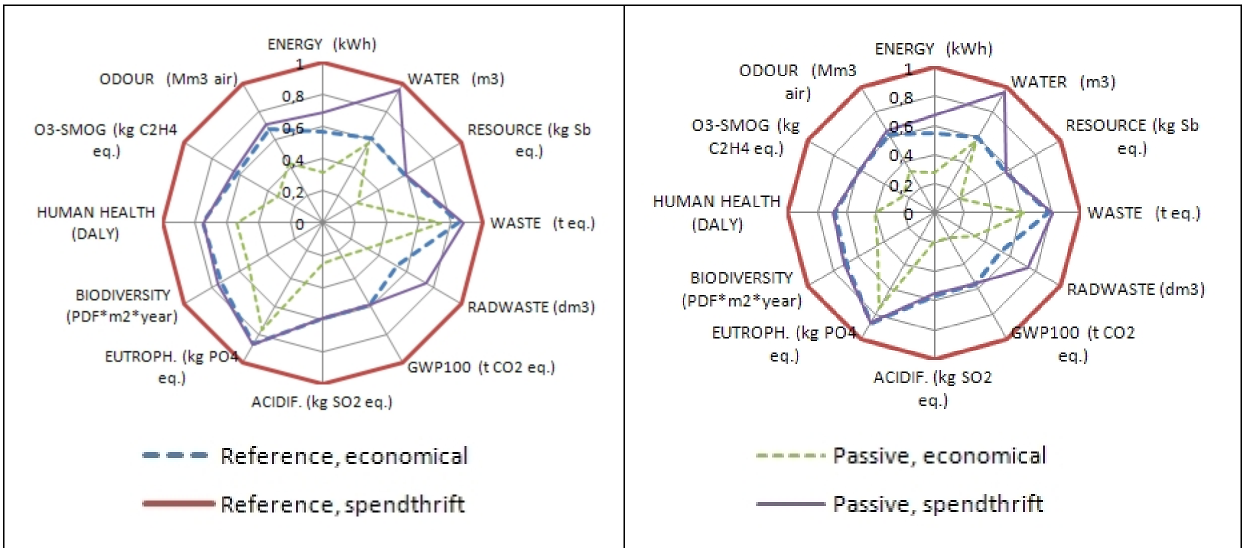
Table 4. Calculated energy use of the houses

Energy use, kWh/m²/yr	**Economical**		**Spendthrift**	
	passive house	reference house	passive house	reference house
Heating load	5	59	51	116
Domestic Hot Water load	5	10	12	23
Cooking, Lighting, other Appliances	11	11	20	20
Ventilation	7	3	7	3
Total	28	83	*90*	*162*

Regarding life cycle assessment, the material quantities have been derived from the 3D geometric model and wall composition data used for thermal simulation. A 5% surplus is added in order to account for on-site processes, broken elements and purchased quantities. An average 100 km transport distance (by truck) is considered from the factories to the building site, 20 km from the building site to incineration, and 2 km to landfill. The life span is 10 years for building finishes (painting), 30 years for windows and doors, and 50 years for the other elements and the whole building. End of life is modelled here very simply, assuming landfill for all demolition waste.

The French electricity production mix is the following: 78% nuclear, 14% hydro-electricity, 4% gas and 4% coal thermal plants. Using electricity for heating induces a high peak demand during cold days, e.g. 94,000 MW compared to around 60,000 MW in summer. This requires a larger use of thermal plants and imported electricity. For this reason, the European electricity production mix has been considered for the electricity consumed by the heat pump for space heating: 37% nuclear, 15% hydro-electricity, 10% gas, 28% coal and 10% fuel thermal plants. 9% losses are considered in the electricity grid, and 20% losses in the water mains.

The following Figure 2 presents the comparative results for both occupancy scenarios (economical and spendthrift) and both performance levels (reference and passive houses). Each axis corresponds to an environmental impact indicator. The indicators are represented in relative values related to the worst case (reference house and spendthrift scenario) used as a reference. For instance, the CO_2 emissions are reduced by 40% thanks to a more appropriate behaviour, by 80% in the best case corresponding to the passive house and an economical behaviour. A sensitivity study has been performed regarding the building life span, considering 100 years instead of 50. This parameter is very uncertain, but the trend is very similar regarding the impact reduction obtained by higher construction quality and responsible behaviour.



