Should building energy simulation tools integrate life cycle assessment? A discussion of the potential benefits and challenges

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Abstract

Buildings use energy in all phases of their life cycle and there is interaction between the energy used throughout different phases. In conventional buildings energy use in the use phase is largely dominant, however as we move towards low energy buildings, the share of embodied energy related to life cycle energy use increases. Building energy simulation tools assess energy use in the use phase only, while life cycle assessment (LCA) tools cannot compute energy calculations in the use phase. Ideally, a single tool capable of providing accurate LCA results of buildings would very much facilitate design choices based on environmental performance.

This paper reviews the standard practice in building LCA, and identifies its limitations. It suggests a method to communicate energy simulation and LCA tools to facilitate an integrated environmental assessment, and suggests a method to include variability of the power supply system into the analysis.

1 Introduction

Buildings use about 40% of global primary energy (International Energy Agency, 2010), and energy efficiency measures in the built environment offer some of the most cost effective means of reducing energy use and carbon emissions (Brown, 2001, McKinsey&Company, 2010). In this context, energy polices worldwide are targeting energy use in buildings as "low hanging fruit" to meet their climate commitments (Cubi Montanya and Salom Tormo, 2011). However, buildings are complex systems, and cannot be accurately assessed with traditional design methods (Clarke, 2001). Building energy simulation offers the potential to cope with building performance related concerns (during building operations or "the use phase"), and is increasingly being used to aid in the design decision making process (International Building Performance Simulation Association, 2013).

Buildings use energy directly or indirectly in all phases of their life cycle (from construction to decommissioning) and there is interaction between the energy used throughout different phases (e.g., embodied energy in materials and operating energy). The use phase typically accounts for 70-90% of building total life cycle primary energy use (Adalberth, 1997, Winther and Hestnes, 1999, Sartori and Hestnes, 2007, Ramesh et al., 2010). However, as we move towards low energy buildings, the system becomes more complex. One example is new technologies that use energy more efficiently tend to increase the share of embodied energy related to life cycle energy use. A second example is a technology that generates or stores electricity onsite that alters the impacts of the electricity system in the region differently over different time periods. Therefore, buildings should be analyzed from a life cycle perspective (both over the full life of the building as well as through the full supply chain (Ramesh et al., 2010).

Life cycle assessment (LCA) is a technique to assess energy and environmental impacts associated with all the stages of a product life cycle (cradle-to-grave). Integration of life cycle assessment into building energy simulation tools would allow a better evaluation of building design alternatives, particularly for high performance buildings. However, the best method to integrate tools at different levels of scale, detail and sophistication remains unclear to date.

Objective

This paper presents a discussion of the potential benefits and challenges of integrating life cycle assessment into building energy simulation tools. It addresses the following questions: How can these tools account for the dynamic interaction between buildings and local/regional energy systems (e.g., grids)? How can the assessment boundaries be defined in a systematic way to enable comparison across studies? What data is required? Is this data available (and if not, how can it be collected)? What are the pros and cons of integrating life cycle assessment into building energy simulation tools? The paper concludes with a discussion of new research that is required in this field.

2 Overview of existing tools

There are several tools available for evaluation of building energy performance (building energy simulation tools) and building life cycle assessment (building-specific LCA tools). This section reviews the most popular tools in each set. The following sections focus on the (currently limited) connection between the two sets of tools.

Building energy simulation tools

Building energy simulation is a powerful method to perform ex-ante assessments of energy performance of buildings and building systems. Building energy simulation is widely used by researchers and building design teams to estimate energy use of commercial and residential buildings, and sometimes used for mandatory energy rating systems or voluntary third-party environmental performance evaluation systems such as the USGBC LEED certificate (U.S. Green Building Council, 2010). The most widely used building simulation software packages include DOE2 interfaces (U.S. Department Of Energy, 2013a), EnergyPlus (U.S. Department Of Energy, 2013b), TRNSYS (University of Wisconsin et al., 2013), and ESP-r (Energy Systems Research Unit. University of Strathclyde et al., 2013).

DOE2 was the pioneer building simulation system. Its interfaces (the most popular being e-QUEST) are accepted for LEED certification and energy rating, however, DOE2 interfaces do not have specific models for novel high energy performance systems (e.g., radiant systems, displacement-like ventilation systems, ground source heat pumps, or complex mechanical systems) and therefore, its use for modeling high performance buildings is becoming marginalized.

