The Metrics of Sustainable Buildings

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Introduction

Design is a complex process taking into account at the same time objective and more intuitive criteria. In some areas our human senses are not sufficient. Only relying on a tactile experience of the environment can be misleading. The gases causing Global Warming are not only invisible but may also stem from processes that can be remote from our immediate environment.

Until now, tools that support green or sustainable design are still only used for a small fraction of buildings. In order to integrate such tools in mainstream design, the tools need to become at the same time simpler and more transparent and credible. Life cycle assessment (LCA) is a methodology that can provide the necessary framework. LCA is limited to impacts on the environment and on human health, other aspects of sustainability such as social equity and local economies need to be covered by other means.

During the aftermath of the oil crisis in the seventies many people became aware for the first time of how limited our world's resources are. Air and water pollution were the next environmental problems that made headlines. Whereas some problems like Ozone Depletion seem to be solved, others are still to emerge. At this time it seems that the limits imposed by nature will rather be on the side of releases of pollutants into the environment and destruction of habitat than on the input of resources into our economical system. Some limits are close to being or have already been surpassed.

Taking into account these limits, and future population and economic growth of the US, and much more in evolving industries, it becomes clear that the environmental effectiveness in providing services to people has to be improved. Different studies come to the conclusion that the material, energy, and emissions intensity per unit of service provided needs to be improved by a factor of four to ten compared to current average western technology [Weizsäcker 1997]. The building sector, which consumes about one third of the primary energy and more than two thirds of the materials in the US has to play a major role in this process. In addition the whole building stock has a very slow turn over rate in the order of decades. To reduce the average energy consumption of the building stock, new buildings therefore need to be several times more efficient than the average efficiency we aim for.

As it has been shown in prototype buildings, a reduction of the whole life cycle environmental impact by a factor of four and more is possible. In terms of primary energy this means that a low energy building in a New England climate consumes 25 GJ per square meter instead of the 100 GJ per square meter of an old residential building over a lifetime of 50 years. The annual heating energy is reduced to less than 100MJ per square meter compared to more than 1000MJ of an old building. Such lowest life cycle energy buildings can be built by using existing simple technology including an airtight and highly insulated envelope, high performance windows, controlled ventilation with heat recovery, and by using solar energy to cover some of the remaining necessary energy [Feist 1996]. The extra costs are acceptable compared to the long-term external costs and risks of the environmental damage by continuing with a business as usual.

The environmental impact of a building starts with so called upstream processes, which include the mining of materials and fuels, transportation, and the production, manufacturing and packaging of building materials and components. As presented in Figure 1, in a lowest energy building, these upstream processes for construction and renovation consume about as much energy as the operation of the building over a 50 year life cycle [Ospelt 1999]. In order to increase the environmental effectiveness of buildings, we have to take a life cycle view, taking into account these upstream processes. The designer needs to be informed of the impact of his design options.

