# Life Cycle Assessment of Buildings – a review

S. Reiter, University of Liège, Liège, Belgium. Sigrid.Reiter@ulg.ac.be

## 1. The LCA methodology

Environmentally, according to the United Nations Environment Program in 2006, construction and operation of buildings accounts for 40% of total energy use, 40% of raw materials use, 30% of solid waste generation and 16% of total water withdrawals (Burgan & Sansom 2006). From the perspective of sustainable development, performance of buildings should be analyzed on their **entire life cycle**, taking into account the design, construction, in-use, renovation and deconstruction stages.

A **Life Cycle Assessment** (LCA) is the investigation and evaluation of environmental impacts of a given product, system or service, over its entire life cycle. It quantifies resource use and environmental emissions associated with the system evaluated. (ISO 2006a; ISO 2006b).

Life Cycle Assessment (LCA) is one of the tools increasingly being used to consider the environmental issues associated with the production, use, disposal, and recycling of products, including the materials from which they are made. By integrating LCA into the building design process, design and construction professionals can evaluate the life cycle impacts of building materials, components, and systems and choose combinations that reduce building's life cycle environmental impacts. This method is increasingly used by researchers, industries, governments, and environmental groups to assist with decision-making for environment-related strategies and materials selection.

LCA is used for:
- comparing two competing systems over their complete, or partial, life cycle ;
- comparing the life cycle phases of the same system;
- comparing a system and its alternatives;
- comparing a system to a reference.

These comparisons are useful in order to assist in identifying opportunities to improve the environmental aspects of products at various points in their life cycle as well as to promote strategic planning, priority setting and marketing of products (e.g. via ecolabelling scheme or environmental product declaration).

**According to the ISO 14040 and 14044 standards, a Life Cycle Assessment is carried out in four distinct phases following an iterative process:**

- **Goal and scope,**
- **Life cycle inventory (LCI),**
- **Life cycle impact assessment (LCIA),**
- **Interpretation of results and search for improvements.**

### 1.1/ Goal and scope:

In the first phase, the LCA-practitioner formulates and specifies the goal and scope of the LCA study in relation to the intended application. This is an important step that will be used to determine **the functional unit and the boundaries of the study**.

The functional unit specifies the function performed by the system studied and it can be used to analyze the impacts on a common unit (for example : the product impacts during a year of use). For buildings, the chosen functional unit is often a unit of living area (1 m²) per year because it allows the comparison of different projects on a homogeneous basis (Peuportier 2001).

This phase also includes the choice of the LCA study boundaries. For example, would we take into account the building alone or transportation of persons who live or work there? Do we take into account the actions of maintenance, building retrofit and recycling of materials at the end of life? What is the lifetime of the building that will be taken into account in the LCA?

Fundamentally, sustainability is a medium- to long term concept. Therefore, it is not sufficient to study only what happens at present. Future recycling at end of life must somehow be taken into account (Fujii & Nagaiwa 2005). Ideally an LCA shall include the entire life cycle of the product system and all unit processes that are linked to it, but in practice there may not be sufficient time, data or resources to conduct such a comprehensive study. Therefore, decisions have to be made (and clearly documented) regarding which life cycle stages and unit processes from the product system will be included within the LCA. The key here is achieving the best compromise between practicability of the study and validity of the results (Vrijders & Delem 2010).

1.2/ Life cycle inventory (LCI)

The Life cycle inventory (LCI) is an exhaustive collection of all emissions and consumption for each step of the life cycle analysis. This second LCA-phase involves **data collection and modeling of buildings components**, as well as **description and verification of data**. The results of the LCI provides information about all inputs and outputs in the form of elementary flows to and from the environment from all the unit processes involved in the study.

**Allocation procedures** are needed when dealing with multiple output processes (systems that generate more than one product). Indeed in such case, the inputs (raw materials and energy flows) to the system and the resulting environmental impacts need to be divided amongst the various product outputs. An example thereof is the production of steam and electricity in a power plant, the environmental impact of the power plant (ex. Infrastructure, fuel), needs to be divided amongst the two products (steam and electricity). In the case of recycling materials for example, the environmental benefits (avoided raw materials extraction) and burdens (collection of waste, energy use during the recycling process) need to be divided amongst the process that generates the waste (primary product system) and the process that will use the recycled fraction (secondary product). For processes where allocation is necessary the allocation procedure should be clearly stated and justified and it shall be applied uniformly to all similar in- and output streams in the system. ISO 14040/44 gives following basic rules for allocation. The sum of the allocated in- and outputs of a unit system must be equal to the sum of the in- and outputs before allocation (so-called 100% rule). (Vrijders & Delem 2010).

The quality (precision, completeness, representativeness) of the data used has a significant impact on the results of an LCA. Therefore, it is necessary to establish requirements about the data quality and to extensively describe the consulted data sources (Vrijders & Delem 2010). The quality of the LCI data and results should be sufficient to conduct the life cycle impact analysis (third phase of the LCA) in accordance with the goal and scope definition of the study (ISO 2006b).

Different data sources are regularly used for this step. These are the most often used materials databases in the litterature:

- The Ecoinvent database has been used in various LCA studies on buildings (Peuportier 2001; Popovici & Peuportier 2004; Blengini & Di Carlo 2010 ; Verbeeck & Hens 2010; Oritz-Rodiguez et al 2010). This database contains emissions and resources inventories for more than 4000 industrial processes, services and products. Verbeeck and Hens (2010) selected the Ecoinvent database (version v2.0) and affirm that it is the most extensive, the most complete and the most frequently updated database at the moment, with representative data for Western Europe, including Belgium. More details on the methodology of the Ecoinvent database (version v2.0) are available in Frischknecht & al. 2000, Frischknecht & Jungbluth 2007, Weidema et al 2009 and ECOINVENT 2007.
- The SimaPro database (Scheuer et al 2003; Ortiz et al. 2009; Blengini & Di Carlo 2010). More details on this database are available in PRe 2000.
- Worldwild LCI Database for Steel Industry Products (Brimacombe & al. 2004, Fujii & Nagaiwa 2005). More details on this database are available in IISI 2002, IISI website, Thomas 2009.

These are other databases used in the literature (RMIT 2001; Scheuer et al 2003; Erlandsson & Borg 2003; Forsberg & Malmborg 2004, Oritz et al. 2009; Oritz et al 2010b, Blengini 2009):

- the Swiss Agency for the Environment, Forests and Landscape. More details on this database are available in SAEFL 1998.
- the BEDEC PR/PCT 08 database that contains reference costs, generic technical documents and environmental information on more than 800 construction products. More details on this database are available in iTEC.
- CML
- Idemat 2001
- GaBi 4 Professional,
- the Boustead Model 5.0
- US Life cycle inventory database.