EnergyPlus is the next generation of building energy simulation tools supported by the U.S. government. It is currently among the most used simulation tools in the U.S. and worldwide (U.S. Department Of Energy, 2013b), and it is capable of better handling advanced building mechanical systems. EnergyPlus remains a “building-focused” modeling tool (i.e., the focus of the model is the building itself, and the mechanical systems are included in the model as a means to match the building's needs). Stand alone models of systems are not possible in EnergyPlus.

IDA Indoor Climate and Energy (EQUA Simulation AB, 2013) is a whole building energy simulation sofware developed in Sweden. It is also a building-focussed modeling tool. The most salient feature is likely its "building integrated modeling interoperability". The developers claim that it can easily import models from a large variety of computer aided design (CAD) software packages.

TRNSYS is a modular simulation tool that features an extensive library that includes a building model and the components commonly found in thermal and electrical energy systems. The modular nature facilitates the addition to the program of mathematical models not included in the standard TRNSYS library. In a TRNSYS model, the user specifies the components that constitute the system and the manner in which they are connected (University of Wisconsin et al., 2013). Therefore, while TRNSYS allows simulation of buildings, it is also capable of defining tailor-made HVAC systems outside the building model.

ESP-r "is an integrated energy modeling tool for the simulation of the thermal, visual and acoustic performance of buildings and the energy use and gaseous emissions associated with associated environmental control systems. In undertaking its assessments, the system is equipped to model heat, air, moisture and electrical power flows at user determined resolution" (Energy Systems Research Unit. University of Strathclyde et al., 2013). ESP-r is, therefore, a "building-focused" modeling tool.

The aforementioned building energy simulation software packages define spaces as a single (or very few) airnode (representing the thermal capacity of the zone air volume and capacities which are closely connected with the air node, such as furniture), assuming homogeneous environmental conditions in the entire space (or the volume associated with the airnode). Spaces have heat gains and losses through envelope elements (walls and windows), and internal heat gains associated with occupants, lighting and equipment. The heating or cooling load resulting from the building model is an input to the HVAC system model, which in turn results in final energy use (fuel or electricity, depending on the HVAC system type) for space conditioning. Electricity use for lighting and internal equipment is usually calculated based on user defined use schedules and equipment nominal power, although more advanced controls are also possible (e.g., lighting control based on available radiation). The simulation timestep is typically 1h, although detailed models of fast-response systems require shorter time steps (e.g., air-based systems).

Building-specific life cycle assessment tools

There are several life cycle assessment databases of building-specific products and materials. These LCA databases usually account for the impacts throughout the whole product life cycle (cradle-to-grave), including the use phase. It must be noted, however, that they do not assess impacts of a given product on building energy performance and, therefore, do not account for impacts derived from building energy use in the use phase. Due to the local nature of construction techniques, distances, and energy and transportation networks in which buildings are integrated, differences among inventory data in different databases can be substantial (Zabalza Bribián et al., 2009). Selecting the relevant database for the building location is critical for the accuracy of the environmental assessment.

The Athena Impact Estimator for buildings (Athena Sustainable Materials Institute, 2012) is developed by the Canadian based Athena Sustainable Materials Institute. It is a stand-alone software tool that provides a cradle-to-grave life cycle inventory for a whole building. According to its developers, it is applicable for new construction and retrofits in all North American building types. It can model over 1,200 structural and envelope assembly combinations. The Impact Estimator "allows users to model their own custom assembly and envelope configurations, and provides flexibility for proposed designs and existing buildings. (...) The Impact Estimator allows the user to input energy simulation results to calculate their operating effects alongside their embodied effects". Therefore, it requires final energy use (i.e., an energy simulation result) as an input to compute the whole building life cycle environmental impacts.

The BEES online database (Lippiatt et al., 2010) is developed by the National Institute for Standards and Technology (NIST). BEES includes environmental and economic performance data for over 230 building products. "BEES measures the environmental performance of building products using the environmental life-cycle assessment approach specified in International Organization for Standardization (ISO) 14040 standards. All stages in the life of a product are analyzed: raw material acquisition, manufacture, transportation, installation, use, and waste management. Economic performance is measured using the ASTM International standard life-cycle cost method (E917), which covers the costs of initial investment, replacement, operation, maintenance and repair, and disposal". BEES is developed in the US, and, therefore, it is the most suitable for LC assessments of buildings in the US.