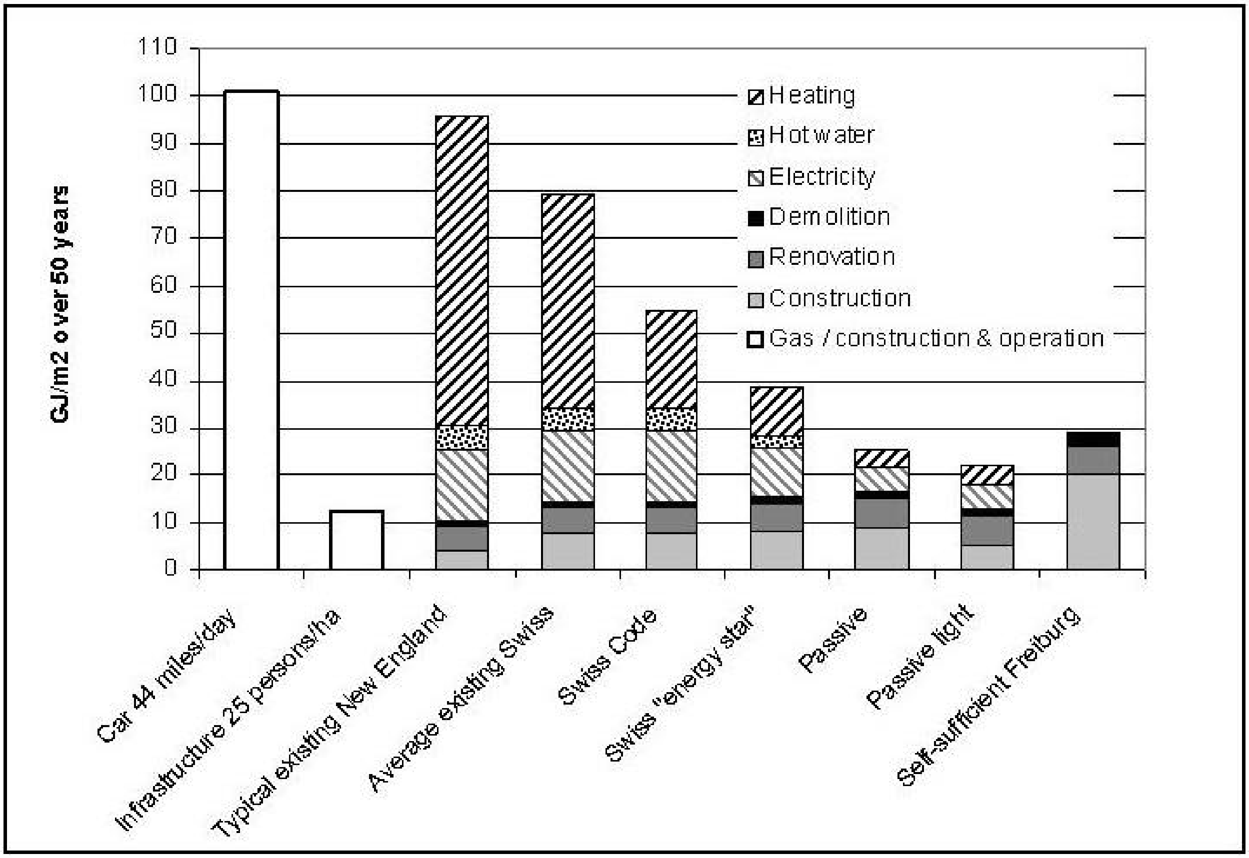


Figure 1 Primary energy consumption of residential buildings over 50 years [Ospelt 1999]

Life Cycle Assessment

Life cycle assessment (LCA) is now widely recognized as the method of choice, that gives a systematic and quantitative framework for a cradle to grave assessment of products. "The code of practice" published by the Society of Environmental Toxicology and Chemistry (SETAC) presents an international consensus among the LCA community on how to establish an LCA in principle [SETAC 1993]. Based on the work by SETAC, the International Standard Organization (ISO) established standards that present the framework for an LCA [ISO 14040]. In recent years, LCA has been applied successfully to buildings and building components in different countries.

According to the ISO guidelines, the following four stages of an LCA are distinguished:

- Goal and scope definition (defining the subject and boundary of the study),
- inventory analysis (quantifying inputs and outputs),
- impact assessment (looking at environmental effects), and

- interpretation (including identifying areas where the environmental burden could be reduced).

In the inventory step, LCA determines pollutants released into the environment and extractions of resources from the environment throughout the entire life cycle of a product. Taking cement as an example, this means that not only direct emissions at the cement production plant are taken into account, but also all indirect emissions and resource consumption due to mining and transportation of the raw materials. The consumption of electricity for production does not imply emissions on site, but at the power plant, that needs to be accounted for. The result of the inventory step is a list of typically hundreds of different releases into the environmental media and consumption of many different raw materials taken from the environment.

In the next step of impact assessment, this list of environmental interventions needs to be translated into impacts on the environment and human health. Different methods for impact assessment have been developed. Some of them are briefly described below. A more detailed review of existing impact assessment methods can be found in [Ospelt 1999].

Impact Assessment

SETAC, CML and Eco-Indicator 95/99

The impact assessment methodologies developed at the center for Environmental Science, Leiden, CML [CML 1992] and the Eco-Indicator [Goedkoop 1995] most closely follow the principle proposed by SETAC, which is presented in Figure 2.

