A Framework for Sustainable Buildings

An Application to China

by

Christoph Ospelt

Dipl. Natw. Environmental Sciences
Swiss Federal Institute of Technology, 1995

Submitted to the Department of Architecture in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Building Technology

at the

Massachusetts Institute of Technology

June 1999

Signature of Author ....
Department of Architecture
May 7, 1999

Certified by ....
Leon R. Glicksman
Professor of Architecture and Mechanical Engineering
Thesis Supervisor

Accepted by ....
Stanford Anderson
Chairman, Department Committee on Graduate Students
Head, Department of Architecture

A Framework for Sustainable Buildings
An Application to China

by

Christoph Ospelt

Submitted to the Department of Architecture
on May 7, 1999 in Partial Fulfillment of the
Requirements for the Degree of Master of Science in
Building Technology

ABSTRACT

A framework has been established to discuss the different topics of Sustainability in the context of buildings. The framework includes the dimensions of time and space and the dimensions of ecology, society, and economy.

Buildings are shown to have a substantial share on the total environmental and human health impact of an economy. In an energy efficient building, the impact embodied in the building construction can be dominant over the impacts from building operation.

Life cycle assessment is a tool that provides the means for establishing quantitative indicators of sustainability. The different existing impact assessment methods used to aggregate hundreds of different pollutant releases and resource consumption into a few useful indicators are analyzed. Ways of integrating these indicators into the design process are shown and existing design tools and building assessment methods are discussed.

A case study on Chinese buildings shows the potential for energy conservation measures as the primary means of directing the Chinese building stock towards a more sustainable path. Developed countries will have to lower their impact on global ecosystems substantially in order to allow countries like China to approach our standard of living. Taking into account the slow turn-over rate of buildings, new buildings have to be at least four times more environmentally effective on a lifetime basis. The necessary data on building materials needs to be made available

Thesis Supervisor: Leon Glicksman

Title: Professor of Architecture and Mechanical Engineering

Acknowledgements

I am grateful to Professor Leon Glicksman for his continuous support. Not only in his classes but also from his guidance throughout the writing of this thesis I had the privilege to learn an approach for problem solving from him, that probably could have helped to avoid so many problems in the first place. It is the combination of thorough understanding of the details, keeping the major issues in mind, that makes this approach so successful.

I would also like to thank the faculty of the Building Technology Program for making my time at MIT a rewarding experience.

I am also grateful to the V. Kahn-Rasmussen Foundation that supported my research at MIT.

A big thanks also to my fellow students here in the BT group and in particular to Ambrose Spencer and Dan Arons for reviewing the draft of this paper.

Finally I would also like to thank Jean-Bernard Gay and Professor Peter Suter from the Swiss Federal Institute of Technology. Not only have they done much of the research on which this study is building, but they have also encouraged and supported me with my studies at MIT.

Any comments or questions on this report are welcome:

ospelt@alum.mit.edu

"I personally think that human nature & god are in partnership.!"

[note by Ambrose on a draft of chapter 2]

Thanks Ambrose

Contents

Abbrevations

AHP	Analytic Hierarchy Process
CED	Cumulative Energy Demand
CFC	Chlorofluorocarbon
COD	Chemical Oxygen Demand
CO	Carbon monoxide
CO_2	Carbon dioxide
CRB	Swiss Research Center for Rationalization in Building and Civil Engineering
IAQ	Indoor Air Quality
IFC	Industry Foundation Classes
NO_x	Nitrogen oxide
RAV	Route specific risk Assessment Values
SO_2	Sulfur dioxide
SPM	Suspended particulate matter
TEP	Toxic Equivalency Potentials
TRI	Toxic Release Inventory of EPA
VOC	Volatile Organic Compound

1 Introduction

1.1 The Challenge of Sustainability

During the aftermath of the oil crisis in the seventies many people got aware for the first time of how limited our world's resources are. Pollution of air and water were the next environmental problems that got into the headlines. The abatement strategy for ozone layer depleting CFCs was the first global agreement to solve an environmental problem. The success story of CFC abatement gives some hope that the global community will also be able to solve another global threat; Global Warming. This won't prove an easy task, as the solution to this problem involves more than replacing some cooling fluids, compressors, and aerosol propellants as in the case of CFCs.

Meanwhile global population and economy keep growing and resources consumption and pollutant releases keep increasing on a global level. Some of the effects are felt much more at a regional and local scale than globally. Many regions in the world, in particular urban areas, suffer from water shortage. Forests are being plundered in many countries. Most industrialized countries have to cope with old dumpsites, where hazardous waste was disposed in an uncontrolled fashion. Urban air pollution is a serious problem in many cities, in particular of countries with an evolving industry.

Indoor building environments are not safe from pollution either. Many recent buildings in developed countries cause concerns due to health related problems of the occupants. Reasons are found in building materials and poorly designed and maintained ventilation systems. In developing countries it is mainly indoor combustion for the purpose of cooking and heating that causes severe health problems.

As more and more limits are reached, people progressively get aware that air quality standards and national parks are not enough to save the natural environment on which we are depending. A comprehensive approach involving environmental, social and economic issues is needed: Sustainability and Sustainable Development are the buzzwords that point down to a solution. Since the Rio conference on Sustainable Development in 1992 much has been done, but we are still far from a sustainable society.

There exist numerous definitions of Sustainability. However a few principles are common in most serious attempts of defining Sustainability in a way that allows for subsequent action. If our objective is not merely to engage in fruitless discussions, we have to take a pragmatic approach to sustainability and act now.

1.2 Purpose of this Study

Buildings interact in many forms with topics related to sustainability. This is mainly based on the fact that large shares of the world's material and energy fluxes are used for the construction, operation and maintenance of buildings. Another important factor is that people spend most of their time indoors. Buildings also interact in another way with our limited resources; in the occupation of land by their sheer dimensions.

Buildings are long-lasting and so are therefore design decisions. Anybody involved in the design, construction and operation of buildings needs to be made aware of his responsibility. Many people are aware of this fact and would like to act, but they miss directions. The free market makes use of this situation by green washing its products saying for example that they are 'high recycled content', 'biodegradable' or 'low in VOC emissions'. Often it is also simply a lack of knowledge that makes people taking a narrow view on sustainability, optimizing for one topic of sustainability, but neglecting many others.

Green Building manuals and Building assessment systems have appeared over the last years. These also sometimes lack comprehensiveness in addressing the many problems we are creating with our buildings. Some of the tools are quite comprehensive, but lack a balance of the difference topics, which would be adequate to the severity of the different problems we are facing.

Building design is restricted by regulations. It is important that those regulations are set in a way that directs building on a path of sustainability. Today's regulation are too much focused on the immediate impact of single buildings on the local environment and building occupants.

The purpose of this project is to develop a framework in which the principles of Sustainability can be discussed. As we will see, the preservation of the natural environment and human health are considered as primary objectives for a sustainable future. Many social and economic aspects of sustainability could not be treated adequately in the framework of this study.

Once the fundamental goals of Sustainability are established, we can look for indicators that can guide us in achieving these goals. The question on needed versus available indicators needs to be answered. The indicators have to be adequate to the user. However the principles of Sustainability are the same for any application.

1.3 Structure of the Report

Chapter 2 takes a detailed look at the principles of Sustainability. The word Sustainability has been much used and abused in recent years. A cloud of definitions surrounds it. However, most authors share a few basic principles. A framework is established that allows discussing the different topics of

Sustainability. The framework includes the dimensions of time and space and the dimensions of ecology, society, and economy.

Chapter 3 discusses the existing means of measuring the progress towards Sustainability. After showing the need for indicators, macro scale indicators that are used on a national level are presented. Most of the chapter is devoted to life cycle assessment, used on a micro or product level. The principles of life cycle assessment are explained. The different existing methods to aggregate hundreds of different pollutant releases and resource consumption into few useful indicators are analyzed. A summary highlights areas which are only poorly covered by existing indicators.

The first section of Chapter 4 analyzes the life cycle of a building. The energy consumption and environmental impact in upstream processes for the construction of buildings are compared with the energy consumption for the building operation for buildings of different energy efficiency. The second section sets the building into a larger context. Building related energy and material flows are compared with flows for the whole economy. Land use and building related health effects are also addressed.

Chapter 5 takes a look at how sustainability indicators could be integrated in the design process of a building. A simple building description model that can serve as framework for different tools is presented. Existing software tools and building assessment methods are discussed. The last section discusses the availability of the necessary building materials data.

A selection of building related indicators is made in chapter 6. The selection process builds on the findings of the preceding chapters and an analysis of today's gravest impacts on the environment and human health. Two sample applications, a manual for the selection of wall assemblies and building assessment methods, are presented.

Chapter 7 applies the framework developed in chapter 2 to China. Different building related aspects of sustainability are discussed. A case study on the life cycle energy consumption of Chinese buildings is the subject of the last section.

2 What is Sustainability?

2.1 Principles of Sustainability

A classic example for unsustainable behavior is described in Hardin's "Tragedy of the Commons" [Hardin 1968, p.68]. "Picture a pasture open to all. It is to be expected that a herdsman will try to keep as many cattle as possible on the commons. [...] Since the herdsman receives all the proceeds from the sale of the additional animal, the positive utility is nearly +P1. [...] Since however the effects of overgrazing are shared by all the herdsman, the negative utility for any particular decision-making herdsman is only a fraction of -1. [...] Each man is locked into a system that compels him to increase his herd without limit-in a world that is limited." The system will be pushed beyond its carrying capacity, ending in "[...] ruin to all."

The bigger the commons, i.e. the more people or parties sharing it, the more difficult it can become to find an agreement of what is the carrying capacity of a system. Today the whole world is the commons. Emissions don't stop at political frontiers. Production sites can be placed anywhere in the world. Even orbital space is already subject to uncontrolled pollution with space debris, which devalues space in the limited geosynchronous orbit.

"Nachhaltigkeit", the German word for sustainability, originally was used in forestry. It means you should not cut more timber than there is growing in a forest. We can apply this principle to nature in general and add the principle that releases of pollutants and waste should be limited to an amount where they do not harm the environment. If the whole economy follows these two basic principles, we would have a steady-state economy, which could exist forever.

In the examples of the commons and the forests the impact of going beyond the carrying capacity is obvious and the originator can be identified. But as mentioned, in the commons the system inherently will be carried beyond its carrying capacity if no agreement on restrictions is applied.

In general the situation becomes more problematic to get under control

- if we have inadequate or imperfect information on the damage,
- if the damage will only appear with a time lag,
- if the cure shows only a slow or no response (irreversibility of the system or persistence of the damaging substance),
- if the damage is severe or the cure economically expensive
- if a large entity is affected (whole population, large landscape etc.) or

- if the originator can not be identified.

The more of these criteria apply, the bigger is the danger of an overshoot or collapse and the more precautions have to be taken to prevent it. Another important criterion for an overshoot:

- momentum.

Many of the achievements of our society are very pleasant and found their interest groups, who are ready to defend them actively or passively. In the case of fossil fuel, our whole system heavily depends on it and the momentum of the pressure groups that would like to continue with business as usual is immense.