These materials data represent in general conditions in industrialized countries. Extensive data from developing and emerging countries is still lacking (Hertwich 2005; Oritz et al. 2009). Note that the use of European and American database may not lead to correct decisions in developing countries.

For steel components, we recommend the **IISI Worldwide LCI Database for Steel Industry Products** using a common worldwide methodology for cradle-to-gate steel product (IISI 2002, IISI website, Brimacombe & al. 2004, Fujii & Nagaiwa 2005, Thomas 2009, Rossi 2010 (a), Rossi 2010 (b)). Both worldwide and regional averages (Western Europe, Far East Asia and Rest of the World) are available. In these cradle-to-gate data, the effects of recycling on process parameters are included. In order to assess more accurately the profiles of steel products, credits for recycling at end-of-life must also be considered.

### 1.3/ Life cycle impact assessment (LCIA)

The impact assessment phase of LCA is aimed at evaluating the **conversion of emissions into environmental and health impacts** of a product, system or service using the results of the life cycle inventory analysis. In general, this process involves **associating inventory data with specific environmental and health impacts** and attempting to understand those impacts. The level of detail, choice of impacts evaluated and methodologies used depend on the goal and scope of the study. LCIA is never a complete assessment of all environmental issues of the product or system under study. It will only address the environmental issues that are specified in the goal and scope of the study. This assessment may include the iterative process of reviewing the goal and scope of the LCA study to determine if the objectives of the study have been met or to modify the goal and scope if the assessment indicates that they cannot be achieved.

There are several life Cycle Impact Assessment methodologies and tools. Depending on the system studied, it can be more or less relevant to study some environmental and health impacts, like global warming, acidification, etc. To each impact category corresponds a category indicator : a unit used to quantify the potential impact (ISO 2006a; ISO 2006b). One very well known impact category is for example climate change. All emissions that contribute to climate change (all greenhouse gases) can be assigned to that impact category, as for example $CO_2$, $CH_4$, CFK, $O_3$, $N_2O$. A commonly used impact indicator for that category is emissions in kg of $CO_2$. Therefore, to quantify the potential contribution of the system under study to climate change, all the inventoried greenhouse gases need to be translated into $CO_2$ equivalents. There are still many uncertainties and limits to the present state of the art of LCIA. The uncertainties concern both the inventories data and the impact indicators: for instance, the global warming potential (GWP) of other gases than $CO_2$ is known with 35% uncertainty (IPCC 1994).

The ISO 14044 does not prescribe any impact categories but gives some general recommendations for the selection of impact categories. Life cycle indicators are often chosen to be representative of broadly recognized areas of environmental concern, as well as being based on international conventions, agreements, and guidelines. This approach is consistent with the International Standards Organization's (ISO) recommendations for LCIA methods, which state that ''the impact categories, category indicators and characterization models should be internationally accepted, i.e. based on an international agreement or approved by a competent international body'' (ISO 14040).

In a life cycle impact assessment (LCIA), there are essentially two methods: problem-oriented methods, called mid-points, and damage-oriented methods, called end points (Procter and Gamble 2005; Peuportier 2006).

The mid-points approach involves the environmental impacts associated with climate change, acidification, eutrophication, potential photochemical ozone creation, human toxicity, etc. These impacts can be evaluated for example using the CML baseline method 2001, EDIP 97& EDIP 2003 or IMPACT 2002+. Peuportier (2001) and Blengini (2009) have proposed lists of indicators for LCA of buildings. There are objective and internationally recognized LCA indicators. But we should also notice that there is a need for specific indicators to be used in LCAs of the built environment (Vrijders & Delem 2010). Given the significant consumption of resources in the construction sector, impact categories related to the depletion of non-renewable resources, like land use for example, are also particularly relevant for building related LCA studies. But all models used for inventory analysis or to assess environmental impacts may not be available for all potential impacts or applications, e.g. models generally accepted by the scientific world for the assessment of land use or noise do not exist yet in the litterature (Peuportier 2006). On the other hand, Scheuer et al (2003) say that "All impact categories measured (global warming potential, ozone depletion potential, acidification potential, nutrification potential and solid waste generation) correlate closely with primary energy demand". The choice of appropriate indicators and commonly accepted methodologies to analyze inventory results is thus always a subjective step (Blengini & Di Carlo 2010).

One example is performed by Marique & Reiter (2010) : it concerns the modelling of environmental impacts of three isolation levels on a detached house for Belgian climate. For all types of houses studied, insulating external faces allows reducing significantly all the environmental impacts calculated by the software EQUER. The first centimetres of insulation are the most efficient. As it can be seen on the figure below, the reduction of the impacts is bigger between the non-insulated house and the light-insulated one (3 cm of PUR in all the external faces), than between the light-insulated house and the standard-insulated house (6 cm of PUR).