Impacts over 50 years

Impacts over 100 years

Figure 2. LCA results from EQUER, comparison of occupants' behaviours

It is also useful to identify the source of the impacts in order to find ways to reduce them. The following graph shows the contribution of different life cycle stages in the global energy balance. Similar graphs could be drawn for other impacts. Construction related impacts are higher for the passive house due to increased insulation thickness, triple glazing and solar system, but impacts are reduced during the operation stage, see Figure 3.

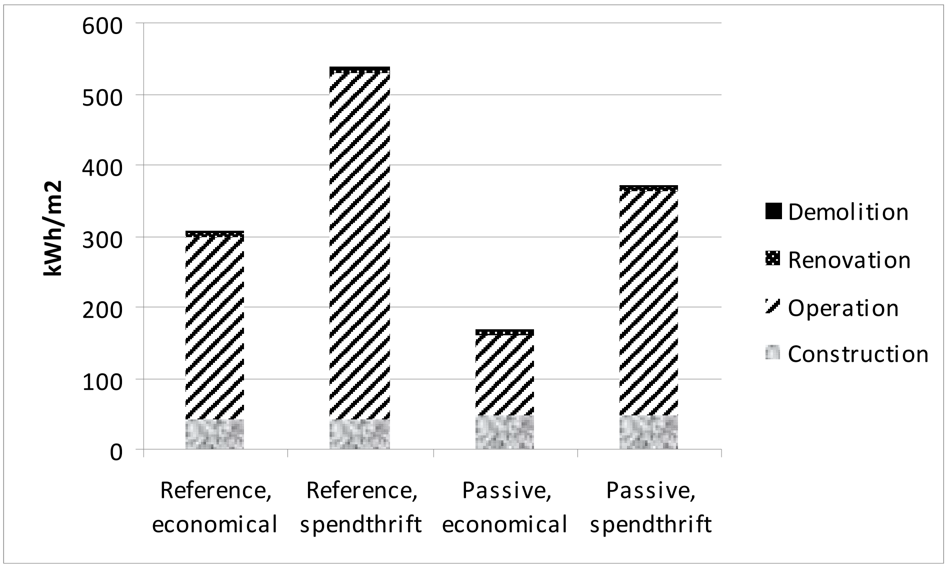


Figure 3. LCA results from EQUER, contribution of the life cycle stages

These results show the possibility to reduce dramatically most environmental impacts by combining efforts made by professionals in the design and construction of low impact buildings, and made by inhabitants to adopt a more sustainable behaviour.

DISCUSSION AND CONCLUSIONS

LCA has been applied to energy efficient buildings, showing the environmental benefit of such higher quality constructions, but also how occupants' behaviour strongly influences the environmental performance of these buildings.

End of life has been modelled very simply in the calculation presented above. Different scenarios could be studied (e.g. incineration with heat recovery, recycling or re-use) if the objective of the LCA study are also to compare different building materials.

The studied house includes wooden elements, which raises the problem of accounting for biogenic CO_2. Carbon is absorbed when the trees are growing, then it is stored over the building life span and finally stored again if the wooden element is re-used or recycled, or released back to the atmosphere, possibly avoiding other emissions if the waste wood is incinerated with heat recovery. This complex chain has not been modelled here because landfill is considered at end of life. Again, other end of life scenarios could be studied, as well as accounting for carbon storage like it is proposed in the International Reference Life Cycle Data Handbook [12].

Only the building envelope, partitioning, wall painting and main equipment (heat pump and solar system) have been accounted for. Some elements in minor quantity have been neglected, assuming that the related environmental impact is negligible. Indoor emissions are not integrated in the model due to lack of data at the moment.

In the present model, fixed values have been used for the electricity production mix, and the corresponding impact assessment is not very precise, particularly regarding the electricity consumed by the heat pump for space heating (which induces an important peak demand and high related CO_2 emissions due to the use of thermal plants and imported electricity). A dynamic LCA model is under development, accounting for a seasonal, weekly and daily variation of the mix. This model also includes allocation of impacts according to the different electricity uses (heating, cooling, hot water, other household consumption, other business consumption). Such a development allows innovative control strategies to be studied in order to reduce emissions, e.g. by reducing the electricity demand during peak hours.

Perspectives for methodological improvement are discussed e.g. in the frame of the European LORE-LCA research coordination action, aiming at identifying good practice and knowledge gaps regarding the application of LCA in the building sector.

An extension of the building model is under development in order to study urban blocks including several building types (e.g. residential, tertiary...), open spaces (streets, parks...), and networks (water mains, district heating...).

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