Sustainability and Sustainable Development are two expressions that are sometimes used synonymously. Beyond the ecological considerations Sustainable Development stresses more the aspect of development. This can include economic development, to combat inequities between rich and poor, North and South, empowerment and participation of the underprivileged etc. In the example of Hardin it would not only consider the maximum amount of animals that can be kept on the commons, but also how this total number should be shared in a fair way between all the shepherds. Sustainable Development concerns industrial nations as much as so called developing countries. It is a process towards Sustainability.

Any form of impact on the environment or human beings can be represented in the following form:

$$total\ impact = \frac{impact}{unit\ consumed} * \frac{units\ consumed}{unit\ service} * \frac{units\ services}{person} * \#of\ persons$$

This simple equation indicates the four principal possibilities to tackle sustainability in the sense of lowering the total negative impact:

- Increasing **efficiency**, i.e. producing less negative impact for each unit produced or consumed.
- Increasing the **effectiveness** of services, i.e. providing the same service with less consumption.
- Changing consumption patterns towards **sufficiency**. Simply meaning that everyone has to consume less.
- Controlling the number of **consumers** by a controlled population growth.

This study primarily aims at the first two possibilities of directing buildings on the road towards sustainability. This 'technological optimism' is not without reason. Mc Donough calls for more effectiveness of the economy in general and the building industry in particular. It means to completely reinvent products or services and close material cycles by recycling and reuse. This can lower the environmental impact by orders of magnitude for the same service to the consumer [Mc Donough 1998]. There exists a huge potential for increasing efficiency and effectiveness in the building sector. A passive house in Germany reduced the heating energy by a factor of 20 compared to average existing houses by using readily available, simple technology [Feist 1996]. Such results are achieved by using more efficient new products in an intelligent and effective way. The increase in efficiency and effectiveness has to look at the whole life cycle of a building, including building materials production, fuel cycles and the disassembly or demolition of the building.

The sufficiency approach is considered equally important. It has not gathered much attention in the past. Further research in this field is necessary. For architecture this means to create smaller but better and more optimized spaces. It is well possible to halve the pollution per square meter of built surface by increasing efficiency and effectiveness. However, these efforts are set off by an ever increasing number of square meters per person (see chapter 4). Changes in lifestyle will be needed to achieve sustainability.

The third approach, controlling population growth, is very controversial. As a first, incremental estimate the impacts on the environment grow linearly with the number of people. More sophisticated models can be found for example in Meadow's computer world model [Meadows 1972 and 1992] where the number of people is one of the major variables.

2.2 Ecosphere, Society and Economy

The Rio conference in 1992 used the three systems approach to sustainability. Sustainability has to include ecological, social and economic aspects. In its first principle the Rio Declaration states: "Human beings are at the centre of concerns for Sustainable Development. They are entitled to a healthy and productive life in harmony with nature." [Rio 1992].

Meadows summarizes this approach of three overlaying systems to sustainability by the question: "How to bring about a society that is materially sufficient, socially equitable and ecologically sustainable and one that is more satisfying in human terms than the growth-obsessed society of today" [Meadows 1992].

There is a strong hierarchy between the ecosphere, society and economy. The human subsystem depends on its ecological parent system, which represents the top of the hierarchy. Although only being a subsystem, the human system has the potential to distort its parent system to an extent where a further existence of the human system might not be possible. The economic system is at the low end of the hierarchy. It only makes sense in the context of the human system.

Despite this inherent hierarchy, there is an infinite amount of feedback and loops between the three systems. The Systems Analysis based World Model, developed by Jay Forrester in the 1970's, expresses some of these links explicitly. Although only some main parameters are represented, it illustrates how impossible it is to separate economic development issues from social and environmental issues.

This strong interaction explains why different authors show the same criteria for sustainability as belonging to different systems. The same impacts that affect human health can occur in lists of ecological as well as social issues. Social and economical issues, for example, are so strongly connected that it is often hard to keep them apart. Poverty is as much a social issue as an economical state.

In traditional economics, the ultimate dependence on the ecological system was neglected, it was considered as an infinite source of natural services and goods and an infinite sink for emissions. In a sustainable world, the carrying capacity of the ecological systems defines the thresholds, which are not to be exceeded. Within these constraints the social and economic factors have to be optimized.

Economy does not know limits by itself. With an increasing economy we reach and pass more and more limits. To know these limits is important. In order to control this process, we have to impose regulations, or we can introduce this information into the economy in some other form. Goods that were free before get an economic value. Tradable emission certificates, for example, reflect the value of a clean-or lets better say acceptable dirty-atmosphere.

The ultimate limits are on the ecological system. This ecological imperative has to be accepted. Know-how, which has also an economical value, can increase infinitely. The task is to use know-how to create more economical output with less environmental and societal burden.

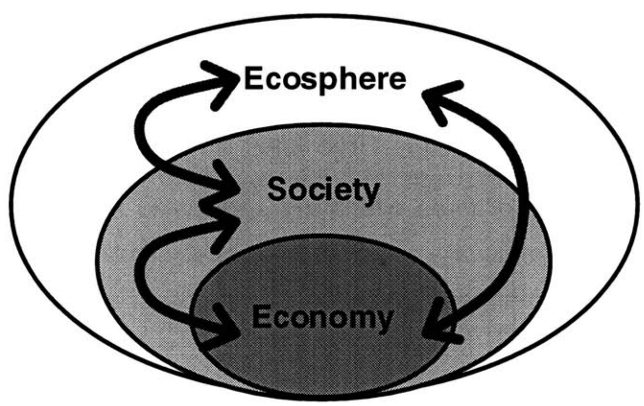


Figure 2.1 There exists a hierarchical relationship between Ecosphere, Society, and Economy. An infinite number of feed back loops link the three systems.

Accepting this hierarchy explains the strong focus on ecological problems when dealing with sustainability in this text. Even if the development aspect of Sustainability is seen as the primary goal, in particular for developing countries, the ecological aspects have to be considered in parallel.

2.2.1 The Ecosphere

The ecosphere is defined here as to consist of its abiotic, or non-living, life support systems, and its living part, the biosphere. The abiotic structure can be subdivided into three major compartments: **lithosphere**, **hydrosphere**, and **atmosphere** or in other words **land**, **water** and **air**. The definitions are taken very broadly here. The lithosphere is included to a depth accessible to humans by technical means. The hydrosphere is included as a whole, as is the atmosphere. The major division of the organisms in the **biosphere** is into fauna and flora (**animals** and **plants**).

There is a strong interaction between the different elements of the ecosphere. Emissions are released into one compartment, e.g. into air, and transferred into others, e.g. washed out into the ground. The local form of the biosphere depends strongly on the local geosphere. Emissions and toxins can be transferred from the geosphere to the biosphere and accumulated over the food chain, or taken in directly with water or by breathing. There is also an influence of the geosphere by the biosphere. Hutton's Gaia hypothesis of the18th century considered the earth as one superorganism. Microbiological processes play a central role in the modern form of the Gaia hypothesis, developed by Lovelock and some other scientists. In this model the earth is capable of regulating itself within limits by an interaction of living organisms with atmosphere, hydrosphere, and lithosphere. A more visible example of a biosphere-geosphere interaction is overgrazing followed by erosion of the ground.

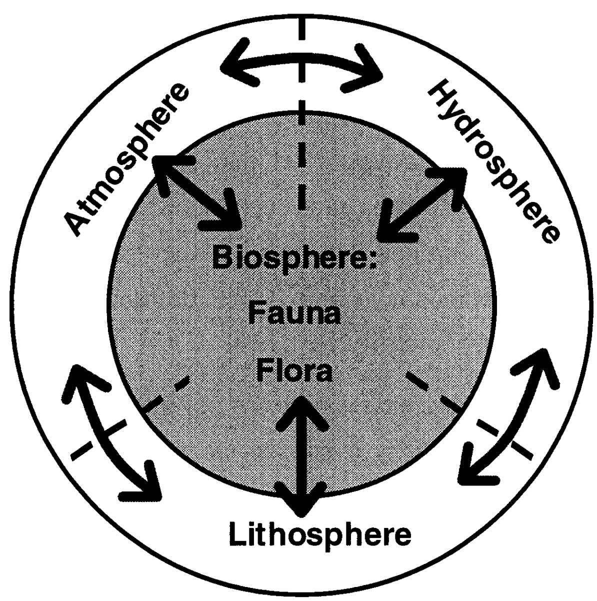


Figure 2.2 Lithosphere, hydrosphere, and atmosphere together with the biosphere (fauna and flora) form the Ecosphere, our natural environment. All elements interact with each other.

Releasing emissions into, or extracting resources from this natural network can start a complicated chain of reactions. It is difficult to define the ultimate resulting damage. Modeling approaches usually only can consider the main reactions at the beginning of the chain. Impact assessment methodologies, as described in chapter 3, therefore often only quantify intermediate impacts at an early stage of a chain. A very simple model represents the complex ecosphere. More research is needed yet to better understand reaction chains across compartments. Also synergetic effects by the parallel release of different emissions need to be better understood.

Both, the living biosphere and the non-living part of the ecosphere take the irreplaceable role of **source** for resources and also as **sink** for emissions. As outlined above, the conservation of the ecosphere is an essential issue for Sustainability.

For the implementation of the concept of Sustainability, Daly defined the following three fundamental rules [Daly 1990]:

1. Rates of use of renewable resources do not exceed regeneration rates.
2. Rates of use of non-renewable resources do not exceed rates of development of renewable substitutes.
3. Rates of pollution emissions do not exceed assimilative capacities of the environment.

The first rule applies for example to the use of fertile soil, which is part of the geosphere. An excessive use degrades the quality and can destroy the ground. Water is another example for a renewable resource of the geosphere. Forests and fish are examples for renewable resources of the biosphere.

The second rule gives a theoretical answer to the problem of how to further use non-renewable resources within a sustainability framework. It is aimed at triggering innovations, which reduce dependence on non-renewable resources and continuously increase the share of renewable resources. It justifies the use of nonrenewable resources as long as part of the proceeds from the exploitation of non-renewable resources is invested in the development of renewable alternatives. Our present economic system does not comply with this rule.

The third rule is getting more and more attention. In the seventies the fear of dwindling non-renewable resources was the major concern. Today it seems like the limited load-bearing capacities of the ecosphere will be reached before the resources are run down. The focus is shifting from sources to sinks.

Although these rules are relatively concrete requirements, their application in decision making is still difficult. It is hard to define the assimilative capacities of the environment. Radioactivity for example has no lower threshold. Any amount of radiation has an incremental effect. The same is true for many other emissions, where a somehow gradual degradation takes place down to the total destruction of the environment. The definition of thresholds and the acceptable level of change of the environment has to be a societal decision.

Biodiversity is not explicitly mentioned in the three fundamental rules above. Rule two and three can be interpreted such that an exploitation of renewable resources or an amount of pollutant releases that lead to an extinction of a species do not comply with the rules.

For many people biodiversity has an intrinsic value based on ethical and religious beliefs. It is also part of the human well-being purely from the point of aesthetics, recreation etc.

Solow agrees with the intrinsic value of nature but argues that it then should not be considered as an element of sustainability. "What about wilderness or unspoiled nature? [...] It is perfectly [...] logical and rational, to argue for the preservation of a particular species or the preservation of a landscape. But that has to be done on its own, for its own sake, because this landscape is intrinsically what we want or this species is intrinsically important to preserve, not under the heading of sustainability" [Solow 1991, p.181].