Generic life cycle inventory databases that may also be used to assess building materials and components in North America include the U.S. Life Cycle Inventory Database (National Renewable Energy Laboratory (NREL), 2012) and the input-output based CEDA4 (Industrial Ecology Research Services (IERS), 2010). According to the CEDA website, "CEDA is currently being used in the development of an integrated Input-Output/BEES database in matrix form for the U.S. construction industry that would enable sustainability performance evaluation of 42 specific building types covering new and existing commercial and residential buildings".

Other building-specific life cycle assessment tools available internationally include EnerBuiLCA (CIRCE et al., 2012) for Spain and Portugal, LEGEP (König and Batteiger, 2012) for Germany, EQUER-IZUBA (GEFOSAT et al., 2012) for France, OGIP (EMPA Materials Science & Technology, 2013) for Switzerland, and Envest 2.0 (BRE, 2002) for the UK.

3 Standard practice in building LCA

Building-specific LCA databases are the single tool used to assess environmental impacts during pre-construction, construction and post-use phases, while they are combined with energy simulation tools to assess the environmental impacts in the use phase. Assessment of the non-use phases of buildings is relatively similar to that of other products, and can be handled by LCA tools. On the other hand, building use phase assessment differs from conventional products due to:

1- The longer life-span of buildings (typically 50yrs (Berggren et al., 2013))
2- The amount of agents that affect energy use, and the very complex interactions among them. These agents include building construction characteristics (envelope materials, size, window to wall ratio, shape, orientation…), building location and

corresponding climate, type and efficiency of HVAC equipment, building type and use, and occupancy patterns.

Figure 1 shows the typical process of a building life cycle assessment.

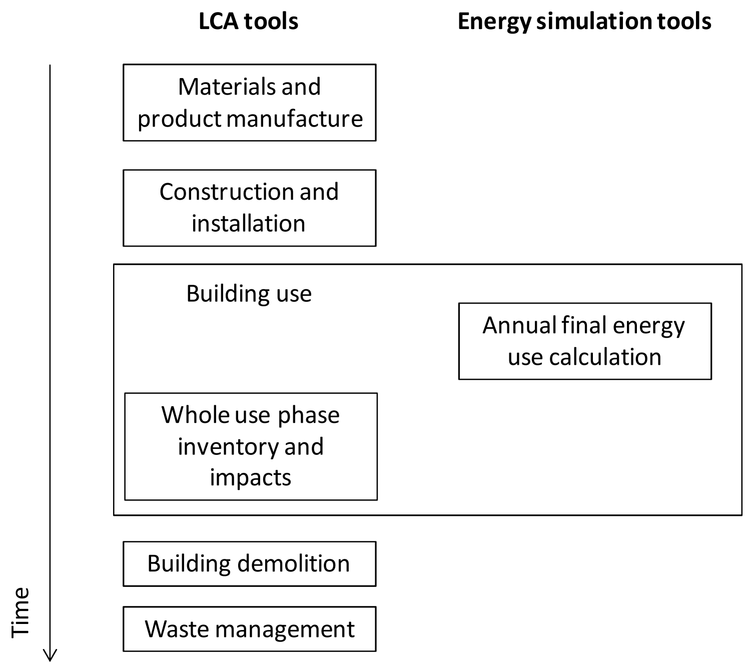

Figure 1 – Typical use of tools in different stages of a whole building LCA

Focusing on the assessment of the use phase, energy simulation tools are used to calculate instantaneous performance of the building and its energy systems at short time steps (typically 1h). Instantaneous energy results are integrated over one year, that is, the simulation runs for 1 year under varying conditions of occupancy and climate, and the instantaneous energy use results are added up to calculate annual final energy use (electricity and/or fuels).

Annual final energy is normally used as an input for the LCA tools, and converted to annual primary energy use by applying annual average conversion factors. Electricity conversion factors depend on the local electricity mix and transmission losses, while fuel final-to-primary factors (i.e., kWh of primary energy in the source per kWh of final energy available at the use site) basically depend on the type of fuel, extraction techniques and transportation distances from source to site. National energy agencies provide annual updates of these values, some of which were compiled in (Sartori et al., 2012). Other energy-related life cycle inventory data to be provided by national energy agencies include emissions of gases (e.g., CO_2, CH_4, NOx) and disposal of waste (e.g., nuclear).

The use phase inventory of primary energy use and emissions, is calculated by multiplying the annual values by the expected life-span of the building ("n" years). Finally, items in the use phase inventory are multiplied by their corresponding impact factors, resulting in relevant information by impact category to be added up in the overall building impact assessment.