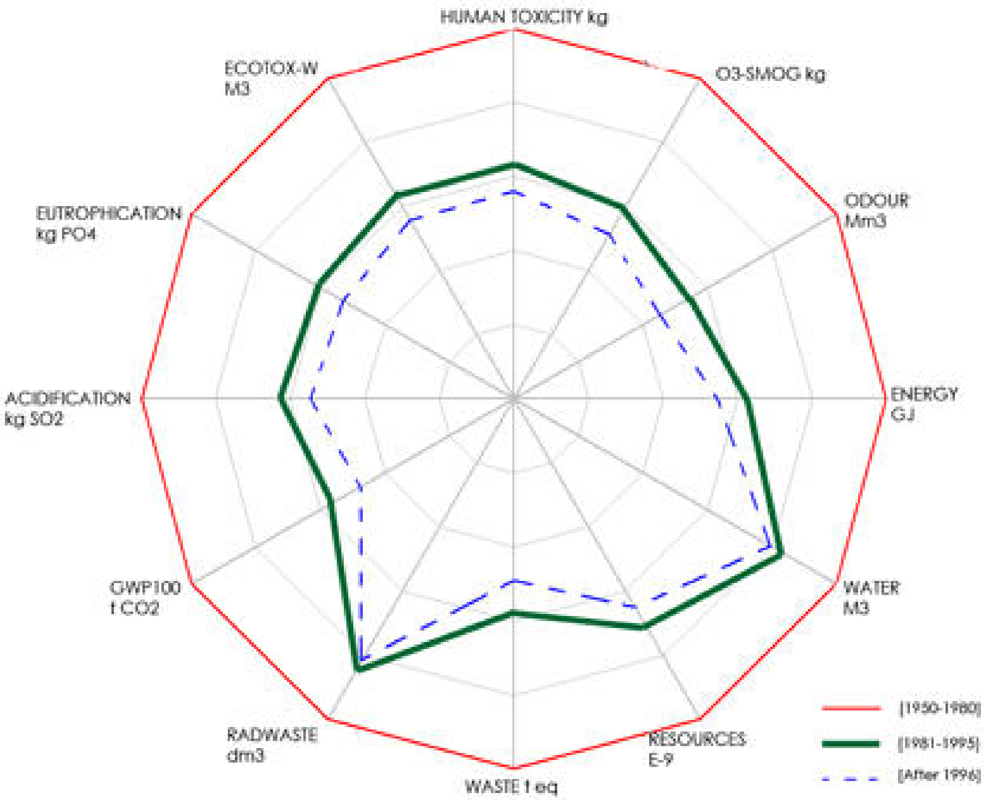


Figure 1: Comparative ecoprofile for three type of insulation: the non-insulated house (regular line), the light-insulated house (bold line) and the standard insulated house (dotted line), calculated with Equer, an LCA simulation tool linked to a thermal simulation code (COMFIE). The resulting eco-profiles allow comparison of several designs. (Marique & Reiter, 2010)

The end points approach classifies flows into various environmental themes, modeling the damage each theme causes to human beings, natural environment and resources. Ecoindicator 99 is a well-known method used in the damage-oriented method.

The LCIA can also include following optional steps (ISO 2006b):

- Normalization: it is the calculation of the magnitude of the individual category indicator results relative to reference information. The aim of this step is to gain a better understanding of the relative size of an effect.
- Grouping: It is the assignment of impact categories into one or more groups as predefined in the goal and scope definition. Impact categories can be sorted on a nominal basis (e.g. global, regional, local scale) or ranked in a given hierarchy (e.g. high, medium, low priority). Ranking always implies some value-choices, so depending on the organization that performs the grouping different ranking results can be achieved based on the same indicator results.
- Weighting: It is the process of multiplying the category indicator results by a numerical factor

(weighing factor) based on value choices. Eventually, the converted results can then be aggregated to one single score. This can be very useful for decision making. Indeed, in case the goal of an LCA is to compare various alternative product designs, it is very unlikely that the LCA results will be straightforward in favour of one alternative (e.g. alternative A may contribute less to climate change, but more to acidification than alternative B).

Grouping and weighting steps of a LCIA study makes it easier to interpret the results; however it irremediably implies some value choices and loss of information. Ecoindicator 99, Ecological Footprint (EF) and Environmental Priority Strategy (EPS 2000) are three single score indexes. Note that single score indexes have been severely criticized (Boustead et al. 2000) and there are divergent opinions on weighting methodologies and factors (Blengini & Garbarino 2006; Boustead et al 2000; Citherlet & Defaux 2007; Frischknecht & Jungbluth 2007; Georgakellos 2006; Huberman & Pearlmutter 2008; Mesa et al. 2009; Scheuer et al. 2003; Thormark 2001). Moreover, ISO 14044 recommends not to use weighting and aggregation in LCA studies intended to be used in comparative assertions. In any case the weighing and aggregation step have to be done in a transparent way and data and indicator results reached prior to weighting should be made available together with the weighting results. Also, it may be desirable to conduct a sensitivity analysis to assess the consequences of the different weighting factors (value-choices) on the LCIA results.

Finally, it is important to note that LCA calculated indicators do not correspond to any real and measurable impacts. The evaluated environmental impacts are potential impacts, calculated in standardized and hypothetical conditions defined by each impact characterization model.

### 1.4/ Interpretation and search for improvements

The last stage leads to the conclusion whether the ambitions from the goal and scope can be met. According to the ISO 14043 standard, the interpretation phase should include three steps :

- **the identification of the significant issues** : important inventory data, significant impact categories, dominant contributions from one life cycle stage, etc.
- **the evaluation**. The objectives of the evaluation are to establish the reliability of the results of the study, with particular attention to the significant issues identified in the first step of the interpretation. **Sensitivity check or uncertainties analyses** are needed. They determine whether the LCA results are affected by uncertainties in the data, allocation methods or calculation of category indicator results, etc. A sensitivity analysis estimates the effects of the chosen data and methods on the results and conclusions of the study.
- **the recommendations, conclusions and reporting.** Limitations of the LCA are described and recommendations are formulated. All conclusions are drafted during this phase. A search for improvements can then be performed, identifying opportunities to reduce environmental impacts and developing strategies.

The interpretation phase may involve the iterative process of reviewing and revising the scope of the LCA, as well as the nature and quality of the data collected consistent with the defined goal.

The existence of uncertainties in input data and modelling is often mentioned as a crucial drawback to a clear interpretation of LCA results (Sonnemann & al. 2003; Blengini & Di Carlo 2010). In order to understand the reliability of LCAs in the building sector more clearly, the LCA models should be elaborated using data uncertainty estimations. They are particularly important when performing comparative LCAs. A judgement based solely on mean values, with no confidence interval, may not result in an appropriate choice of a component or process (IEA 2005). Although it is widely recognized that uncertainty is an essential part of LCA , it is rarely considered in practice. The main reason for this being is that there is no international consensus on how uncertainty should be treated or which method should be used to calculate it.

These uncertainties calculations could be done not only through a deterministic approach, but also in terms of probability distribution, using for example the Monte Carlo method (Sonnemann & al. 2003; Blengini & Di Carlo 2010) or the Pareto analysis (Peuportier 2006) that is a statistical procedure which identifies those data having the greatest contribution to the indicator result These methods allow to define new strategies and to investigate increased priorities to ensure that the most efficient decisions are made.

The interpretation phase includes also recommendations, conclusions and reporting. Environmental priorities and issues change in different communities, and therefore the analysis is specific in both location and time. There is a danger in reducing complex issues to simplistic and partial analysis (IISI 2002). In addition, it is sometimes difficult to find the best solution from an environmental perspective: one may choose to limit some specific impact and an other will choose a different impact (Papadopoulo 2009). LCA is a tool supporting decision by allowing comparisons of environmental impacts generated by different scenarios but it should never replace the critical thinking and final choice of the user.

## 2. Specificities of LCA at the building level

Two main types of methods are used in order to evaluate the environmental impacts of buildings (Peuportier 2006):

- **simplified methods**. They evaluate several building issues but do not model the life cycle of the building. BREEAM (Building Research Establishment Environmental Assessment Method) [BRE, 1993] and GBC (Green Building Challenge) [Cole and Larsson, 2002] constitute examples in this group. These effects are concerning only the building construction and its use. The phases of renovation and demolition are neglected. Several indicators from different types are included in these tools : quantitative, qualitative, expressing performance or means. Each indicator result is expressed as a score related to a "reference level" or "benchmark". The values are afterwards summed in order to have a general score for each main category.
- **life cycle assessment (LCA)**. LCA is an important tool for assessing quantitatively the environmental impacts of buildings through their complete life cycle. The interest of using LCA for building evaluations began to rise in the last decade and today several building LCA tools are developed in different countries (IEA 2005).