But also from a much more rational viewpoint biodiversity needs to be protected. The economical value of genetic material can be seen by the efforts of companies to scan wild species and use their genetic information for higher yielding crops, drugs and medicine. The economical value of all natural services including air renewal and other 'life-support' functions is immense but can not really be quantified. From a scientific standpoint diversity is an inherent criteria for stability of the natural system. This diversity also includes genetic diversity of a species.

There are different arguments for the reason why, but broad agreement that biodiversity should be sustained. As an absolute rule we can say:

- Nature's diversity has to be preserved.

The preservation of biodiversity usually means the preservation of **habitats** and whole ecosystems. Many organizations and countries that have established criteria for Sustainability see the preservation of biodiversity as one of the top priorities.

Holmberg et al. and Robèrt also see biodiversity and the physical habitat as two parts of a whole. One of their four principles of sustainability states: "The physical conditions for production and diversity within the ecosphere must not systematically be deteriorated" [Azar 1995].

Renewable and non-renewable **resources** are addressed in rule one and two. Solow is one of the economists that take the standpoint that "goods and services can be substituted for another [...] it suggests that we do not owe the future any particular thing [...] but the capacity to be as well off as we are" [Solow 191, p.181]. But this is also a theoretical concept in so far, as future capacities can not be determined.

Holdren, Daily and Ehrlich [Holdren 1995, p.4] propose a pragmatic approach to put the rules in practice. "A tentative rule for prudent practice then would be to constrain the degradation of monitorable environmental stocks to not more than 10 percent per century. [...] Current rates of degradation of essential resources are in the range of 100 percent a century or more." This accepts the fact that non-renewables will be used up one day if we continue to exploit them. The idea certainly is not to run down stocks completely at a rate of 10 percent, but to slow the exploitation down enough to "give society a chance to change behaviour, react appropriately or compensate."

The global demand growth rates for metals and minerals have slowed from about 6 percent in the 1960s to fewer than 2 percent in the 1990s, though this represents a considerable increase in absolute terms. Despite the rising levels of energy and materials consumption, there is no short-term prospect of scarcity. Proven reserves of the majority of important metals and minerals have risen since 1970. Consumption as a proportion of reserves has declined and long-term prices for most raw materials have trended steadily downward [UNDPCSD 1997, p.21].

Energy takes a special place among non-renewable resources. Our whole Economy depends on it. Today it seems like rule three of limited assimilative capacities will be the more stringent criteria than the exploitation of the resource itself. Estimates of world energy reserves have increased significantly over the past 20 years and indicate no shortage in the near future (see Appendix B.). Energy prices in recent years have remained low, indicating no perceived or anticipated scarcities in the near future. At the same time concerns of atmospheric degradation, in particular Global Warming, Ozone Depletion, Acidification, and Toxic emissions, have risen.

The unsustainability related to the exploitation of resources also has secondary reasons. Even if we assume no intrinsic value for natural resources and that goods and services can be substituted for one another, it still is important to lower the consumption of natural resources. High material consumption usually goes hand in hand with side effects: The total amount of material removed is much higher than the useful content of ores. In the case of iron more than 60% of removed material will become waste. For many other materials, the waste fraction, which does not enter standard trade statistics, is higher than 99%. Whole landscapes are changed and habitats destroyed by this process. Many mines use toxic chemicals to separate metal from ore. It is estimated that the U.S. government will have to spend $32-72 billion cleaning up the toxic damage left at its thousands of abandoned mines [Gardner 1998]. All these materials have to be transported and processed in industry. In 1990 Americans on average shipped freight 11,000 ton-miles per capita [Wernick 1996]. This again represents associated emissions and additional consumption of materials and land.

It also seems reasonable from a long-term economic point of view to control the exploitation of resources. The more we exploit easily accessible resources today, the more difficult it will be for future generations to make use of the remaining lower grade resources.

As was shown above, the long time preservation of the ecosphere is one key element to sustainability. This means preserving, or 'safeguarding', the abiotic (non-living) structure and the biosphere living part of the ecosphere. Another important aspect of sustainability is the management of renewable and non-renewable resources, in particular energetic resources. Table 2.1 lists these 'safeguard subjects'.

Table 2.1 Safeguard subjects of the ecosphere

Abiotic structure		
	Air	
	Water	
	Land, Soil	
Biosphere		
	Plants	
	Animals	
Resources		
	Renewable	
	Non-renewable	
		Energy
		Ores, Minerals

2.2.2 Society

Society comprises the world's population. The organization of society is expressed on different scales. The smallest entity is the individual. Larger groups in society are for example families, communities and nations.

Sustainable Development or Sustainability summarizes different goals that have been defined earlier in different contexts, like e.g. the declaration of human rights. Depending on the author, social issues receive a different weight and detail in defining sustainability. There seems agreement for the following set of minimal goals of social sustainability applied to the individual: to provide a life in health, freedom, security and sufficient wealth to everybody.

For many people Sustainable Development also means more equity between peoples, nations, social classes, genders and also generations. The objective of intergenerational distribution equity is a particular goal of sustainability. Sustainability is a concept that evolved in democratic societies. The right for participation in the political process is not only a basic human right, but it seems also a necessity to achieve a sustainable society.

In the framework of this project, social issues are only treated partially. **Human health** is the primary issue of concern. It is another ruling guideline for our building related concept of Sustainability in this report.

- Human Health has to be protected.

Some authors consider the general human well being and the **quality of life** a criterion for sustainability. Quality of life has many aspects. Taking into account that many people spend 90% of their time inside buildings, issues of comfort are part of a comprehensive framework for building related sustainability.

Further impacts on society, in particular socio-economic impacts, of building related activities should be investigated and probably included in an assessment method.

Population growth is a multiplier in the overall sustainability impacts. Almost 6 billion people live on the earth today. More than twice as many as in 1950. The annual growth has peaked in 1965 at 2% and has dropped below 1.3%. In 2050 the worlds population is expected to be between 8 and 11 billions[UNDPCSD 1997, p.11]. More than 90% of the population growth is in the so-called Developing Countries. On the other hand, some developed countries show a decreasing population or the number of people is only maintained by immigration. The increase in global population demands a rapid increase in the production of energy, food, housing and industrial goods.

On a global level more than one billion people live in poverty. For them sustainable development can simply mean having a shelter, access to clean drinking water, food and sanitation. Before the problem of poverty is solved, it is nearly impossible to improve their living conditions. And as long as their living conditions are not improved, concerns about the environment will have no importance for them.

Almost half the population is now urban and by 2025 the majority-over 5 billion people-will live in urban settlement [UNDPCSD 1997]. As Figure 2.3 shows, **urbanization** is a global phenomena, but the major increase in urban population will happen in developing countries.

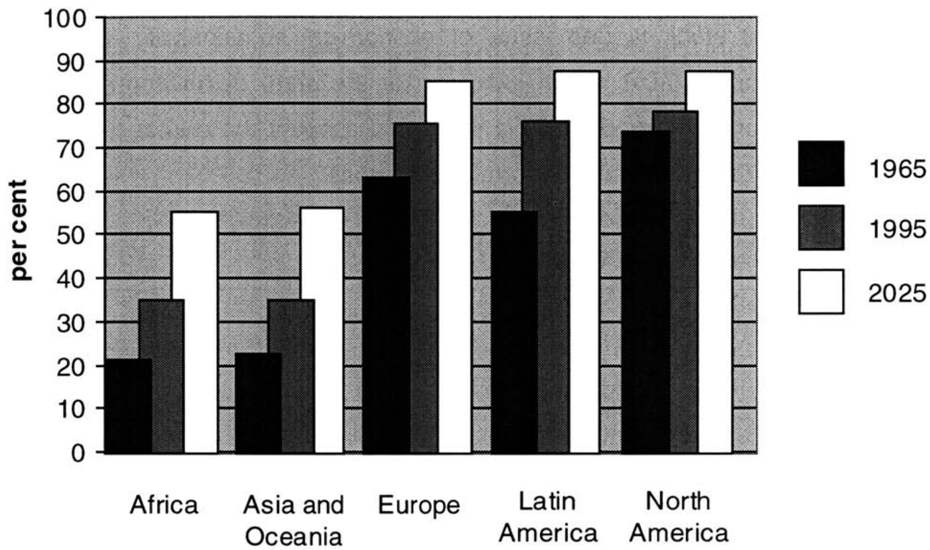


Figure 2.3 Population living in urban areas 1965-2025. (source:[UNDPCSD 1997])

The steady trend towards urbanization and industrialization is not necessarily accompanied by a general improvement of quality of life. Stresses from pollution, traffic, noise, isolation, crime etc. are high.

The social, economic and environmental impact of urban centers reaches far beyond their administrative borders. Their resource demand and pollution are transferred in surrounding regions and onto future generations. On the other hand they create large shares of income and welfare.

The preservation and restoration of a more livable and healthier environment is one of the means towards a sustainable society, be it in urban or rural areas.

2.2.3 Economy

Everybody agrees on the obvious goal of a 'healthy' economy as an element of a sustainable world. However there is much less consent on how this economic health is expressed and which issues should run under the heading of economic sustainability.

A construction method, which requires more labor, might be considered as economically advantageous, as jobs are created. Others might consider it as economically inefficient, as a similar performing wall assembly could have been built much less expensively.

Economy is a network of processes that rely on resources taken from the environment and emissions releases returned to the environment. The flow of goods and services can be measured by the corresponding flow of money. GDP per Capita is an agreed upon measurement of the average individual economic activity per capita. All economic activity can be considered as induced by the individual consumer in a market-based economy.

The preservation of natural stock is one issue of economical sustainability. Several economists recommend not only calculating GDP as an indicator for the state of an economy, but rather the environmentally adjusted Domestic Product. This takes into account the damage done to nature and people, and the exploitation of natural stock in form of resources.

Many of the social requirements are reflected in economical requirements. Equity between generations and within generations would require a leveling of economic resources. A stable and predictable economy is also part of social security.

Like social issues economy only is addressed marginally in this project. One of the focuses is the combined economical and environmental evaluation. The economical aspects of sustainability are reduced here to achieving an ecological and healthy building for low costs.

2.3 Sustainability and Time

The most popular definition of sustainability from the "Brundtland Commission" stresses the time aspect: Sustainable Development is "the ability of humanity to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs" [Brundtland 1987]. This solidarity with future generations has strong implications. We do not only have to take into account the possible effects of our activities in the actual world, but also the possible implications for the future. Without this principle we would not have to bother about Global Warming for example.

Societal values change over time. The same as the definition of sustainability only became popular in 1987, it may be become obsolete at a certain time, and new priorities will be in the foreground.

In many cities after three decades of inner city decay, inner city environments have been rejuvenated due to, amongst other things: A sharp increase in the desirability of "downtown" and inner city living; a greater incidence of childless couples and singles, with no need for those urban amenities traditionally focused on the needs of children and a greater number of two-career couples with the financial resources to afford the high costs of "downtown" housing [OECD 1990].

A city is the sum of elements with a different rhythm of existence. It is following a permanent actualization due to changing demands of the society and reinterpretation of the place. To keep up with the seemingly ever increasing speed of cultural and societal changes, buildings and infrastructure have to be adaptable. At the same time, by their static behavior and relative long life span, they can provide some form of hold in a restless environment.