The whole calculation process is illustrated in Figure 2. The figure shows the distribution of tools throughout the calculation of impacts in the building use phase, as well as the calculation steps that require input data (shaded boxes).

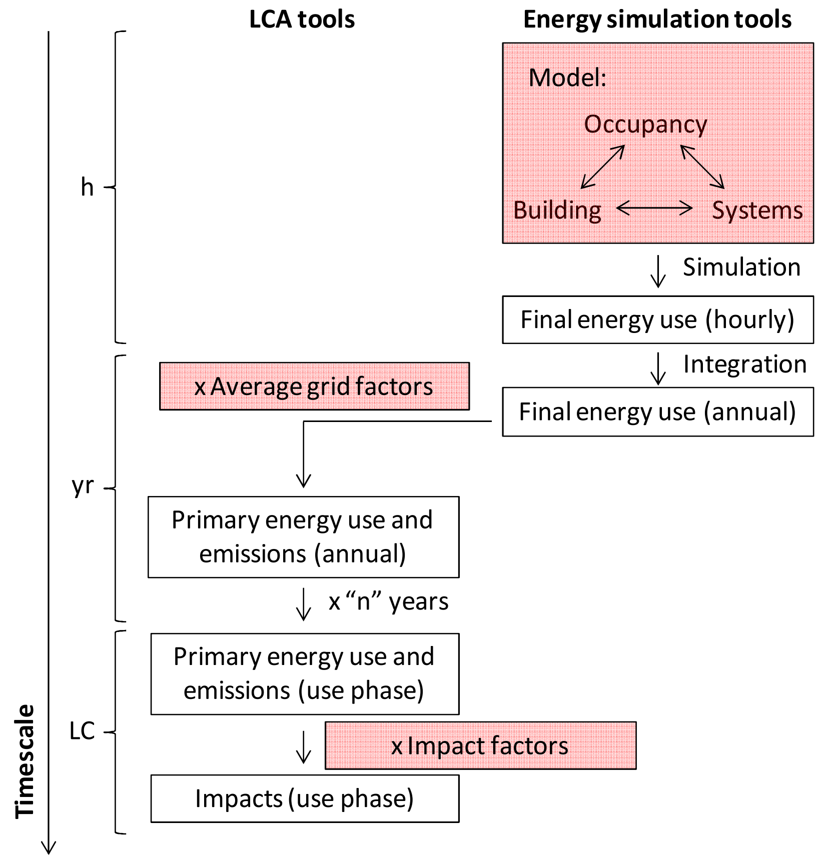

Figure 2 – Typical use of tools for use phase impact evaluation. Shaded boxes show steps that require input data

Accuracy of the typical use phase environmental assessment is limited because the process neglects variations of key parameters over time:

- The use of annual average final-to-primary conversion factors (and derived emissions) of the energy carriers assumes that these are constant. However, electricity factors show large variations hourly, daily and seasonally due to variations in overall electricity demand and availability of renewable sources.
- The direct multiplication of annual inventory results by the expected building life-span assumes that there will be no variations in the grid infrastructure over 50 years.

The following example illustrates these issues.

Example – Short-term electricity storage

A building is designed to be equipped with a grid-connected PV system for electricity generation. The design team is considering adding a short-term electricity storage system (batteries) to improve the interaction between the building and the grid, thus also the overall environmental performance (including both the building and the supply grids in the assessment). The potential benefits of a short storage system are (Salom et al., 2011):

- Peak shaving, which reduces the capacity requirements in the electricity generation plants and the transportation and distribution grids
- Higher overall efficiency of the electric system, due to the better use of base-load sources and renewables

On the other hand, adding batteries to the building bill of materials would add a heavy burden to the non-use phases, particularly materials extraction and waste management.

If the design team uses the standard calculation method to assess the tradeoffs of adding a short-term storage, only the negative impacts will be accounted for. Due to the use of average grid factors, the potential benefits in the overall efficiency of the electric system cannot be seen (the total annual electricity use of the building would remain constant, and so the corresponding impacts).

Furthermore, considering the long life-span of buildings, the design team may want to assess how a future scenario with larger contribution of renewables in the electricity mix would affect the building environmental performance. This could be instrumental to make the decision on the HVAC system type. However, current building energy simulations are not capable to running such a scenario.