A general framework for applying LCA in buildings has been elaborated in the European project REGENER (1997). The life cycle of a building can be broken down in following phases and related processes:

1. Production: manufacturing of construction materials (including raw materials extraction, internal transport, manufacturing processes)
2. Construction: transport of materials to the construction site, construction process
3. Use: maintenance (including necessary replacement of building components), energy use, water use, and eventually other building related processes (e.g. transport of occupants, domestic waste,…)
4. Potential retrofit of the building
5. Demolition of the building
5. End-of-life: evacuation and treatment of demolition waste. The possible reuse and recycling of components should be taken into account.

LCA was mainly developed for designing low environmental impact products but buildings are special products. There are practical differences between LCA of building materials and components combinations and LCA of the full building life cycle (Ortiz et al. 2009). The functional unit for the building material and component combinations was focused on a final product, while for whole building the functional unit is often one m² usable floor area. Most LCA data of the full building life cycle are taken from architects drawings and engineering specifications while the LCA for building materials and components are based on industrial processes.

Some specific issues of LCA studies at the building level are (SETAC 2001; Erlandsson & Borg 2003; IEA 2005, Bribian et al. 2009; Ortiz et al. 2009; Vrijders & Delem 2010):

- each building is a unique product,
- long life of buildings in comparison to consumption goods,
- impact of the use phase,
- various function and composition of buildings and their components,
- time evolution of environmental performances with functional changes, building retrofit, etc.
- impact of the surroundings,
- allocation for recycling.

Buildings are locally produced and they are normally unique (there are seldom many of the same kind). In addition, two buildings constructed in the same way may evolve differently during their lifetime (Lutzkendorf & Lorenz 2006; Pushkar et al. 2005).

Buildings life is long and difficult to predict. This causes a lot of uncertainties, especially for the evaluation of the use and end-of-life phases. For example, the energy production and the end-of-life processes are very likely to evolve over the lifespan of the building, but these evolutions are very difficult to predict (Peuportier 2006; Blengini & Di Carlo 2010). Therefore data are often based on actual practice. Furthermore, some basic hypotheses of the LCA methodology, such as time stability, do not cope with the characteristics of buildings. Time stability, meaning that the product system is considered as a time stable system, implies that when a product reaches the end of its service life, the LCA assumes that the resulting waste will be treated as it used to be at the beginning of its service life (Chevalier & Teno 1996). Due to the very long lifetime of building products and buildings, this hypothesis will result in highly uncertain results.

The impact of the use phase is not only very dependant on the assumed service life of the building, but also on the occupant’s behaviour. As the latest is very difficult to predict, average values or scenarios usually have to be used. Among the environmental loads considered in the building sector the operation phase is the most critical in European scenarios. This is because of the higher environmental loads emitted into the atmosphere due to the high-energy requirement for HVAC, domestic hot water and lighting. The contribution made by the operation phase in buildings from tropical zones is not as significant due to lower energy consumption for HVAC (Ortiz et al 2009). Thus, researchers and LCA users need to properly evaluate energy requirements during the building use phase depending on bioclimatic conditions and people behaviors.

Buildings often have multiple functions and they contain many different components. Moreover, buildings and building components vary greatly in their composition and function over their life cycle. Since both the building and its utilization will change over the time, a building life cycle analysis must be regarded as a dynamic system including potential phases of building retrofitting and functional changes. However, apart from replacement of glazing or system components, most LCA’s of buildings never take into account the renovations or thorough modifications that most buildings undergo before reaching its end of life (Verbeeck & Hens 2010).

The building's performance is influenced by it's surroundings (climate, orientation, proximity of infrastructures,…). Part of the environmental impacts generated by the building are locally specific: e.g. neighbourhood impacts (e.g. microclimatic conditions, wind pattern, solar access, …), indoor environment (e.g. indoor air quality, thermal comfort,…), impact on local ecology (e.g. connected green spaces, ecologically senstive areas, …) and urban infrastructure (e.g. carrying capacity of transportation system, water supply). Thus, the system boundaries for buildings LCA are not clear.

Each LCA study on a building has to specify the chosen boundaries. Local impacts can not be measured with traditional LCA methods and are therefore usually not considered. For example, Peuportier consider in the environmental assessment of a building only its influence on the outside environment. The aspects related to the inside comfort are supposed to be addressed by other existing tools. Therefore, the calculation of the inside air quality, illumination and noise level as well as the thermal comfort analysis are not dealt with in this research. They are, however, implicitly taken into account in the definition of the "functional unit" (Peuportier 2001). Note that the LCA tool BEES (Lippiatt 2000; NIST 2001) includes indoor air quality in the impact assessment as an impact category based on the total of the VOCs emitted by products, but it is stated that there is little scientific consensus about the relative contribution of different emissions to indoor air performance (Erlandsson & Borg 2003). In REGENER and in SAFE projects the transportation of buildings occupants are assumed to be part of the building service and to contribute to the overall building impact (Peuportier & Kohler 1997; Marique & Reiter 2010).

A common allocation issue and discussion point for LCA on the building level is the allocation for recycling. Recycling products reduces in general environmental impacts, particularly the use of resources and waste creation. There are two different building materials recycling types. Steel is an example for a material, which after recycling can be reused for the same application. This is called closed loop recycling. On the other hand, recycled concrete can less easily be reused for the same application but the recycling process of concrete produces granules which can be used in road construction, avoiding the use of other resources like gravel. The corresponding recycling process is called down-cycling or open loop recycling. It concerns materials which were degraded during their use or recycling process, or composite components if the materials cannot be separated. Reusing a building material is handled like closed loop recycling. We define as reuse a process during which a material is not transformed between two cycles, whereas it is transformed temporarily into another state during the recycling process (e.g. melted).

The selection of the building materials that can more effectively be recycled at the end-of-life could lower the full life cycle impacts. The more energy needed for operation decreases, the more important it is to pay attention to both energy for material production and to the aspects of the recycling potential (Huberman & Pearlmutter, 2008 ; Blengini 2009). Note that it may be assumed that mixing materials, like concrete with polystyrene or wood for instance, will make the future waste management difficult (Peuportier 2001). The choice of construction techniques can also significantly lower environmental burdens of the building shell.