Due to the long life-time of buildings, studies on the sustainability of Buildings are particularly sensitive to time aspects. Also the response of the total of all buildings on improvements of new buildings is very slow.

Different issues have their natural pace of change. A policy for improvement of local air quality can show results within few years, as it was seen in East-Germany after reunification, where the air quality in some cities has improved tremendously within a few years. Ozone Depletion on the other hand will continue for decades, although the emissions of the chemicals causing the damage have been reduced strongly. The accumulation of fossil energy resources takes an infinitely long time in terms of human lives. Peat, with a regeneration rate in the range of hundreds of years, is considered as renewable energy resource by some institutions, while others consider it as a non-renewable resource. Scientists are not only worried about the amplitude of the temperature increase due to Global Warming. What makes it an even bigger problem is the rate at which this increase seems to happen. It is much faster than it has ever been in former temperature changes of the earth and also faster than the assimilation time of the ecosystems.

For all mentioned issues it is important to have a long term perspective. The structure of a society changes over time in terms of population growth and age distribution, importance of economic sectors, behavior and preferences etc. Modeling scenarios can support such thinking. Scenarios do not predict the future, but answer the question "what happened if...?"

The expected improvement and development of new technologies in the future is a fundamental thesis of our approach towards a sustainable world. New renewable energy systems will have to replace fossil fuels, as there is no doubt about their extermination.

The more diffuse and later an impact occurs, the more difficult it is to quantify it. It sometimes is not clear, if there will be any significant impact at all. For example the intensive use of copper for roof covers and other tinsmith work will contribute to a long term poisoning of fertile soils according to scientists, but as the process is very slow and diffuse such problems often lack their advocates [Boller 1998].

- In the case of uncertainty it is better to be cautious and follow a no-regrets approach. This is in particular indicated if the impact threatens one of our immediate foundations of life.

It has to be discussed if discount rates for emissions should be used, the same way as we do it for financial costs that will only be due in a few years. We care less about a dollar that we have to pay in a year than a dollar we have to pay today. The same way a discount rate would represent the fact that future emissions were considered less problematic than actual emissions. A discount rate reflects the human tendency to prefer the present over the future. This is in particular true, if the time scale goes beyond the length of a human life. Accepting equal rights for future generations, there is no justification for discount rates for emissions. Indeed the discount rates used in economics are one of the roots of our unsustainable behavior of today: It is more profitable to cut down as many trees, use as much oil etc. as possible now, than to use it in a sustainable way. The discount rates lessen the revenues in the future from today's perspective.

One justification to apply discount rates is technological optimism, e.g. assuming that the consumption of one unit of electricity in the future will have less impact as the systems efficiency is increased constantly. In this case it seems more reasonable to explicitly declare and model the assumed improvement on the technology side and not to apply a discount rate for future emissions and the damage they cause.

Looking at different phenomena in the time dimension, the following time scales seems useful as an orientation:

- immediate (e.g. noise)
- days to yearly (e.g. Photosmog)
- human lifetime (e.g. Ozone Depletion)
- long term (e.g. leaching of landfill) and permanent (e.g. depletion of fossil fuels)

Some effects, such as noise, appear with no delay and also disappear immediately, once the source is removed. Other effects like Photosmog appear seasonally and have a half-life in the order of hours or days. Ozone Depletion is an effect that has a 'half-life for cure' in the order of decades, corresponding about to human lifetime. Some environmental impacts, like leaching of landfills will affect our great-grand children. The last category of effects are irreversible and they last forever. This is for example the case for the depletion of fossil fuels.

2.4 Sustainability and Space

Global warming, as the name says, is a global problem. The emissions causing acid rain, can be hundreds of kilometers away from the location of immission. It therefore can only be solved on the level of a large region, covering sometimes several countries. Urban settlements create their own set of problems due to the high density of human activity. The individual building creates a local impact by the occupation of land but also a visual impact by its mere appearance. Indoors we have to deal with another set of sustainability issues such as indoor-air-quality and comfort.

Sustainability has to be achieved on all levels from the global down to our immediate surrounding. Depending on the nature of the **impact** it can be very locally focused or spread diffusely over a large area.

The sources for **emissions** can also have different extensions. A large share of some emissions is due to a small number of facilities e.g. power stations with a known location. The sources for emissions like CO_2 are spread very diffusely. At the source of any emission is a local emitter.

From an ethical point of view the most unfair and therefore unsustainable impacts are those which cause local damage in a place different from its source. This is for example the case in dumping hazardous waste in countries with lower restrictions. The same is true for the depletion of resources: at the moment much of the affluence of our society is based on the plundering of resources in developing countries, whose population is not compensated by a fair price.

Different spaces have different ecological, social and economic backgrounds. What is acceptable in one place might not be in another. It depends which emissions are released into which compartment of the geosphere, at which location to define the spatial range of an effected area.

The fundamental rules of sustainability, which were presented above, can not be applied in an urban area. A city is not isolated and autonomous. It depends on the interaction with the surrounding areas. The city itself is not in a sustainable state. What is important is the balance between the city and the surrounding area. The combined system has to achieve sustainability. Some authors argue that society will achieve sustainability more easily by concentrating human activity in cities. Where the boundaries for the combined system of the city and its surrounding have to be set is case specific.

For the purpose of this project it seems helpful to distinguish four different spatial scales, each differing by a factor of one hundred to the next scale. Dividing and multiplying the shown characteristic length scale by 10 gives about the upper and lower bounds for each range.

- 10m immediate surrounding (indoor/building)
- 1km local (site)
- 100km regional
- 10.000km continental & global

For each of these spatial scales there also exist social and political entities that are responsible for managing ecological, social and economic sustainability. These are for example, families on the immediate surrounding scale, neighborhoods on the local scale, governments on the regional scale, and finally associations of countries like the European Union or international organizations like the United Nations on the continental and global scale.

Ideally, each entity would set goals for the spatial scale it covers. Every underlying entity also follows goals defined by bigger entities. Generally formulated goals on a larger scale are refined on a smaller scale and result in concrete local decisions: "Sustainability would need to be made an intrinsic part of all policies, and then 'trickled' down through plans, programmes, and ultimately to projects "[Therivel 1994].

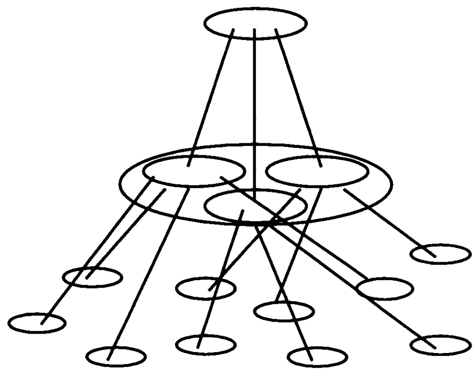


Figure 2.4 Large scale goals have to achieved by action with local projects

2.5 The Challenge of Sustainability

The dimensions of space and time are represented graphically in Figure 2.5. Each **topic of sustainability** can be located in this two dimensional graph. As we see in the next chapter, it is very easy to get lost in the many topics and **indicators of sustainability**. Figures 2.5 to 2.9 give a framework that allows situating such topics and indicators. At the same time the figures also allow to check sets of indicators for their completeness in the sense of covering different aspects of sustainability.

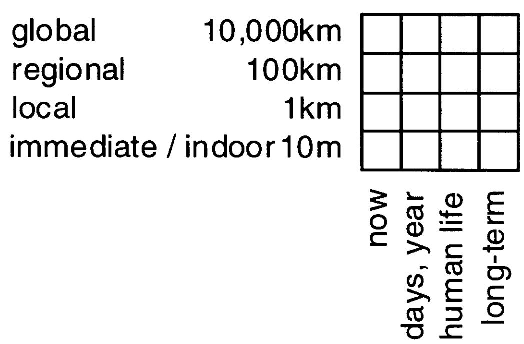


Figure 2.5 Space and time as two of the dimensions of sustainability

The graphics in Figure 2.6 to 2.8 are based on qualitative reasoning. For each 'safeguard subject' the potential range of problems in time and space is depicted. Dark areas show a **high possibility** of problems arising. Gray marked areas show **potential** problems only for very persisting problems.

Air related problems will reach the local level practically immediately after the release of a substance. Within the order of days emissions spread to a regional level and in a year they will be diluted in the worlds atmosphere, where they usually will not cause short-term problems. If the emission continues and the pollutant is persistent, the problem becomes global after a few decades. At the same time, the purely local problem disappears, as the air is very quickly diluted. Care has to be taken in the case of indoor air pollution. In this case the pollutant source can be continuous and air might not be diluted as quickly as it would in the in the free atmosphere. The problem endures as long as the source. This problem field is marked gray in Figure 2.6.

Flowing water can range to a local level in the order of hours. Within the order of weeks, it covers a regional area. Locally, water should be able to recover in the order of decades. In the case of very persistent problems, regional or even global problems can arise. It can be expected that water regenerates to a healthy state by its natural cycles in a very long-term view, if the pollution source is removed. Stationary groundwater will show a behavior similar to soil.

As soil is stationary, dispersion of pollutants depends on transfer processes primarily by water. It can spread in the worst case to a regional level. If no water is available to dilute a pollutant, it can stay locally concentrated for an infinite time. Atmospheric depositions and large-scale depositions of pollutants for example through agriculture can lead to a long-term degradation of soil on a regional scale. Decontamination of soil in general is a very slow process for persisting substances.

The biosphere can be affected as fast and as much as the pollutants are present in its habitat. The area of potential problems is therefore the overlaid problem areas of air, water and land. The extinction of a species is considered as global from the intrinsic value viewpoint. Considering it as an element of the ecosphere, the spatial level depends on its occurrence.

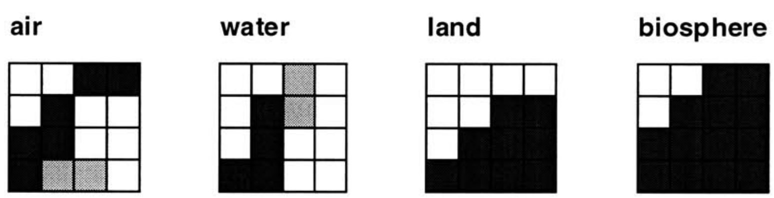


Figure 2.6 Potential areas of problems related to air, water, land, and biosphere.

The same logical model can also be applied for resources. The first graphic in Figure 2.7 shows renewable resources. Over time, an increasing area can be overused. An initially local over-consumption becomes a regional problem. On a global level most renewable resources are abundant. It is expected that areas with an over-consumption can recover in a very long-term view.

In Chapter 2.2 different reasons were presented for safeguarding resources. The major reason is related to their preservation. The reserves for most non-renewable materials last for several decades. Only in a long-term view, the fading of certain materials can become a global problem. The second reason for safeguarding resources is related to secondary effects like emissions. These potential secondary problems are marked in light gray.

Non-renewable energy shows the same pattern, except that the extinction of the first types of fossil fuels can already be expected within the order of decades. On a regional level the problems of a fossil fuels shortage will be felt sooner.