4 The ideal assessment of the use phase

Ideally, the system evaluation time-step should be consistent with the dynamics of the system under evaluation.

Building and mechanical system models are static (their characteristics remain constant throughout the building life cycle), and only need to be defined once. Building occupancy and use patterns change hourly (e.g., work hours / nights), weekly (e.g., working days / weekends), and seasonally (e.g., summer holidays). Of course, weather also changes very dynamically. Building use type may also change over the years (depending on business type in commercial buildings, and family size and age distribution in residential), although these changes are often difficult to accurately predict. Simulation tools use hourly profiles of occupancy and weather data to calculate hourly[1] values of final energy use by end use type and energy carrier (electricity/fuels), which is a sufficient degree of detail unless grid factors (in the following calculation step) vary with faster dynamics can be defined with more resolution than 1h.

Final-to-primary energy conversion and emission factors of fuels do not vary greatly over time, and could therefore be considered constant throughout the year. On the other hand, the breakdown of sources in the electricity mix varies with very fast dynamics depending on the overall demand curve, the availability of resources and market dynamics in market systems. In order to consider these important variations in the environmental assessment, primary energy use and emissions should be calculated with “instantaneous” grid factors. It must be noted that this is an important difference compared to the current standard practice, in which annual average grid factors are used (Ramesh et al., 2010, Sartori et al., 2012).

The ideal calculation of use phase inventory of primary energy use and emissions integrates the instantaneous (hourly) values over the building life-span. This would consider both the hourly variations over days, weeks, and seasons, as well as the long-term variations over the building life-span. Since the latter variations are less predictable, inventory data could be integrated over a single year (embedded in the energy simulation run), and combined with probabilistic hypotheses or scenarios of annual variations in the long term.

[1] Evaluation of fast-responding systems require simulation time steps shorter than 1 hour, but can still provide hourly final energy use results

Impact factors of the use phase inventory items (such as emissions of CO_2, CH_4, or NO_x) are only updated periodically [2], and can therefore be applied to the integrated use phase inventory values, and updated in the system as new data becomes available.

Figure 3 shows the ideal use phase assessment process.

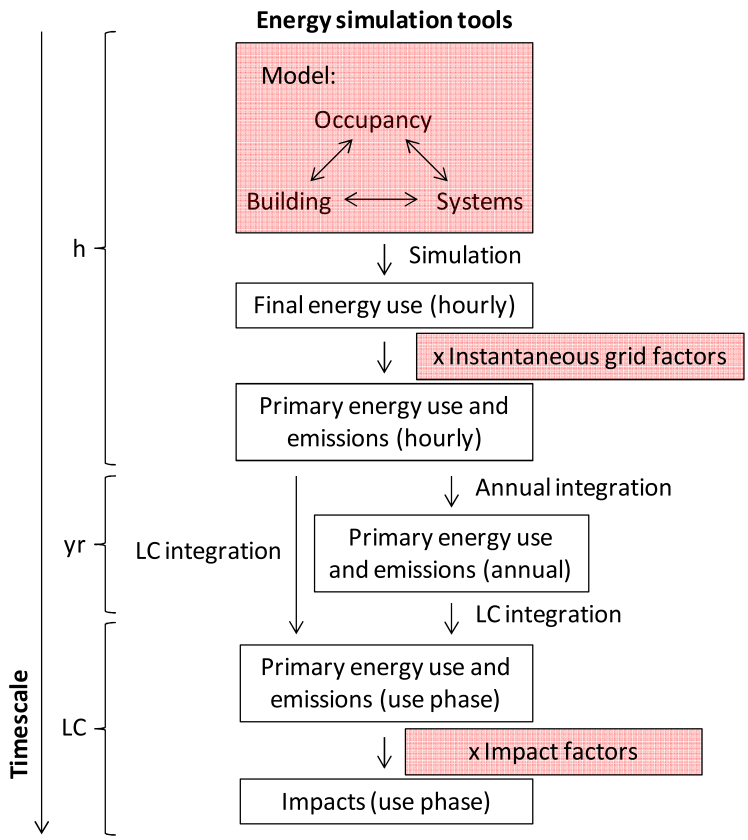

Figure 3 – "Ideal" use phase impact evaluation. Shaded boxes show steps that require input data

5 Getting closer to the ideal LCA

Data requirements and data available

The long life-span of building implies that most of the use-phase impacts will be in the future. Since long term projections are highly uncertain, the ideal accurate life cycle assessment of buildings is not possible with the precision needed to inform critical decisions at the design phase.