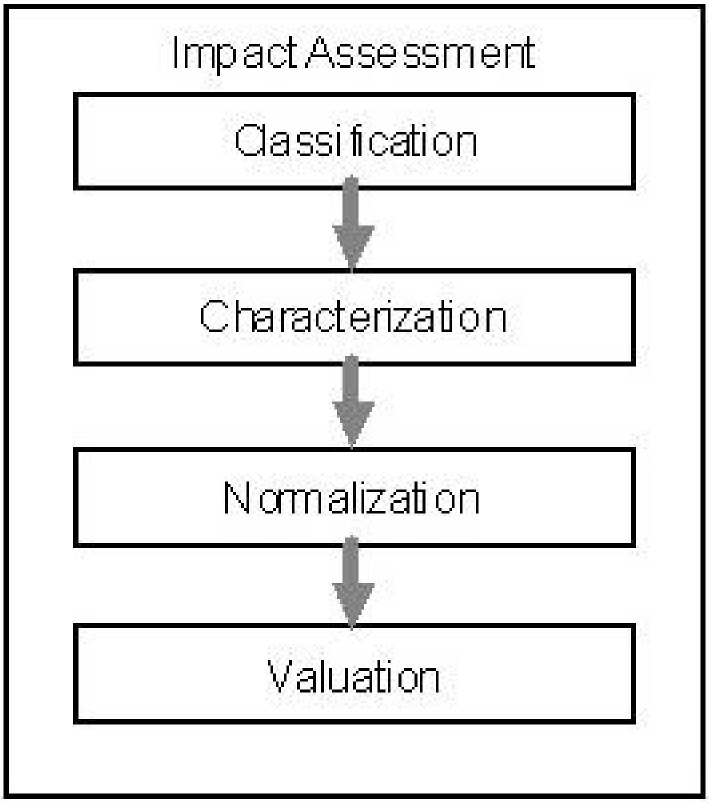


Figure 2   The steps of an impact assessment

In the **classification** step, emissions and extractions are sorted by their contribution to effects like Global Warming. In the **characterization** step, emissions and extractions are multiplied with the weight with which they contribute to a certain effect. In the example of Global Warming the weight is defined as the contribution of a substance to Global Warming relative to CO_2. The weight of CO_2 is 1 accordingly. The unit for Global Warming is CO_2 equivalents. For CH_4 the weight is 24.5, meaning that 1kg of CH_4 has a 24.5 times greater contribution to Global Warming than CO_2. In order to see how important the effects of a product are relative to other effects of the same product, the effect-scores can be **normalized**. This can be done in various ways, but the essential feature is that the effects are compared with reference values. As a rule, the average total effect in a particular area, for example the US, is taken.

The number of effects is still large for practical decision making after characterization and normalization. Following the CML method for characterization and classification, we transfer the inventory of hundreds of emissions and resource extractions into about 15-20 impact or effect scores. No further aggregation is performed in the CML methodology.

In the **valuation** step, the effect scores are weighted to obtain a single environmental index. In the case of the Eco-Indicator, this is a two step procedure. The effect scores are first translated into damage to the so-called "safeguard subjects", the things we finally care for. These are resources, eco-system health and human health. A further aggregation into one index has to be based on subjective valuation, which can be fixed or varied for each project.

Human Toxic Equivalency Potentials

The important impact categories of toxicity are not very well developed in the CML framework. The method of Human Toxic Equivalency Potentials (TEP), which was developed by the US Environmental Defense Fund in collaboration with the School of Public Health at the University of California Berkeley [EDF 1999], is a more advanced method. It utilizes an environmental fate and exposure model to predict the dose organisms receive after a toxic chemical is released into different environmental compartments. 23 different exposure pathways (inhalation, ingestion through milk etc.) are modeled to quantify the dose a human will be exposed to. It then compares this dose with indicators of chemical toxicity to produce a risk index. The TEPs from different chemicals can be added.

Cumulative Energy Demand

Cumulative energy demand (CED) or life cycle embodied energy sums the total direct and indirect consumption of primary energy resources in a product's life cycle in terms of energy. Many of the LCA principles stem from CED. In fact a full LCA is a CED extended to include also other than energy resources and also emissions. CED is not directly an environmental impact, but is still used quite often. It is implicitly assumed that there is a high correlation between the use of energy and all other impacts. Some arguments supporting the use of CED are that CED is directly derived from the inventory and does not involve the uncertainties and weighting related to impact assessment. Its simplicity and long term establishment makes it easier to communicate. The correlation of CED with other impacts like toxicity can be quite weak for a particular product. CED then fails to indicate such important impacts.

LCA and Impact Assessment in Practice

Whereas there is wide agreement on how to perform the inventory, there still is disagreement on the best method for impact assessment. The main reason for this disagreement is the fact that different methods can come up with different priorities in a product comparison. In general it can be said that with increased aggregation more subjectivity and a higher error margin is introduced.