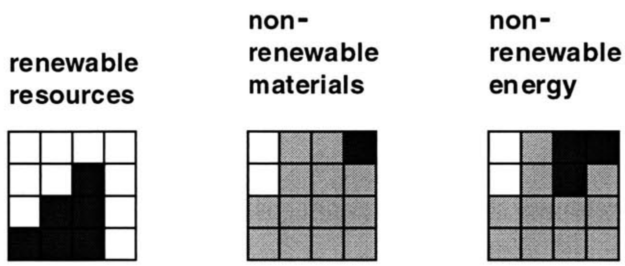


Figure 2.7 Potential areas of problems related to resources.

Social problems can also be outlined in this framework as depicted in Figure 2.8. From a human health point of view, the pattern is similar to that of the biosphere. The range of other social problems corresponds to typical orders of duration for changes in society. On the level of the individual, changes can occur very fast. To achieve changes in a region or country is a process over years. In a long-term view we have to look at social problems on a global level.

Like with renewable resources, potential economical problems are expected to be reversible in a long-term view. Due to information technology the spatial range against time has steadily increased over the last few years. Economy is becoming more and more global. Economical problems can proliferate around the world in the matter of hours.

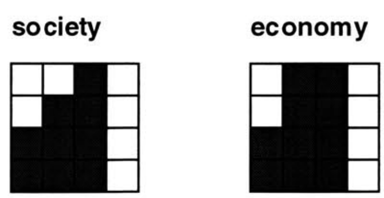


Figure 2.8 Potential areas of problems related to Society and Economy.

The preceding paragraphs outlined different dimensions of sustainability: time, space, and ecology-society-economy. Figure 2.9 graphically represents these aspects of sustainability. All our decisions and activities can be judged by looking at possible impacts at any location in this space.

The Challenge of Sustainability shows up in deciding between different options. We first have to look at the potential impacts in all dimensions of this space. One option might show advantages for some impacts, whereas another might perform better in others. We then have to balance those impacts against each other to make a decision.

The problems of many existing tools that are supposed to support sustainable decision-making are that only a fragment of the total possible impacts is addressed or that the balancing of different impacts takes place on a very subjective level.

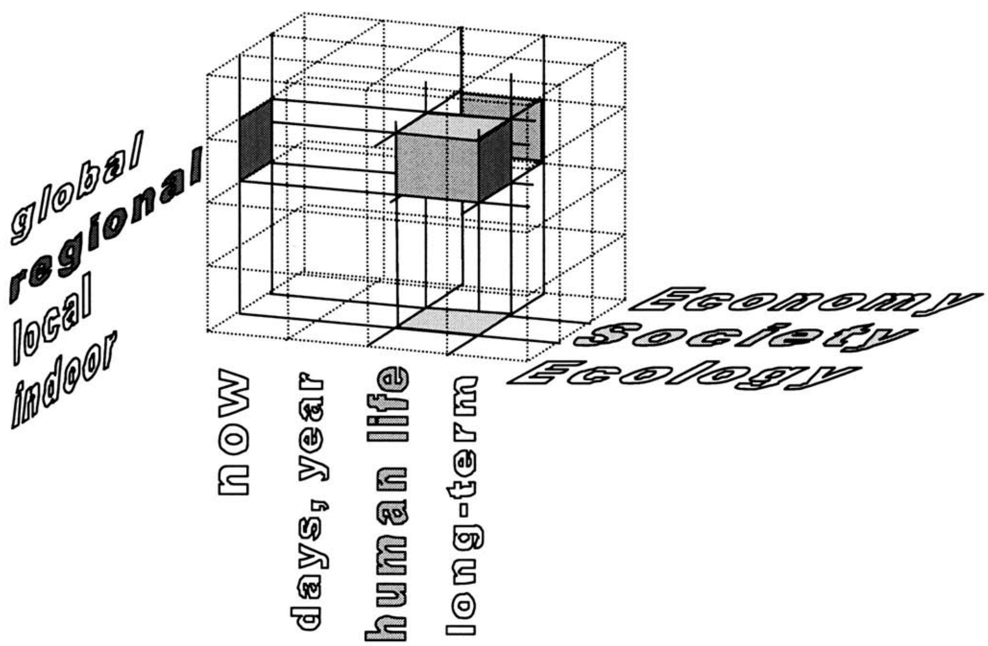


Figure 2.9 Time; space; ecosphere, economy, and society, as the dimensions of Sustainability

3 Measuring Sustainability

3.1 The Need for Indicators

Every day we have to make decisions that are linked to Sustainability. This can be the preference of one product in the supermarket over another or the decision to build a certain type of power plant. If we touch a hot stove and burn our hands, we have a direct feedback because cause and effect are closely related in time and space. The damage is obvious. The links of our activities to Sustainability are usually much less obvious. This can be because the damage is too distant in time and space or because it is only indirectly linked. Indicators that are helpful in daily decision making must reflect these distant and indirect damages in addition to the direct ones. Life cycle assessment is a tool that can help to establish some of those links. It is presented in this chapter.

A second need for an indicator is **simplification** and therefore accessibility of information, making it possible to **communicate**. The Dow Jones for example gives you much quicker and more useful information on the general level of the stock exchange than knowing the exchange rates of all individual shares. Having a common unit, money, makes this aggregation relatively easy. If we deal with pollution and resource consumption this aggregation is more complicated but still possible, as we will see.

The information forming the basis of an indicator does not have to cover everything. Indicators have been in use for a long time already in botanical science. There, certain indicator species represent a certain type of ecosystem. There is a high possibility that certain other plants would show up in the same area, whereas others don't. In the same way it can be expected that certain attributes that form the basis of a sustainability indicator have a high correlation with others.

Another aspect of indicators is the possibility to recognize and quantify **tradeoffs**. The use of coal gasification in Chinese cities for example would bring air pollution advantages at the local level represented by indicators of urban air quality. On the other hand the overall energy efficiency can be lower than with onsite combustion. The contribution to Global Warming will therefore be higher in the case of gasification as can be shown by indicators of Global Warming. A weighting mechanism has to be found to balance the two aspects.

Indicators usually are distinct from primary data. The information pyramid in Figure 3.1 shows the principle of increased aggregation and according simplification. It leads from primary data or measurable attributes of indicators to indices. In the process of simplification some information is lost. A good indicator has to be **robust** in the sense that the lost information will not seriously distort the answer to the question.

In the following I use 'indicator' as a generic expression. Depending on the context, it can include indices, but also primary attributes before aggregation, which are used for decision making.

If the primary data are measured in different units, a valuation is necessary in order to aggregate the data. As long as Sustainability indicators have existed there has been a debate on how and if this aggregation should be done.

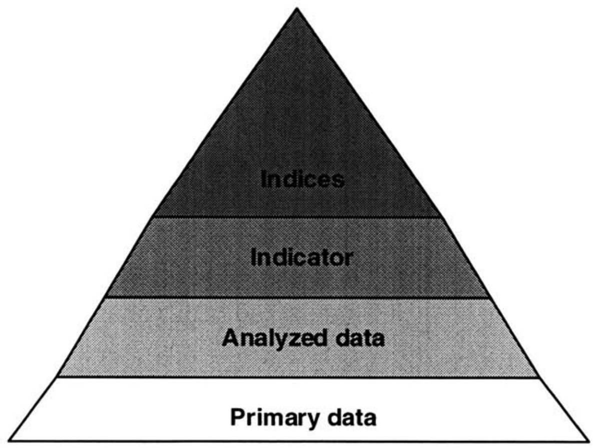


Figure 3.1 The information pyramid

Showing measurable primary data eliminates the errors involved in aggregation and can give more detailed information. But if the information flow becomes too large, it will be ignored and its value is zero. This would be the case in showing primary emission data of hundreds of toxic chemicals to support architects or engineers in designing buildings. Indicators in such an environment will only be used if they allow for a quick and, if possible, unambiguous decision. All toxic emissions could for example be aggregated into one indicator that represents their health effect on human beings. A different situation would be given for building-related policy making or a very large housing project. There it can make sense for specialists to look at many individual attributes and their exact sources.

Resisting explicit aggregation and valuation means subjective and often unconscious weighting of different attributes. The error involved in such a procedure can be expected to be much larger than for a valuation based on a systematic approach. It has also been shown that people tend to underestimate the relative importance of two aspects if those vary in importance by orders of magnitude based on scientific findings. A seemingly more important problem might get an increased weight, but the other problems are also considered as somehow important, although their absolute damage might be negligible compared to the top impacts on the list.

There can't be a unique set of indicators. The level of necessary aggregation as well as the indicators themselves has to be context specific. It will depend on who is addressed by the indicator to take what kind of decisions.

For an indicator to be trusted and used it should fulfill the "Bellagio Principles", named after the location of a workshop. The International Institute for Sustainable Development had brought together an international group of measurement practitioners and researchers from five continents in November 1996 to review progress and synthesize insights from practical experience. The Bellagio-Principles are the outcome of that meeting. The principles that seemed most important to me are listed below. These principles hold for any applied indicator [IISD 1996]:

Practical Focus

Assessment of progress towards sustainability should be based on:

- an explicit organizing framework that links vision and goals to indicators and assessment criteria;
- a limited number of key issues for analysis;
- a limited number of indicators or indicator combinations to provide a clearer signal of progress;
- standardized measurement wherever possible to permit comparison;
- comparing indicator values to targets, reference values, ranges, thresholds, or direction of trends as appropriate

Openness

Assessment of progress toward sustainability should:

- make the methods and data that are used accessible to all;
- make explicit all judgments, assumptions, and uncertainties in data and interpretations.

Effective Communication

Assessment of progress toward sustainability should:

- be designed to serve the needs of a specific audience and set of users;
- draw from indicators and other tools that are stimulating and serve to engage decision- makers;
- from the outset, aim for simplicity in structure and use of clear and plain language

3.2 Existing Sustainability Indicators

Many national and international organizations have developed hundreds of sustainability indicators since the late 1980s. The number of people working on indicators has increased strongly after the 1992 United Nations Conference on Environment and Development in Rio de Janeiro and the Agenda 21's call for indicators. It is difficult to keep track of who has developed which set of indicators for who and with what intentions. The still very young field will need a few years to mature and find an international consensus. An overview on existing sustainability and environmental indicators can be found in [Murcott 1997], [SCOPE 1997], and [Rogers 1997].

Often these indicator sets do not show the interrelationship among themselves and are not structured in a way that would allow a reasonable aggregation into high level indices. Many indicators document some state but are poorly suited to help motivate action for an improvement, as they do not diagnose cause and effect. A good indicator allows for the link of some environmental measurements with practical policy options.

Some Indicator sets have been established by a particular interest group and take a narrow viewpoint. This can be helpful as long as the user of the indicator is aware of that fact. Otherwise it can result in decisions that optimize for one issue but neglect others.

There are two more problems. Often indicators are defined in phrases without describing what the metrics are. A very different problem exists with indicators, which have an extensive theoretical framework describing how they should be calculated, but the necessary data are far from being available and sometimes will never be available. These two problems are often encountered in the context of biodiversity for example. Many indicator lists include biodiversity. Whereas most leave it as a simple requirement to be included, neglecting to specify how it is to be quantified, others come up with mathematical formulas for which the necessary data does not exist.