The sensitivity of results to methods and data demands extreme caution when using LCA to compare the impact of alternative materials on the environment (IISI 2002). Most LCA tools provide a database with generic inventory data and some with building-oriented data. These data have to be checked for their quality and relevance. Taking into account the high degree of variability of inventory data in many cases, developers should calculate value intervals or conduct any other uncertainty or sensitivity analysis in a way that is readily understood (IEA 2005). Comparisons of LCA studies on the same building (IEA 2005) show that uncertainty related to a LCA inventory can be significant and must be considered when performing comparative LCAs. It is thus important to undertake sensitivity and uncertainty analysis for improving decisions and comparability of the LCA results.

Finally, although the general LCA methodology is well defined, its application in the building industry still suffers from a lack of sector-specific standardization. This implies that making a full LCA of a building is not a straightforward process like for many other consumer products. But the interest of LCA at the building level is obviously that decisions based on isolated LCA for materials or components might lead to unexpected secondary effects when the materials or components are applied in buildings without taking into account their impact on the performance of the building as a whole (Verbeeck &Hens 2010). Moreover, case studies of IEA Annex 31 (2005) showed that LCA tools affect descision-making. The case studies all demonstrated that the application of life-cycle assessment tools resulted in significant environmental improvements. Using an assessment process during the design phase created a positive impact on the built environment and in most instances on the users.

## 3. LCIA tools for buildings

Several LCIA tools have been developed to help building designers incorporate LCA into building design (Bribian & al. 2009). They can be used to guide general building planning, select building materials and components or evaluate a complete building. They vary in their areas of application, geographic relevance and data quality. The amount of LCIA expertise and time required to employ these different tools varies also widely.

**There are three main types of LCIA tools** :

- **Detailed LCA modeling tools (material level)**

  Detailed LCA tools are focusing on materials, components and processes. These tools are mainly used in selecting materials, while also allowing material producers to optimize production processes. The software GaBi (an engineering oriented tool), developed at the IKP University of Stuttgart in cooperation with PE Product Engineering GmbH, is an interesting example of this type of complex tools. Other examples : Simapro (an industrial design oriented tool), TEAM (a French software which has been applied to many European projects including building and waste management), Boustead (a UK LCA tool that is building and construction focused although it can be used for other purposes), BEES (Building for Environmental and Economic Sustainability, a USA based software which allows the balancing of environmental and economic performance of building products; NIST 2001), …

- **Design LCA tools (building component level)**

  Design tools use LCA as a basis but are simplified to single indicator points or to an aggregation of impacts to building component levels. These tools include pre-set material data. The aim of these tools is to facilitate easy use by designers and architects. The software Equer, developed at the "Ecole des Mines de Paris", is an example of this type of LCA tool dealing both with the materials environmental impact and building operational impact. LCAid combines LCA results form materials with the operational modeling capabilities of EcoTect. EcoQuantum, developed in the Netherlands, uses SimPro LCA capabilities and has building components defined but it has limited operational energy and water capabilities. Other examples are : Athena (ATHENA 2001), Envest (BRE 2002), LISA, Becost, BEAT 2000, Greencalc, Ecoeffect, …

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. Regarding data quality, there are two approaches represented on how to collect data and how to handle data gaps. The data used in the tools is either generic data, in this case typical UK (Envest), or company specific (ATHENA) or variations on the theme like he BEAT 2000 and the Eco-quantum tools that use both types of data. (Erlandsson & Borg 2003).

- **LCA CAD tools**

These tools provide environmental impact and embodied energy information through CAD design and documentation tools. Refurbishment and end-of-life processes are not taken into account in these very simplified tools. The software EcoTect, released by Autodesk, is an example of this type of quick tools that are used from the first stage of buildings design. EcoTect is predominantly for operational modelling but has the ability to analyse materials at a limited – embodied energy – level. Other examples are : CSIRO, Ener-rate.

There are four study levels for LCA of buildings: the material level, the element level, the building level and the services level. The services level integrating dynamics of retrofitting, function conversion, building extensions is never included in practical tools. To establish a flexible LCA methodology, the concept of sequential life-cycle thinking should be necessary. Scenario modeling can include one or more of the topics: replacement rate of various materials and products, service life definition and estimation, risk of substitution or changes in the demand for the provided service, estimation of sunk costs in renovation projects, etc. All parts of the scenario modeling have to be in relation to the goal of maintaining the services that the studied system provides and not only be related to the physical building.

Inter-comparison exercises between LCA building tools had been first performed in the European project REGENER (Peuportier et al, 1997, Peuportier 1998) and in a working group (Annex 31) of the International Energy Agency (IEA 2005). Significant differences were found between the different LCA tools applications. But the hypotheses and results of the different tools had not been analysed in detail.

In the IEA Annex 31 (2005) study, the environmental impacts of a single dwelling and an office building were compared with various LCA tools from participating countries, for examples: Eco-Quantum (Netherlands), BEE 1.0 (Finland), EQUER (France), BEES (USA), EcoEffect (Sweden), Ecopro (Germany), SBI tool (Denmark). Each tool was used to calculate the environmental impact of the reference buildings, using common input data. Differences in outputs occurred between the tools used. The source and quality of data, system boundaries, data allocation and weighting factors and environmental profiles had a significant impact on the results. Nevertheless, all of the tools produced similar results: they showed that energy consumption during the use phase was responsible for 75-95 per cent of the environmental impact of these two buildings during their life-cycle. So, reducing energy use produces the greatest environmental benefits; but for highly energy-efficient buildings, reducing the environmental impact of building materials assumes greater importance.

A more precise protocol has been used in the frame of the European thematic network "PRESCO" (Practical Recommendations for Sustainable Construction) where 9 building LCA tools from 7 European countries were tested on 4 application cases. The tools considered in PRESCO 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), ESCALE (CSTB, France). This exercise allowed to clarify the main assumptions in each tool and to identify good LCA Practices. The general conclusion of PRESCO exercise is that building LCA applications are feasible, useful as design support tools, but supplementary work is still needed in order to harmonize the methods and to facilitate the interpretation of the results by the building practitioners. LCA is at the moment more appropriate to study the impacts related to fluxes (energy, water, waste) which have a major influence on environmental performance than for comparing materials. Further improvement of data bases and environmental indicators are thus needed in order to provide designers with more precise advice.

## 4. LCA of buildings – a case studies review

Cole assessed the impacts of different structural materials, and the relative impacts of embodied and recurring energy (Cole & Kernan 1996; Cole 1999). Various studies worked on the LCA of a whole residential building (Adalberth et al., 2001; Gerilla et al. 2007; Peuportier, 2001; Thomark 2002; Schreuer et al 2003; Huberman and Pearlmutter, 2008; Blengini 2009; Ortiz et al., 2009a,b; Marique & Reiter 2010; Verbeeck & Hens 2010). Some LCA studies working on office buildings are also found in the literature (Scheuer et al 2003; Xing et al. 2008). These studies are conducted on existing buildings but no studies were found on the use of the LCA method to improve the performance of a building at the design stage.