Every LCA based tool faces this trade-off between scientific accuracy and objectivity on the one hand; and high aggregation for a simpler and effective level of communication to a wider audience on the other hand. Nearly all existing LCA-based tools are based on impact categories similar or identical to those developed by CML. The impacts typically included are Depletion of Resources, Global Warming, Ozone Depletion, Human Toxicity, Eco-Toxicity, Photosmog, Acidification, Nutrification, Waste, and Land Use. The choice of impacts often is driven more by available indicators then by needs. In some tools, the scores of these impacts are then aggregated into one indicator using weights based on expert or personal opinion.

Many tools seem to neglect the fact that the scientific background for some of these impact categories is still very weak. Also the impacts presented are very different in nature. Whereas some are close to presenting a damage to a safeguard subject, like human toxicity, others, like global warming, are at an early step in the chain between emissions and damage to a safeguard subject.

Setting Priorities

The choice of the impact assessment system depends on the application. In order to bring LCA results into the design process, a limitation to a small number of indicators is unavoidable. As we have seen above, one possibility is the aggregation by valuation into one index, which involves the introduction of an additional error and subjectivity.

Another approach is proposed here: Instead of aggregating a large number of impacts, we concentrate on the most important issues. An impact is considered as being important

- If the extent of damage done to the system is large.

- If it acts on a large scale and affects whole entities or populations.
- If human health is affected
- If the damage shows up with a time lag or is irreversible.
- If the momentum driving the impact is large. This is measured by the rate of change of the emissions or resource consumption. The supporting 'lobby' that resists a reduction is also included in the momentum.
- If there is a high uncertainty on the mechanisms and damage involved. Taking a no-regret approach, the upper scale of potential damage is considered.

The range of building related impacts is large. Based on the following assumptions a concentration on few important aspects is possible:

- A few impacts represent the biggest overall impact of buildings.

There is no need to inventory all potential impacts. The impacts chosen e.g. in the CML classification/characterization method represent only a small but important set of impacts out of all possible impacts. Limiting such methods to buildings, allows further reductions in the number of impacts. For example building construction only is a minor contributor to Eutrophication compared to overall loads; it can therefore be neglected.

- An indicator can represent other correlated impacts in the same dimension.

This is true for example for some impacts that are highly correlated with the use of energy, including Cumulated Energy Demand, Global Warming, Acidification and Photosmog.

- Some impacts are due to very specific materials and components. Banning or limiting those materials specifically can control these impacts.

Here a simple yes or no replaces a numerical value. There is therefore no need to calculate that impact. This corresponds to so called 'red flag' methods. An example is Ozone Depletion due to the use of CFCs, which were primarily used in HVAC-systems and as an expansion gas in certain types of insulation.

It is expected that a design following a few major and transparent impact scores will result in a general reduction of material and energy use and their related impacts. It is also hoped that some of the impacts that are not known to us yet can be limited in the same way.

Integration of LCA in the Design Process

Different tools are needed for each stage in the design process. At the beginning of the design process we consider the whole building. In an LCA based tool, default average values for unknown details can be used for **Initial Choices** and **Programming**. Questions like 'should we build a new building or renovate an existing one?' need to be answered.

During **Concept Design** and **Schematic Design** various principal building options are explored. A comprehensive review of all possible building systems is necessary. Taking a life cycle viewpoint does not necessarily mean a detailed study. Rules of thumb and a comparison with existing case studies can be sufficient.

Later, during **Design Development,** technical choices are explored and construction details defined. We choose between different construction assemblies and systems. It is at this stage that LCA based manuals, as the one described below, and tools can guide the designer in choosing certain types of construction assemblies over others.

During **Construction Drawings and Documents**, individual materials and products are selected taking into account LCA based information.

For the **Assessment** and **Rating** of buildings, LCA can introduce more objectivity. The scores can be derived based on real impacts of different measures taken. The latest version of BREEAM for the UK includes LCA based elements. Other assessment systems like the 'Green Building Challenge' also intend to use more LCA based data in the future.

The same LCA based data can be used for all these tools. Information can be passed along in the design process and different modules integrated.

Application to a Manual for the Selection of Wall and Floor Systems

Once the basic building shape is fixed, construction assemblies must be chosen. Among others this includes wall and floor systems; comprising structural elements, insulation, and interior and exterior finishes. This process can be iterative, meaning different design options with different assemblies are explored.