Most of the indicators that have been established so far are to be applied on a macro scale, meaning a national level, for policy making. Accordingly they almost entirely neglect spatial heterogeneity on a regional or local scale. The boundaries are set by political entities. This can be expected to change with the increased use of Geographical Information Systems in indicator development. More work is necessary for indicators on a micro scale or project level. It is on this level where decisions are taken that finally decide on the progress towards sustainability. These project level indicators should take into account local and regional heterogeneity. Ideally macro and micro scale indicators can be linked. This allows translating macro scale policies into micro scale decisions and action. For example a national goal for greenhouse gas emissions should be set. The emissions of a building can then be judged against that goal.

This chapter shows some of these macro scale indicators. The chapter below on LCA shows how indicators can be established that are useful on a project level.

The OECD pioneering work, which again was based on earlier work from Canada, has influenced many of the existing indicator sets. They developed the model of pressure-state-response indicators. Different authors have extended this basic model. In a study at Harvard this model has been modified to include impacts as an intermediate stage between the state and response indicators [Rogers 1997]. The pressure-state-impact-response model is shown in Figure 3.2. The definition of impacts in this figure is more narrow than the one we will see in the next chapter on LCA.

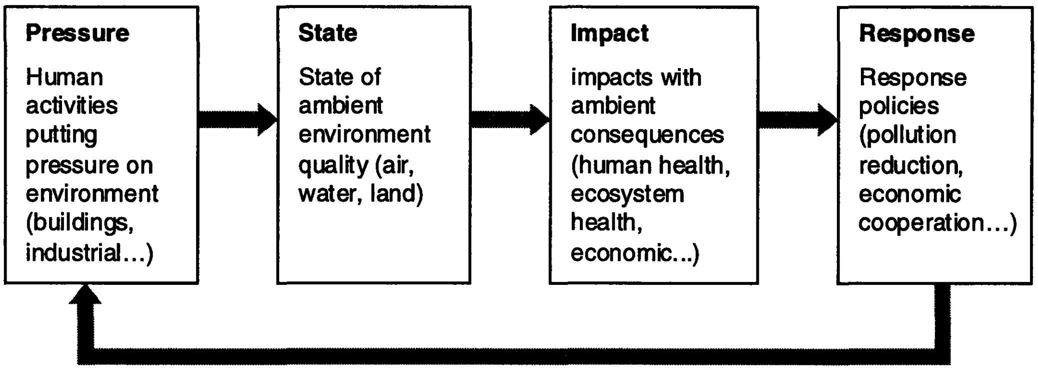


Figure 3.2 Pressure-State-Impact-Response framework for indicators (adapted from [Rogers 1997])

This model gives a comprehensive framework of indicators for problem identification and policy making. Human activities like halocarbon emissions put pressure on the state of the environment e.g. stratospheric O_3 concentrations. Indicators on the state of the considered system are interesting if they are measured or simulated over a certain time span. Trends then become visible. Also state indicators of different locations in space can be compared. A change in the state of the environment will lead to impacts on human health, e.g. skin cancer in the case of Ozone Depletion, ecosystem health, the economy and the social system, and aesthetic health according to Rogers et al. [Rogers 1997]. The response to these impacts are policies and activities to reduce the pressure where necessary. As the OECD warned, the pressure-state-response framework implicitly suggests linear relationships between human activities and environmental effects. Also horizontal inter-linkages between different indicators tend to be neglected.

It is on the level of state indicators where primary long-term policy goals are set, e.g. ambient air quality standards. Regulations often apply on the level of pressure indicators, e.g. emission and release standards. The goals are set in a way that they result in an acceptable level of impacts. The policy goals on pressure indicators have to be derived from goals of the state.

The **United Nations** Commission on Sustainable Development has developed a working list of 134 indicators that is being tested by several countries. The aim is to have an agreed upon set of indicators available for all countries to use by 2000 [UNDPCSD 1996]. The indicators focus on national averages, per capita values and different ratios to document a nation's progress in sustainable development. Users choose indicators according to their needs. Each problem to be addressed by a set of driving force (or pressure), state and response indicators is grouped according to the chapters of Agenda 21. The chapters are organized in the four sections of social, economic, environmental and institutional issues.

More then fifty of the 134 indicators are directly or indirectly linked to housing and buildings. Appendix A, lists those indicators with some comments by the author on how they are related to buildings.

The 'Social' section addresses issues like income, demographic dynamics and urban settlement including floor area per person, informal settlement etc. Human health related indicators include basic sanitation and access to safe drinking water.

The driving force indicators for use of fossil and renewable energies as well as their state indicators that measure energy reserves runs under the 'Economic' section. Also included in this section are mineral reserves.

The 'Environmental' Section includes groundwater withdrawal and reserves, land use and changes in land conditions, wood harvesting and forest area, and biological diversity. Another set of indicators is devoted to the protection of the atmosphere. Included are emissions of greenhouse gases, sulfur oxides, nitrogen oxides and consumption of ozone depleting substances as driving force indicators. Ambient concentration of pollutants in urban areas is a state indicator and pollution abatement is an example of a response indicator. Municipal, industrial and hazardous waste are also part of the environmental indicators.

Although buildings have an influence on many of those indicators, the indicators are not suited as a yardstick for the design of sustainable buildings. The diversity of indicators does not allow an aggregation, but it shows the very many aspects of buildings and sustainability. Not all of them will be reflected in the indicators presented in the next chapter.

The **World Bank** also developed indicators to track a country's progress toward sustainable development. The estimation of national wealth and genuine savings takes into account the depletion of natural resources and degradation of the environment. Human (healthcare, education etc.) and social (interaction of individuals and societies) capital are important in determining the overall wealth [WorldBank 1997].

The **Netherlands** government approach includes regional and global aspects of sustainability. Basically it shows figures with time series for six principal pressure indicators related to Climate Change, Ozone Depletion, Acidification, Eutrophication, Toxics Dispersion and Solid Waste. In the time series, target values for five and ten years in the future is shown. It gives a feedback on how effective the environmental policy is and where more effort for improvement is needed. The indicators are weighted by the distance to the long-tem policy target and aggregated into a composite index. The same indicator themes will show up again in the following chapter on LCA, for which the Netherlands made a strong input in the development of the methodology.

Most of the presented national level indicators do not allow an aggregation. In a study for the **World Resources Institute** Hammond et al. proposed four key aggregate indicators for environmental impacts: pollution, resource depletion, ecosystem risk and environmental impact on human welfare [Hammond 1995]. The four indices are aggregated from 20 indicators, some of which are aggregates themselves. The idea is to provide a comprehensive yet easily comprehensible basis for national reporting.

3.3 The Life Cycle Assessment Approach

3.3.1 Principles

Today's economy is a very complex network of exchanges of goods and services. On nearly all locations in this network some form of resource consumption and emissions take place, that create environmental impact. Consuming one unit of goods or services at one node induces a whole set of activities in the total network. Environmental Life-Cycle-Assessment (LCA) can help to keep track of these direct and induced indirect impacts along the chain of involved processes in this network.

LCA provides a consistent framework for comparing the environmental impact of different technical solutions to a given problem. All pollutants released to the environment and extractions of resources from the environment are determined throughout the entire life cycle, 'from cradle to grave', of a product or service.

LCA in today's framework covers impacts on the environment. Impacts on humans are limited to health effects. Impacts on economy are not included. Life cycle costing would be the economic corresponding method to environmental LCA.

"The code of practice" published by the Society of Environmental Toxicology and Chemistry (SETAC) in 1993 [SETAC 1993] presents an international consensus among the LCA community on how to establish an LCA in principle. Whereas SETAC continues research on LCA, ISO is releasing official standards that present the framework for an LCA [ISO 14040]. According to the ISO guidelines, the following four stages of an LCA are distinguished and presented in Figure 3.3: 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).

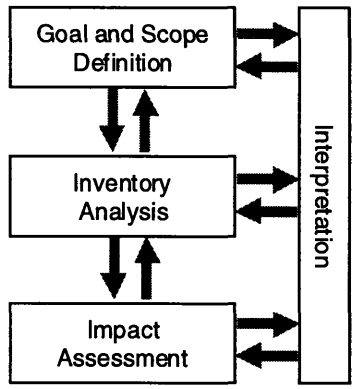


Figure 3.3 The steps in a life cycle assessment according to ISO.

The **goal and scope definition** should state the intended audience and application of the study. A crucial point is the definition of the **functional unit**, which is the subject of the study. Comparing milk containers it would be doubly wrong to equate a 1-quart carton with a 1-liter multi-cycle glass bottle one to one. The correct functional unit takes into account the volume of the bottle and the cycles it undergoes.

Another important point is the definition of system boundaries. They have to be clearly defined and used consistently. Depending on the study, production infrastructure and services are included or not.

In LCA, the world is considered as consisting of two major compartments; the human civilization system, here called **Technosphere**, and the **Natural Environment** as shown in Figure 3.4. Looking at people as biologic human beings, they are part of the natural environment. The Technosphere is a large network of processes. Here the definition of process includes any node in our network model. It can be a good or a service. Depending on the detail of the model, a process could for example be 1kWh of electricity on average or, more detailed, 1kWh of electricity from a certain type of power-station at a certain location. Most of these processes are in **direct** contact with Nature through **emissions** into air, water, and soil as well as through the extraction of natural **resources**. They are also in **indirect** contact with nature through connected processes such as electricity and other goods and services they need as input for their production. This model reflects the fact that the entire economy depends directly or indirectly on the natural environment.

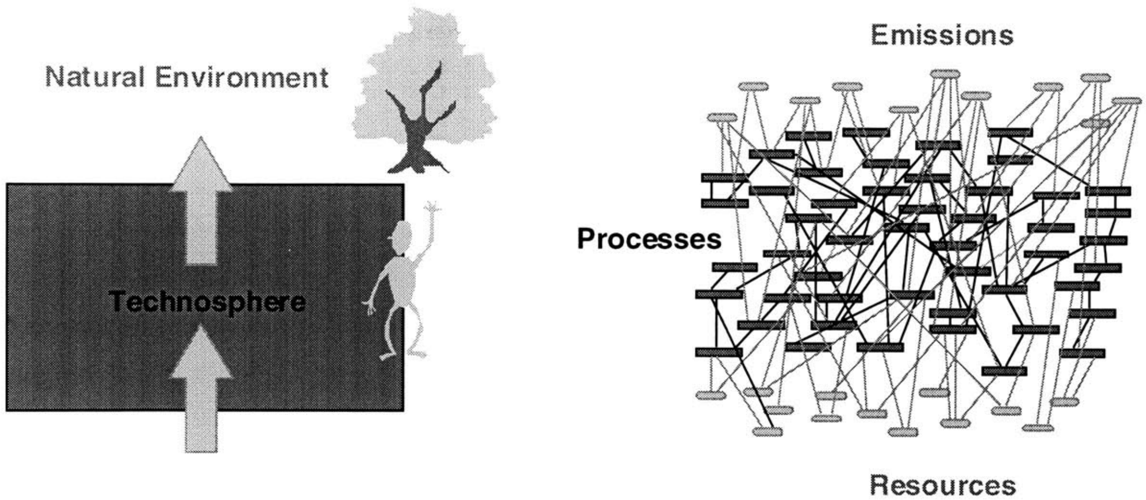


Figure 3.4 The human created technosphere is a network of many processes, which depend on resources from and release emissions into the natural environment

In LCA we are interested in the ecological consequences of each process. For each process a list containing all inputs from nature and other processes and all outputs to nature is established. According to SETAC and ISO notation this is called the **inventory**.