Only one study analyses a retrofit scenario (Erlandsson & Levin 2004). Calculations are performed to compare the previous environmental performance of an existing multi-family house with the performance after the rebuilding has occurred. This study concludes that rebuilding is an environmentally better choice than the construction of a new building, if the same essential environmentally related functional performance is reached.

This review reflects the important developments of LCA studies applied to buildings in the last ten years. However, a lot of modeling challenges remain. Currently LCA gives benefits to design retroactively but has limited use during the design stage. In order for life cycle modeling to fulfill its potential in assisting design decisions, there is a need for detailed data on specific building systems and components (Scheuer et al 2003). Some work has already done in this direction but much more work remains.

Note that a great deal of a building’s environmental impact comes from the use of the building, primarily water and energy use. Issues such as orientation, insulation, building operation, lighting and appliance use, and so forth are therefore very important. Indeed, the in-use building phase is by far the longest one of the building life cycle. By comprehensively reviewing existing literature from a whole building life cycle perspective, the phase with the highest environmental impact is the operation phase with approximately 80–98% of the life cycle’s total, while the construction phase accounted for a total of 1–20% and the dismantling phase represented less than about 0.2–5% (Adalberth et al., 2001; Peuportier, 2001; Schreuer et al 2003; Huberman and Pearlmutter, 2008; Blengini 2009; Ortiz et al., 2009a,b; Marique & Reiter 2010). So, trying to reduce fluxes (energy, water and waste) in the utilisation phase seems to be the first action to achieve. Nevertheless, the recycling potential is important when compared to the shell embodied materials: it accounts for 29%-40% of the energy used for manufacturing and transporting the building materials (Blengini 2009; Thomark 2002). Moreover, recycling portential has been estimated to save other environmental impacts : 18% and 35% for GWP and Eco-Indicator 99 (Blengini 2009).

Comparing two dwellings during the full building life cycle: one in Spain and one in Colombia, assessing the construction, use and end-of-life phases, showed that the use phase in the Pamplona house in Colombia represents a lower percentage for all impacts in the total than in the Barcelona house in Spain (Ortiz-Rodriguez et al 2010). The findings of this study showed that the difference in consumption in Colombia and Spanish dwellings analysed is not only due to the variation in results for bio-climatic differences but also because of the consumption habits in each country. The importance of consumption habits of citizens and the need to decouple socio-economic development from energy consumption are sought for achieving sustainability from a life cycle perspective. (Ortiz-Rodriguez et al 2010). Climate, technological, cultural, socio-economical differences clearly define the standard of a building in any context and in any region.

Although most LCA case studies have been done in developed countries in Europe and the USA, there are very few comparable studies in the literature from developing countries. Therefore, sustainability indicators in design, construction, operations and dismantling need to be developed and used in order to target environmental and energy considerations worldwide.

LCA models should consider credible and reasonable recycling potential and take into account the quality of the recycled products, in comparison to the correspondent virgin products. There are a few studies (Blengini 2009, Thomark 2002; Thomark 2006; Dewulf et al. 2009) that contain some quantitative and methodological information on the role of End-of-life in building sustainability. The demolition and recycling of materials are rarely addressed in LCA studies of complete buildings (Blengini 2009; Blengini & Di Carlo 2010). In some cases, demolition and recycling are simply excluded (Ortiz & al. 2009; Huberman & Pearlmutter 2008). In some other cases, they are taken into accound using literature data (Chen & al 2001; Thormark 2002; Scheuer & et al. 2003; Thormark 2006; Citherlet & Defaux 2007). When it is taken into account, due to the fact that the design for dismantling concept had often not been adopted during the design process, only for some of the building materials is it reasonably possible to assume a selective dismantling and subsequent recycling or reuse. Therefore, it is only possible to consider the recycling potentials for some materials, while, for other materials, the only practicable option is landfill or incineration (Blengini & Di Carlo 2010). In Blengini & Di Carlo 2010, a detailed LCA model of End-of-Live is proposed for a house in Morozzo (Italy). All the energy consumption and environmental impacts due to transportation, demolition and recycling operations were considered in the inventory analysis. The contribution of plants, building process and transportation of materials is minor, though not always negligible.

Sensitivity analyses are also important issues for LCA modeling. Peuportier (2001) compared three types of houses with different specifications located in France. The functional unit was 1 m² living area. The sensitivity analysis was based on the selection of other construction materials (wood versus concrete blocks), the type of heating energy (gas versus electricity), the conductivity of the insulation material and the transport distance of the wood. EQUER tool was used for the environmental impact of the building. Inventories were taken from the Ecoinvent database.

A case study in Turin (Italy) studied the complete life-cycle of a multi-familiy residential building. (Blengini 2009). Data for LCA were retrieved from different sources. Inventory data came from various materials sources :

- bricks, plastic, roof tiles were retrieved from Idemat 2001 (IDEMAT 2001)
- wood and glass were retrieved from Ecoinvent ( ETH-ESU 1996) databases
- data for concrete and cement were retrieved from previous LCA research by the author (Blengini 2006)
- steel recycling from steel scrap were taken form IISI data (International Iron and Steel Industry)

The avoided impacts corresponding to steel recycling were calculated according to the IISI procedure (Brimacombe & Shonfield 2001).

In this study (Blengini 2009), a sensitivity analysis was carried out in order to assess the reliability of the results and to understand the influences of the hypothesis and assumptions of the goal and scope and inventory data on the final results. The impacts relevant to the pre-use phase were re-calculated by considering different data sources for the two most important materials of this building:steel and concrete. The first LCA model has been compared to a second model in which the inventory data relevant to steel and concrete were retrieved from the Idemat 2001 database (Idemat 2001) and to a third model based on steel and concrete data from the Ecoinvent 1.2 database (Ecoinvent 2004). For comparison, the GER of concrete is 831 and 610 MJ/ton and the GWP is 67 and 108 kgCO2(eq)/ton according to Idemat and Ecoinvent, respectively. The differences in terms of global energy requirement of the buildings are lower than 8% in comparison with the first model. For instance, the first model and Ecoinvent models virtually lead to the same result for the entire building because the lower energy requirement for concrete according to Ecoinvent was compensated by the higher energy requirement for steel. The differences in terms of greenhouse emissions fall within a range of -15% and +11%. Higher differences occur when other indicators are considered. The conclusions of Belgini (2009) on this sensitivity analysis are that the uncertainties relevant to the inventory data of building materials are quite tolerable as far as energy and greenhouse emissions are concerned on a whole building but the other indicators are less reliable. Nevertheless, this result can not be generalized because it is dependent of the proportions of each material in the whole building.