A manual can give a quick and simple feed back to the designer. In a Swiss handbook [SIA 1995] that is applied with success, the masses and impacts of the individual layers and materials contained in a system are listed. Different layers have a different lifetime that needs to be accounted for. The structural part will last over the full lifetime of the building, which was fixed at

80 years. Finishes usually need to be replaced over that time. The impacts of the materials divided by their lifetime are then summed up for the whole assembly.

A mock up for a similar handbook is presented in Figure 3. All systems are calculated for a functional unit of one square meter of wall or floor area. Each assembly has to fulfil certain performance criteria. An important one is thermal insulation. A comparison of different wall types therefore has to be based on walls with a comparable U-value. Each impact of the system considered (black dot in the graph of Figure 3) is represented graphically in a range, which is defined by all available alternative assemblies (gray bar in Figure 3). The presentation of the impacts relative to comparable assemblies is more important than the absolute values. Hardly anybody has a feeling for those absolute values and the designer has to choose one of the available alternatives. The designer’s goal must be to keep the impact low relative to alternative choices.

The major criticisms with respect to the Swiss handbook are the represented indicators, which are limited to the presentation of Global Warming and Acidification. Many agreed on taking Global Warming as one indicator. Less consent was on using Acidification as the only additional indicator. Although Acidification is not a major problem in Switzerland anymore, it shows a high correlation with many other indicators. Toxicity indicators available at the time when the manual was published were poorly developed.

For a similar handbook, a minimal set of indicators that should result in a reduction of all impacts could be **'Global Warming Potential'** and **'Toxic Equivalency Potential'**, as shown in Figure 3.

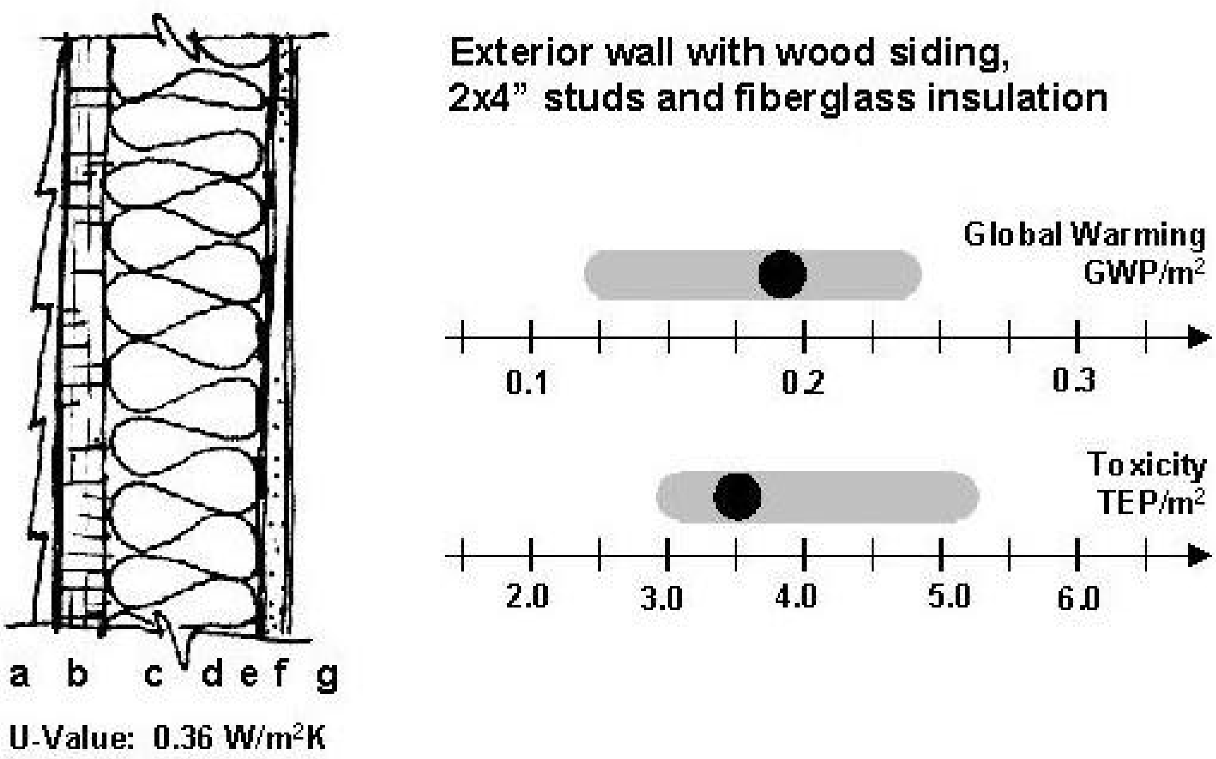
Based on the criteria presented above, Global Warming is considered as one of the most important impacts. It represents other energy-related impacts. For countries with a high fraction of nuclear energy, this choice might need to be reviewed. Global Warming has an infinite damage potential, it acts on a global scale and is irreversible. The momentum that drives greenhouse gas emissions is very high and so is the uncertainty about the absolute temperature increase and the resulting damage.