Figure 3.5 shows the simplified example of inputs and outputs for the production of 1kg cement. It consists of different resource inputs, emissions, and also inputs from other processes like transport and energy. Cement itself is an input for other processes.

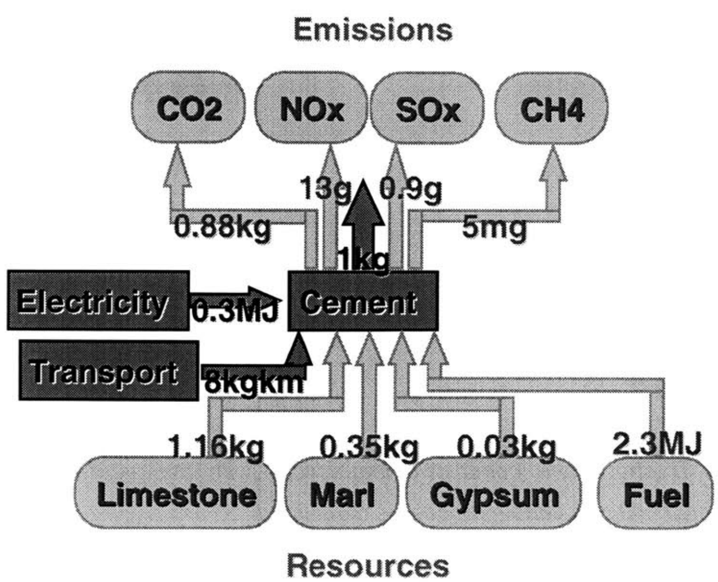
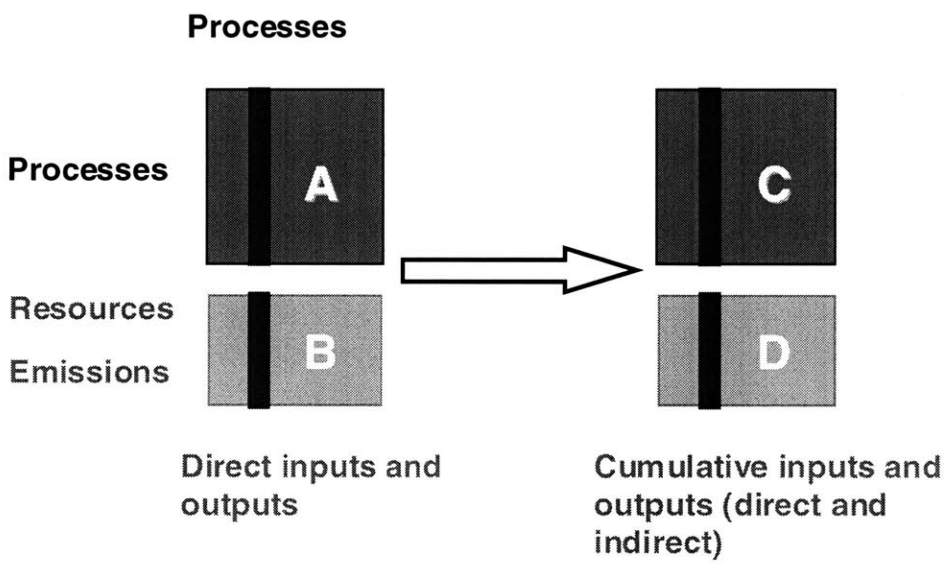


Figure 3.5 Resource inputs, inputs from other processes, and emissions for the production of 1kg of cement.

The inventory data for all inputs and outputs to all processes of the technosphere can be entered into a matrix. Certainly this will never consist of all of the millions of real processes, but typically of some one hundred important processes. The vector marked in dark in Figure 3.6 shows the inputs from other processes in matrix *A* and the direct resource consumption and direct emissions in matrix *B* for one certain process. We are interested in the cumulative effect of an incremental increase or decrease in demand of a certain process. Requiring 1kg less of cement will not only have less emissions on the production site, but also induce a reduced electricity consumption, which in turn will lower emissions and the demand for fuel on the power station etc. By means of linear algebra this infinite chain, which also contains loops, e.g. electricity needs cement itself for the construction of the power plant, can be solved.

What we are finally interested in is matrix *D*, which shows cumulative direct and indirect interactions with the natural environment for each process.



$$C = A + A^2 + A^3 + \ldots = (I-A)^{-1}$$

$$D = B * C$$

Figure 3.6 Matrix D shows the cumulative interactions with the natural environment if one additional unit of a certain process is consumed.

These emissions and extractions, as represented in matrix *D*, influence the state of nature. They will potentially modify the state of living or non-living elements of nature. There are many different impacts related to one process. If we want to assess the environmental qualities of a product, we need to compare the different impacts. If all impacts are aggregated to one single number, we call it an 'environmental index'. **Impact assessment** is the procedure that connects the inventory of emissions and extractions to the various impacts exerted on nature, and further on, to the environmental index. Impact assessment is presented below.

Establishing the inventory for a certain product is not always an easy task. Data has to be collected from different sources. There are some typical problems in the inventory phase that have to be solved in most LCAs:

One is the allocation problem of multi-output processes, where one production step produces more than one product, e.g. the simultaneous production of vegetable oil and animal feed. For which product should the resource consumption and the emissions be accounted? Different rules have been established to solve such problems. If one of the streams is clearly an inferior side-product, then all environmental interaction is counted for the main product. Other rules use the economic value of the several products for a proportional allocation of the environmental burdens.

LCA only includes emissions under normal operating conditions, emissions and damages from accidents are not included.

Another problem is the use of generic data. Which technology best represents the studied case? Is it feasible to use data from one country from a certain time for an other region some years later? This is in contrast to EIA (Environmental Impact Analysis), where a well-defined process or bundle of processes is analyzed at a given location and for a given time period. The main reason for this generic approach is the need for simplification. To accomplish an LCA within a reasonable effort, the use of standard data for electricity, transportation etc. is inevitable. How generic the study is depends on the scope. If we are interested in the question if glass or plastic milk bottles are preferable, we look at mean values from data sets from different suppliers. If we want to know which supplier can provide the more environmental friendly glass bottle, we have to look at the individual inventory of the production companies. Ideally, a local impact assessment could be made. Often the available data does not give much choice and a pragmatic approach to data collection is required.

3.3.2 Streamlined or Simplified LCA

Different authors have proposed simplifying the inventory for a product or service. SETAC has a group working on "Screening and Streamlining LCA". The basic idea is that out of the hundreds of inputs and outputs of a process, a few will make up for the majority of the environmental impact. Considering the relatively large error that usually is involved in LCA, it is acceptable to simplify the LCA in order to reduce time and costs involved in establishing a full LCA.

The full framework is also used as a guide for a simplified version. The first step, the goal and scope definition, should be done the same as for a full LCA and state, if a simplified approach is appropriate in the specific case.

Instead of directly working on a detailed inventory, there follows a screening. Screening identifies the relevant issues and characteristics of the considered system. Screening can be done by expert interviews, checklists or benchmark of existing LCAs. Screening indicators like energy or total mass flow can be used. In cases where the type of critical input and output flows are known, leading substances like total heavy metals or VOCs can be used for a first overview on the system. Screening needs to be done by an experienced person.

Based on the screening results, the system can be simplified. This involves the use of generic data and surrogate data of similar processes. Some flows might even be neglected. Also some life-cycle stages might be neglected if they are expected to have a small impact.

In a last step a reliability check including a sensitivity analysis should be performed.

Another approach for a simplified LCA is the use of top-down data from a national **input-output-analysis** (I/O analysis). These data can be used both in screening and simplifying. Input-output tables show the monetary interactions between different sectors of the economy and the exchange of commodities on a national level. These tables can be combined with statistical data on emissions and energy consumption for the same sectors. The result is an LCA on a national level for the sectors of an economy. Norris and also Hendrickson et al. performed this calculation for the United States, where detailed statistics distinguish a few hundred sectors [Norris 1998] [Hendrickson 1998]. In most other countries statistics are not sufficient to perform an environmental I/O-based LCA with a reasonable level of detail.

The major disadvantage is the high aggregation level of the sectors. For example, different insulating materials used in the building trade, like fiberglass or rockwool, will appear under one heading, although their bottom-up process chain would show differences in environmental impacts. An advantage is the more comprehensive approach taken by an I/O-based LCA. It also takes into account the whole service sector of the economy, which is usually neglected in a bottom-up approach.

In Screening, the I/O results show which inputs from all the sectors contribute most to the environmental impact of a certain commodity. These chains of the LCA have to be studied in more detail.

In a hybrid approach, results from the I/O analysis are combined with traditional process LCA. If, for example, paint is not considered to be a major input of a certain process, there is no need to perform a detailed study on the production of that paint. Instead the I/O results from the industrial sector producing paint can be used.

3.4 Impact Assessment and Weighting of Impacts

As shown in the preceding section, the LCA inventory results in a list of different emissions and extraction of resources related to a process i.e. a good, service or activity. There is widespread agreement on how to perform the inventory. In the next step, called impact assessment, we look at the impact or damage the emissions and extractions will exert on nature or human beings. By this prediction of a potential damage, impact assessment shares many elements with risk assessment. Different approaches to impact assessment are presented in the following.

A prevailing model of impact assessment is to assume that the magnitudes of the different environmental impacts caused by a process are a linear combination of its emissions and extractions. The magnitude of the aggregated environmental index is a linear combination of the impact scores. As nature is essentially non-linear, the linear model represents an approximate linearization of non-linear differential effects. Weighting or valuation is necessary in order to work out the coefficients of the independent variables of those linear combinations.

Considering the great diversity of nature, especially within its living part, it can be assumed that the number of different impacts is in reality larger than the number of different types of emissions and extractions. The dimension of the impact profile would be larger than the one of the inventory table. In practice the steps of impact assessment lead to an increasing degree of aggregation of data. This simplification is achieved by two properties of the model.

First, concentrating on a few impacts that are considered to be particularly serious for nature and mankind makes a selection amongst a large number of possible impacts. Second, the so-called impacts are predominantly not single effects but rather effect groups: the impact "Ecotoxicity", for example, represents changes of the state of millions of different living species.

Weighting systems are simpler, if they only take one class of items into account. If an inventory contains chemical emissions only, aggregation into one index is much less complex than if the inventory contains various classes like noise, land surface degradation, or natural resource depletion.

Valuation coefficients that allow full aggregation of different impacts into one environmental index will always include societal value setting and will be arbitrary to some degree. It will be the result of consensus, hopefully taking into account scientific findings.

In a Swiss study [IWÖ 1994] and [IWÖ 1996] different concepts of impact assessment have been compared. Some of the methods are still under development. Some findings of this chapter are based on that study:

The widely accepted SETAC model [SETAC 1993] gives a framework for impact assessment. It includes the steps of **classification**, **characterization**, **normalization** and **valuation**.