[2] Impact factors are updated periodically by scientific institutions such as the IPCC based on a better understanding of the science of the environmental systems (e.g., the atmosphere), not due to variations in the energy system

Buildings with no flexibility in their electricity use and/or generation can be already assessed with sufficient accuracy with the standard practice in building LCA. However, the assessment of buildings with a dominant role of electricity use, generation, and/or management could be largely improved if variation of the power supply system was somehow accounted for in the calculation. Table 1 summarizes the necessary input data for the whole building LCA and comments on its availability

Table 1 – Data requirements, variability and availability

Data	Phase	Time variability	Availability and source
Building materials and products – LC information (inventory)	Non-use phases	Constant. Single input	Available in the building-specific LCA tools and databases
Building materials and products – Thermal performance	Use phase	Constant. Single input (energy model)	Available in the materials datasheets and most LCA databases
HVAC system performance map	Use phase	Constant. Single input (energy model)	Available in equipment datasheets
Occupancy profile	Use phase (energy model input)	Varies hourly, but the same (or similar) annual pattern can be assumed for the whole use phase	Approximate profiles can be defined based on building program documents
Weather data	Use phase (energy model input)	Varies hourly, seasonally, and annually. The same annual pattern can be assumed for the whole use phase	Typical Meteorological Year (TMY) data sets are largely available (U.S. Department of Energy)
Fuel final-to-primary energy and emission factors	Use phase	Very small annual variability	Annual factors are available from the local energy agencies. Constant values could be assumed for projections
Electricity final-to-primary energy and emission factors (inventory)	Use phase	Largely varies hourly, seasonally, and annually. Projections of future grid characteristics and performance are largely uncertain.	Annual average factors are available from the local energy agencies. Power system operators have detailed data, yet this is not publicly available. Projections depend on future energy policy
Impact factors (impact assessment)	All LC phases	Constant. Single input	Available in the building-specific LCA tools and databases

While hourly electricity grid factors throughout the whole use phase are not available at the design phase, they could be included in the model in a similar fashion to weather data. If the system operator provides detailed (hourly) data of the electricity mix of a full representative year, this could be used in the simulation runs just as the weather files are currently incorporated. This information is currently not publicly available, but could potentially be provided by the system operator. "Typical electricity year" files (similar to the "typical meteorological year" weather files) should be generated for different areas based on electricity networks.

LCA data into energy simulation tools? Or energy use into LCA tools?

A single tool capable of providing accurate LCA results of buildings would very much facilitate design choices based on environmental performance. Should energy simulation tools include LCA? Or rather LCA tools include energy assessment? Accurate final energy use calculations require using dynamic energy simulation tools, and more so if grid variability is to be considered in the assessment.

However, rather than embedding LCA data into energy simulation tools, the most logical solution seems to be a shared use of the materials database (with LCA data) for its use in energy simulation tools. The building bill of materials would be automatically generated based on the building energy model, so that changes in the model (e.g., a change of insulation material) would affect both the energy performance in the use phase and the non-use phase impacts (material manufacture). The materials database would have to include both LCA and thermal performance data, however, this would be a minor modification.

A limitation to this integrated approach to energy simulation and LCA is that it would neglect materials that are not relevant for energy simulation (e.g., structural components, furniture, paintings, …). However, if the assessment is meant to compare design alternatives, including the building components that vary among alternatives it is sufficient to provide meaningful insights.

6 Conclusions

Use of life cycle assessment by the building industry is currently very limited because it is a very time consuming process (buildings have to be "modeled" twice: for energy assessment and the LCA inventory). Integration of life cycle assessment databases into building energy simulation tools would allow design teams to accurately assess environmental performance of building design alternatives. However, it would also imply the existence of various copies of large region-specific datasets that need to be updated periodically. This discussion paper suggests a shared use of the materials database as a means to facilitate interaction between the already available energy simulation and LCA tools (while avoiding data duplicates). Communication between the energy model definition and the bill of materials (for the LCA inventory) would largely facilitate LCA studies, and so increase their popularity among the building industry.

The standard practice in building LCA does not account for variations over time in the impacts related to the power supply system (electricity grid), which is a key factor to accurately assess buildings with a dominant role of electricity use, generation, and/or management. This paper suggests using "typical electric year" data (which should be provided by the local system operator) to include grid variability into the assessment.

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