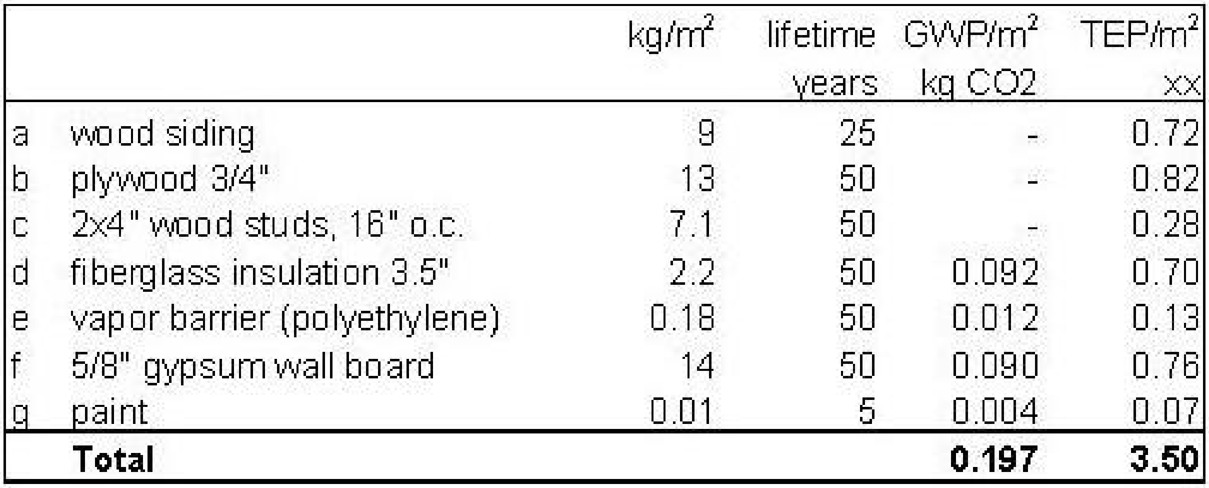
Toxicity as the second impact was chosen because it covers the widest range of effects on humans and nature that are not necessarily correlated with Global Warming. Nearly all criteria that have been considered as defining a high importance of an indicator apply. As mentioned, recent developments can provide the necessary indicators.

'Resource Consumption' would be another impact in a dimension that is not covered by the two other indicators. However, the development of characterization and valuation methods for resource depletion finds itself still in an early phase. Most methods take a use-to-stock ratio approach; others consider the side effects of mining as the crucial effect. Lower grade ores with a larger environmental intervention will have to be used in the future [Müller-Wenk 1998]. Deriving the scarcity of a material on a use-to-stock ratio still leaves the problem of aggregating different resources. Specific problems related for example to the use of timber are therefore better addressed directly, than trying to integrate them in a diffuse indicator.

In our case, this could be for example the requirement to use only wood from sustainable forestry. Some other effects can also be addressed specifically by such 'red flags'. This can include mentioning production processes for certain materials that are particularly problematic in terms of an impact not sufficiently represented by Global Warming and Toxicity.

The example of resource consumption shows how much the young field of LCA and valuation is still under development. The impacts and indicators chosen for a tool therefore need to be reviewed periodically.





		kg/m²	lifetime years	GWP/m² kg CO2	TEP/m² xx
a	wood siding	9	25	-	0.72
b	plywood 3/4"	13	50	-	0.82
c	2x4" wood studs, 16" o.c.	7.1	50	-	0.28
d	fiberglass insulation 3.5"	2.2	50	0.092	0.70
e	vapor barrier (polyethylene)	0.18	50	0.012	0.13
f	5/8" gypsum wall board	14	50	0.090	0.76
g	paint	0.01	5	0.004	0.07
	Total			**0.197**	**3.50**

Figure 3 Graphical representation of the impacts of one wall system relative to comparable systems. Global Warming and Toxicity cover the major impacts.