In Verbeeck & Hens (2001), LCI and cost-benefit assessment are discussed for one reference dwelling in Belgium. It is interesting to note the useful complementarities between environmental impact and cost saving studies to optimize low energy buildings.

Eventually, energy and environmental certification schemes would certainly benefit from the adoption of a life cycle approach, but it should be kept in mind that excessive simplifications, generalizations and blind reliance on user-friendly tools and non-transparent databases still remain a real threat to genuine sustainable development.

## 5. References

ATHENA, 2001. AthenaTM, Athena Sustainable Materials Institute, Merrickville, Canada.

Adalberth K, Almgren A, Petersen E.H., 2001. Life cycle assessment of four multi-family buildings. International Journal of Low Energy & Sustainable 2.

Blengini G.A., 2006. Life cycle assessment tools for sustainable development : case studies for the mining and construction industries in Italy and Portugal, PhD thesis, Instituto Superior Technico, Technical University of Lisbon, Portugal.

Blengini G.A., 2009. Life cycle of buildings, demolition and recycling potential: a case study in Turin, Italy. Building and Environment 44 : 319–330.

Blengini G.A., Di Carlo T., 2010. The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings, Energy and Buildings 42: 869–880.

Blengini G.A., Garbarino E., 2006. Sustainable constructions: ecoprofiles of primary and recycled building materials, in: Proceedings of the International SymposiumMining Planning and Equipment Selection MPES2006, Turin, Italy, (2006), pp. 765–770.

Boustead I., Yaros B.R., Papasavva S., 2000. Eco-labels and eco-indices. Do they make sense? Society of Automative Engineers Inc. Available online at : http://www.boustead-consulting.co.uk

BRE (Building Research Establishment), 1993. "BREAM/New Offices, Version 1/93", Report of the environmental assessment, Watford, U.K., 46 p.

BRE, 2002. Envest 1.0, British Research Establishment, Garston, UK.

Bribian I.Z., Uson A.A., Scarpellini S., 2009. Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification, Building and Environment 44 : 2510–2520.

Brimacombe L, Shonfield P., 2001. Sustainability and steel recycling. International Iron and Steel Institute.

Brimacombe L, Coleman N, Heenan Jr W, 2004. Reduce, reuse and recycle – Life Cycle equations to sustainability, Proc. 12th LCA SETAC Europe LCA Case Studies Symposium, pp 119-122.

Burgan B.A., Sansom M. R., 2006. Sustainable steel construction, Journal of Constructional Steel Research 62 : 1178-1183.

Chen TY, Burnett J, Chau CK, 2001. Analysis of embodied energy use in the residential building of Hong Kong. Energy; 26: 323–340.

Chevalier JL, Le Teno JF., 1996. Requirements for an LCA-based model for the evaluation of the environmental quality of building products. Building and Environment 31(5):487–491.

Citherlet S., Defaux T., 2007. Energy and environmental comparison of three variants of a family house during its whole life span, Building and Environment 42 : 591–598.

Cole R. J., P.C. Kernan, 1996. Life-cycle energy use in office buildings, Building and Environment 31 (4) 307–317.

R. Cole, 1999. Energy and greenhouse gas emissions associated with the construction of alternative structural systems, Building and Environment 34 : 335–348.

Cole R.J. and Larsson N., 2002. GBTool User Manual, NRCan and iiSBE, 75 p.

Dewulf J, Van der Vorst G, Versele N, Janssens A, Van Langenhove H, 2009. Quantification of the impact of the end-of-life scenario on the overall resource consumption for a dwelling house. Resources, Conservation and Recycling 53(4): 231–236.

ECOINVENT, 2007. Life Cycle Inventories of Production Systems, . Ecoinvent data v2. 0, Swiss Centre for Life Cycle Inventories, Available from: http://www.ecoinvent.ch.

Erlandsson M, Borg M., 2003. Generic LCA-methodology applicable for buildings, constructions and operation services – today practice and development needs. Build Environ 38(7): 919–938.

Erlandsson M., Levin P., 2004. Environmental assessment of rebuilding and possible performance improvements effect on a national scale, Building and Environment 39 : 1453–1465.

ETH-ESU, 1996. Okoinventare. ESU Group. ETH Technical University of Zurich.

Forsberg A, von Malmborg F., 2004. Tools for environmental assessment of the built environment. Build Environ 39:223–8.

Frischknecht R, Althaus H-J, Doka G, Dones R, Heck T, Hellweg S, Hischier R, Jungbluth N, Nemecek T, Rebitzer G, Spielmann M., 2000. Overview and methodology. Final report ecoinvent v2.0 N_. 1. Duebendorf. CH: Swiss Centre for Life Cycle Inventories, http://www.ecoinvent.org.

Frischknecht R., Jungbluth N., 2007. Implementation of Life Cycle Impact Assessment Methods, Data v2.0 (2007), Ecoinvent report No.3, 2007, Available from: http://www.pre.nl/ecoinvent.

Fujii H., Nagaiwa T., 2005. How to quantify the environmental profile of stainless steel, proceedings of the SETAC North America 26th Annual Meeting.

Georgakellos D.A., 2006. The use of the LCA polygon framework in waste management, Management of Environmental Quality: An International Journal 17 : 490– 507.

Gerilla G.P., Teknomo K., Hokao K., 2007. An environmental assessment of wood and steel reinforced concrete housing construction, Building and Environment 42 2778–2784

Hertwich EG., 2005. Life cycle approaches to sustainable consumption: a critical review. Environ Sci Technol 39(13):4673–84.

Huberman N., Pearlmutter D., 2008. A life-cycle energy analysis of building materials in the Negev desert, Energy and Buildings 40 : 837–848.

IDEMAT 2001. Database. The Netherlands : Faculty of Industrial Design Engineering of Delft University of Technology : 2001.

IEA, 2005. Energy related environmental impact of buildings, technical synthesis report annex 31: International energy agency buildings and community systems. FaberMaunsell LTd; http://www.ecbcs.org/docs/ annex_31_tsr_web.pdf [accessed 10.06.2010].

IISI (International Iron and Steel Institute), 2002. Appendix 5 “Application of the IISI LCI data to Recycling Scenarios, Life cycle inventory methodology report.

IISI.website : https://extranet.worldsteel.org/Worldsteel/Portal/Categories/LCA%20(Life%20Cycle%20Assessment)/

IPCC, 1994. Radiative forcing of climate change, World meteorological organization and United Nations environment programme, Scientific assessment working group of IPCC, 28 p.

ISO (international Standardization Organization), 2006(a). ISO 14040. Environmental management – Life cycle assessment – Principles and framework .

ISO, 2006(b). ISO 14044. Environmental management – Life cycle assessment – Requirements and guidelines .

iTEC(a) – Catalan Institute for Construction Technology. BEDEC PR/PCT 08 database,

<www.itec.cat/nouBedec.c/presentacioBedec.aspx>.

Lippiatt B., 2000. Building for environment and economical sustainability. Technical Manual and user guide (BEES 2.0). National Institute of Standards and Technology (NIST), report NISTIR 6220.

Lutzkendorf T, Lorenz DP, 2006. Using an integrated performance approach in building assessment tools. Build Res Inform : 34 (4) : 334–356.

Marique A.F., Reiter S., 2010. A method to assess global energy requirements of suburban areas at the neighbourhood scale. Proceedings of the IAQVEC 2010, Syracuse (USA).

Mesa B. L., Pitarch A., Tomas A., Gallego T., 2009. Comparison of environmental impacts of building structures with in situ cast floors and with precast concrete floors, Building and Environment 44 (2009) 699–712.

NIST, 2001. Building for Environmental and Economic Sustainability (BEES), US Commerce Department National Institute of Standards and Technology.

Ortiz O., Bonnet C., Bruno J.C., Castells F., 2009 (a). Sustainability based on LCM of residential dwellings: a case study in Catalonia, Spain, Building and Environment 44 : 584–594.

Ortiz O., Castells F., Sonnemann G., 2009 (b). Sustainability in the construction industry: A review of recent developments based on LCA, Construction and Building Materials 23 : 28–39.

Ortiz-Rodriguez O., Castells F., Sonnemann G., 2010. Life cycle assessment of two dwellings: One in Spain, a developed country, and one in Colombia, a country under development, Science of the Total Environment 2010 (in press)

Ortiz O., Pasqualino J.C., Díez G., Castells F, 2010 (b), The environmental impact of the construction phase: An application to composite walls from a life cycle perspective, Resources, Conservation and Recycling (2010 : in press)

Papadopoulo M., 2009. Analyse du cycle de vie des bâtiments, colloque Bâtiments et énergie, Pau.

Peuportier B, Kohler N, 1997. REGENER. European methodology for evaluation of environmental impact of buildings—life cycle assessment. REGENER project, summary report, European Commission directorate general XII for science, research and development, Program APAS.

Peuportier B., 1998. Le projet européen REGENER : Analyse de cycle de vie des bâtiments, Bologne.

Peuportier B., 2001. Life cycle assessment applied to the comparative evaluation of single family houses in the French context. Energy and Buildings 33(5) : 443–450.

Peuportier B., 2006. Contribution to the Life Cycle Assessment of settlements, PhD thesis, Ecole des Mines de Paris.

Popovici E., Peuportier B., 2004. Using life cycle assessment as decision support in the design of settlements, The 21th Conference on Passive and Low Energy Architecture, Eindhoven, The Netherlands, 19-22.

PRe, SimaPro., 2000.

Procter and Gamble, 2005. Life cycle impacts assessment (LCIA). End points versus mid points. http://www.scienceinthebox.com/ en_UK/sustainability/lcia_en.html.

Pushkar S, Becker R, Katz A, 2005. A methodology for design of environmentally optimal buildings by variable grouping. Building & Environment 40 (8) :1126–39.

REGENER 1997, final reports, C.E.C. DG XII contract no. RENA CT94- 0033, 563 pp.

RMIT, 2001. Background Report LCA Tools, Data and Application in the Building and Construction Industry. Centre For Design, RMIT University : http://buildlca.rmit.edu.au/menu8.html.

Rossi B., 2010 (a). Life cycle inventory of stainless steel – A review of challenges, methods and applications. In Proceedings of the International early stage researchers symposium - Sustainable construction - a life cycle approach in engineering, Malta.

Rossi B., 2010 (b). Sustainable steel construction – Life-cycle inventory, methods and applications , ArcelorMittal International Network in Steel Construction, Sustainability Workshop and Third Plenary Meeting, Bruxelles, Belgique.

SAEFL, 1998. Life Cycle Inventories for Packagings, vol. I and Vol II, Swiss Agency for the Environment, Forests and Landscape, Berne, Switzerland, p. 320.

Scheuer C., Keoleian G.A., Reppe P., 2003. Life cycle energy and environmental performance of a new university building: modeling challenges and design implications, Energy and Buildings 35 : 1049–1064.

SETAC, 2001. LCA in building and construction—A state-of-the-art report of SETAC-EUROPE. Sittard, Holland: Intron.

Sonnemann G.W., Schumacher M., Castells F., 2003. Uncertainty assessment by a Monte Carlo simulation in a life cycle inventory of electricity produced by a waste incinerator, Journal of Cleaner Production 11 : 279–292.

Su Xing, Zhang Xu , Gao Jun, 2008. Inventory analysis of LCA on steel- and concrete-construction office buildings, Energy and Buildings 40 : 1188–1193.

Thomas J.-S., 2009. Steel and Life Cycle Analysis, Conference at the ELM (Environment, Life-cycle and Materials) of ArcelorMittal Global R&D, Maizières.

Thomark C. 2001. Conservation of energy and natural resources by recycling building waste. Resources, Conservation and Recycling 33 (2) : 113-130.

Thormark C., 2002. A low energy building in a life cycle - its embodied energy, energy need for operation and recycling potential, Building and Environment 37 : 429–435.

Thormark C., 2006. The effect of material choice on the total energy need and recycling potential of a building, Building and Environment 41 : 1019–1026.

Vares S, Vanhatalo L, Holt E. 2000. Computer aided environmental assessment for building systems.

Integrated Life-Cycle design of Materials and Structures. ILCDES 2000. Proceedings of the RILEM/CIB/ISO International Symposium, Proceedings PRO 14. p. 236–40.

Verbeeck G, Hens H. 2007. Life cycle optimization of extremely low energy dwellings. Journal of Building Physics 31(2) : 143–177.

Verbeeck G., Hens H., 2010. Life cycle inventory of buildings: A calculation method, Building and Environment 45 : 1037–1041.

Vrijders J., Delem L., 2010. Economical and environmental impact of low energy housing renovation, BBRI, LEHR Research, p. 1 à 107.

Weidema B, Hischier R, Althaus H-J, Doka G, Dones R, 2009. Code of Practice. Final report ecoinvent data v2.1 No. 2. Dübendorf, CH: Swiss Centre for Life Cycle Inventories.