As it has been done in the Swiss handbook, the quantitative impact information can be supplemented by qualitative information specific to the system. For the construction phase, information on the working environment and potential hazards to workers are given. Particularly high hazards could be 'red flagged', meaning they have to be avoided. Information for the use phase covers emissions from materials that present a potential problem for a healthy indoor air quality. Facts on the disposal and recyclability of the individual materials at the end of their lifetime complement the handbook.

An electronic, probably web based version, of such a manual would allow for more flexibility. Different layers could be substituted and dimensions varied. A printed version can only present a selection of the infinite number of possible combinations. It would also be possible to provide more detailed information if requested. Clicking on Toxicity could, for example, reveal the different contributions of heavy metals, carcinogenics etc.

Need for a Database

So far little information based on LCA is used in the design process. One of the main reasons is the lack of inventory data for many building materials. The effort in raising such data is considerable. However it has been done for many materials in several countries. Some of the lists are more complete than others [e.g. Lindeijer 1996, Weibel 1995]. But considering the large environmental and economic impact of buildings, the effort of establishing LCA inventory data is acceptable.

An important aspect for a credible database is the transparency of the inventory. All assumptions, and fluxes through the system under consideration need to be stated. In some European countries, the material data has been raised with support from governmental agencies and the database is public domain. Presenting averages of several companies can prevent the disclosure of secret production data of an individual company. In the future, LCA data will hopefully become more of a criterion for buyers and the individual companies will provide their own LCA data for their clients. In any case it is important, that everybody uses a standardized method to establish the inventory.

References

[CML 1992] Heijungs et al.: Environmental life cycle assessment of products, Guide and Backgrounds. CML, Leiden, 1992.

[EDF 1999] Environmental Defense Fund: EDF's Risk Scoring System. http://www.scorecard.org/env-releases/def/tep_gen.html (May 1999)

[Feist 1996] Feist, Wolfgang: Life Cycle Energy Balances Compared: Low-Energy House, Passive House, Self-sufficient House. In: CIB W67 Symposium Vienna, August 1996.

[ISO 14040] International Organization for Standardization (ISO): Environmental management - Life cycle assessment - Principles and framework. ISO 14040.

[Lindeijer 1996] Lindeijer, E. and Ewijk, H. van: The IVAM Environmental Research LCA database on building materials. IVAM Environmental Research, Amsterdam, 1996.

[Müller-Wenk 1998] Muller-Wenk, Ruedi: Depletion of abiotic resources weighted on the basis of virtual impacts of lower grade deposits used in the future. IWÖ Nr. 57. Institut fuer Wirtschaft und Oekologie, Universitaet St. Gallen, 1998.

[Ospelt 1999] Ospelt, Christoph: A Framework for Sustainable Buildings, An Application to China. Master thesis at the Massachusetts Institute of Technology, 1999. (a free copy in electronic format can be ordered at: ospelt@alum.mit.edu)

[SETAC 1993] Consoli F. et al.: Guidelines for Life-Cycle Assessment: A code of Practice, Edition 1. SETAC, Brussels, 1993.

[SIA 1995] SIA D0123: Building constructions according to ecological criteria. Schweizer Ingenieur- und Architekten-Verein, Zürich, 1995.

[Weibel 1995] Weibel, Thomas and Stritz, Alexander: Ökoinventare und Wirkungsbilanzen von Baumaterialien. ESU-Reihe Nr. 1/95. Swiss Federal Institute of Technology, Zürich, 1995.

[Weizsäcker 1997] Weizsäcker, E. U.; Lovins, A. B. and Hunter Lovins, L.: Factor Four. Doubling Wealth - Halving Resource Use. Earthscan London, 1997.

Biography

Christoph Ospelt recently graduated from MIT with a Masters of Science in Building Technology. His research at MIT focused on Life Cycle Assessment in the context of buildings and on the sustainability of buildings. Before joining MIT he worked for two years as a researcher at the Laboratory for Solar Energy and Building Physics at the Swiss Federal Institute of Technology Lausanne (EPFL). He also holds a degree in Natural and Environmental Sciences from the Swiss Federal Institute of Technology Zurich (ETHZ). Christoph Ospelt now works as a consultant to the building industry.