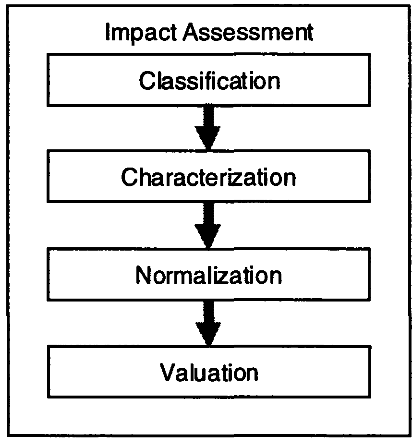


Figure 3.7 The steps of an impact assessment

In the **classification** step, emissions and extractions are sorted by effects like Global Warming. One emission or extraction can have several effects. NO_x, for example, contributes to Acidification and Eutrophication (Nutrification).

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. Following the CML method [CML 1992] for characterization and classification, we transfer the inventory of hundreds of emissions and extractions into about 15-20 "effect scores".

In order to see how important the effects of a product or service are relative to each other, 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. A normalization step does not always take place explicitly. In that case it is included in the following valuation step.

The number of effects is still large for practical decision making after characterization and normalization. In the **valuation** step, the effect scores are weighted to obtain a single environmental index. Valuation is similar to the problem of how to add apples and oranges. Hence some people refuse it. But also for apples and oranges we have reasonable units to add them up. In the simplest case you can count the number of fruits. A more sophisticated approach could add their energetic content or their overall nutritional value. Another possibility would be to add their economic value.

The weighting in valuation is not only based on a scientific background. Depending on the applied method, subjective and political views, which reflect social value setting, may determine the weights more than natural sciences.

Goedkoop identifies six categories of weighting criteria that are used in today's methods:

"1. The social evaluation (expressed in financial terms) of damage to the environment. The impairment of human health, for example, is based on the costs the society is prepared to pay for healthcare. [...]

2. The prevention costs for preventing or combating the relevant environmental impact by technical means. [...]

3. The energy consumption that is necessary to prevent or combat the environmental impact by technical means. [...]

4. Avoiding the use of weighting factors by using only environmental effects [...] as a measure of the total environmental pollution.

5. The evaluation of experts (for example, a group of respondents in a panel) who express the relative seriousness of an effect by assigning a weight to the effect or impact.

6. The degree by which a target level is exceeded. The greater the gap between the current environmental impact and a target level, the higher the rating given to the seriousness of the impact. This method has become known as the Ecopoints method." [Goedkoop 1995, p.12]

None of the existing methods for Valuation is fully satisfactory, but progress has been made the last couple years in structuring the process. Further research in this field is ongoing.

3.4.1 Combining Ecological, Social and Economic impacts

Often we are interested in knowing how different solutions perform economically, environmentally and socially at the same time. The objective is to find an optimal solution.

In a **one-dimensional** approach, the damage to nature and humans is expressed as social costs in a monetary value. This can be added to the direct cost of a good and an optimal solution can be found taking into account direct and social costs.

In a **two-dimensional** model, the emissions and extractions are aggregated to one index, covering damages to nature and humans. Each solution can be considered in terms of aggregated environmental and social vs. economic performance.

In a **multidimensional** analysis the emissions and extractions are not or only partially aggregated. An optimal solution has to be found in a multidimensional space.

3.4.2 Distance to Target

Most actual methods use some form of a 'distance to target' approach to define the relative weight of the individual emissions or impacts. The target value is a critical flow for which no or an acceptable damage is expected. This is the **carrying capacity** of the system. Usually this carrying capacity is not known. In practice the target values used for calculations can be based on different sources and principles. Often immission standards and immission quality goals are used.

The use of critical flows fixed by legislation has advantages and disadvantages. In the ideal case the critical value has been fixed in a democratic process based on scientific knowledge. It combines societal value setting and science. Unfortunately in practice critical values fixed in legislation are influenced by many different factors. Interest groups with a strong lobby, or simply availability of the technology to control the emissions can be more important than the actual impact. The slow political process will not allow the method to be up to date with the latest scientific findings. On the other hand it stabilizes the method, which will not follow every hype on environmental issues. Another problem is the loss of information on what was the driving force in establishing a critical value. Usually legislation will not include information on why certain emissions should be limited. Was it human health, acidification, degradation of soils? Often diffuse mixes of impacts initiate environmental laws.

For large scale and irreversible problems traditional cost-benefit analysis is not an appropriate tool to determine target values and evaluate mitigation measures. Toman proposes the concept of safe minimum standards, which put a socially determined demarcation between moral imperatives to preserve natural resources and the free play of resource tradeoffs [Toman 1992].

Some European countries are acting in this direction by establishing national environmental plans that address environmental problems with a holistic view, instead of a set of independent laws. These national environmental plans often include statements on the target values not only for certain individual emissions, but also for impacts representing a group of emissions. These target values can be taken to calculate weights for aggregating impacts into one environmental index. As valuation is to a large extent depending on social values, the use of values found in a political process is acceptable on a high level of weighting impacts.

3.4.3 Area and time dependency, damage functions

The weighting factors used for the classification/characterization and valuation procedure have to be determined with respect to the overall-loading situation in an area. It is therefore necessary to define geographical areas with comparable ecological conditions. On the spatial scale these areas typically vary somewhere between regional and continental areas due to a lack of more detailed data. LCA-data are therefore very generic and usually do not take into account local conditions.

The differentiation of smaller regions can be imagined and is also necessary. Developments in statistics and geographical information systems allow for such a procedure. Overlaying databases of emissions, land use, population and wind roses is used in the European ExternE project to model site specific external costs of energy production [EC 1995]. A similar model can be applied to choose for example the main energy system for a building in a certain location. Depending on the existing air quality, different indicators will get different weighting.

The LCA inventory data for buildings will stay on a generic level. The inventories are often based on a few manufacturers and the data is then applied for a large region. During planning of a building this is less problematic, as the specific manufacturer of construction materials will not be known during planning anyway.

The problem of time dependency shows up at different levels in LCA: the process chains of the product life cycle with the corresponding interventions can be distributed over many years, beginning with the extraction of raw materials and ending with the disposal of the obsolete object. The magnitude of the environmental interventions is dependent on the technology applied and therefore linked to the preference year for the technology. In addition to that, there may be large time lags in the environmental effect chains. An example is the water pollution effect of landfills which may continue hundred of years after discharging the solid waste.

The decay of certain emissions, which results in different residence time for different substances, has to be taken into account. Multiplying each emission of a class by its residence time can do this. This works for example for ozone depleting substances, which have residence times in the order of decades. This calculation can be questioned, if the residence time is very long or infinitely long, as it is for example the case for CO_2. What time horizon are we interested in? In the CML method, the Global Warming Potentials for different time horizons (20, 100 and 500 years) are calculated. Substances with a long residence time gain weight if a long time horizon is considered.

A fundamental problem of many existing methods is the use of critical flows fixed by legislation, while neglecting the fate of the emissions. It is implicitly considered to be the same for all substances, independent of their real residual time and effect chain. This can lead to very misleading results, especially if emissions into different environmental compartments (media) are included. Heavy metals emitted into air will be washed out in some days but they will stay in the ground for a very long time. A full **fate** and **exposure** analysis links emissions and the exposure of nature or humans, taking into account inter-media processes. The "Critical Time Surface" methodology of Jolliet and Crettaz [Jolliet 1997] and the CalTox model used to calculate Human Toxicity Potentials [EDF 1999] are steps in this direction.

The relationship between the magnitude of an emission/extraction and the resulting damage is called the **damage function** or ecoscarcity function. Most models apply a linear relationship between emission/extraction and the effect it causes. For many effects this is not true and the closer the actual concentration of a pollutant is to a limiting value, the larger is the incremental damage. On the other hand a decreasing incremental damage can be imagined for other effects. Additional emissions then will not cause as much additional damage as the previous ones. Many effects are functions of several variables. A relatively simple but still hard to quantify function e.g. is the formation of ozone from NO_x and NMHC. The gradient of the damage function depends on the ratio of the two pollutants. The research on damage functions is still in an early stage.

For reasons of practicality, LCA and the weighting methods will generally be independent of time. More research on area-dependency is necessary in order to represent unequal ecological background situations and societal preferences.

3.4.4 One-step and Multi-Step Weighting

Not all weighting methods follow the pattern of classification/characterization, normalization, and valuation as described above. In one-step methods, the transition from emissions/extractions to an environmental index is done in one step. The effect is calculated by multiplying each emissions/extraction with a linear valuation coefficient (a).

Index score = a * emission (or extraction) quantity

The first models in LCA were one step models. Newer models take a two or multi-step apporach.

In two-step weighting methods, like in classification/characterization and valuation, an effect for each emission/extraction is calculated in a first step. In the next step of valuation, the effects are weighted against each other.

Effect = b * emission (or extraction) quantity

Valuated effect = c* effect

More coefficients would be needed if weighting is structured into three or more steps or if non-linear combinations have to be included.

Multi-step weighting has the advantage that the determination of weighting factors can be split into a number of special problems, to be solved by suitable specialists. Multi-step weighting is more transparent. It also allows the separation of scientific from social weighting. One-step weighting is less elaborate, less transparent and less analytical. But this does not always mean that it is not useful. If uncertainties in the scientific part are large, the result of a holistic one step approach can be better.

3.4.5 The ideal impact assessment method

A valuation factor or system should include the following elements: (list from [IWÖ 1994 and IWÖ 1996] extended and modified by the author).

- The **spatial scale** of the damage: Valuation factors for a type of pollution should be smaller if only a small area is affected in the considered area.
- The **reversibility** situation: effects that are reversible in a short time should have lower valuation factors.
- The **severity of** the potential **damage** that the emissions could have.
- The **scarcity** situation (distance to target), which can be expressed as some function of actual flow of emissions and resources and its trend in the area, and of a reference flow. This reference flow could be a pre-industrial-age-flow, a no-observed-effect-flow, a political-target-flow, or any other flow, which would be acceptable as a yardstick to the actual flow.
- The **substitutability** situation: The valuation factor should be lower in case a resource can easily be replaced by an other.
- The **uncertainty** situation: If there exists a considerable risk that the damage could be larger than presently anticipated, the valuation factor should be increased.
- **Fate** of the emissions and **exposure**: The method has to take into account the different possible pathways an emission can take and its residual time in an environmental compartment as well as the final exposure of the safeguard subjects (humans, animals, plants) to the chemicals.

3.4.6 Existing methods

In the following some of the methods that are in use today or that have a promising concept are presented. The methods presented take into account emissions into air, water and soil. Only a few consider resource depletion.

Impact Oriented Classification of CML

The method developed by the Centre of Environmental Science (CML), Leiden University, [CML 1992] follows closely the SETAC steps of impact assessment as described above. This in not surprising, as people of the CML were also involved in establishing the SETAC guidelines. It is the most widespread model in use today.

The inventory includes some hundred different emissions and extractions. In addition to more common emissions and resources; land-use, noise, waste heat and radiation are also included.

In the classification step the inventory is reduced down to 15-20 different impact categories, which are considered to be important. The expression 'impact' is used here in a general sense including effects (e.g. human deaths) and impacts (e.g. Global Warming). This list is thought to be flexible to follow new findings. The weighting of emissions/extractions to derive impacts is based on principles of natural sciences. As the impact categories are very different in nature, the following step of valuation is difficult.

The quality of classification and characterization varies a lot from impact to impact. Table 3.1 gives an overview on the CML indicators and also gives an indication on the quality of the model, which is used to calculate the indicator, as perceived by the author of this report.

For biotic resources the effect score was calculated as

effect score = Extractions * (1/reserves).

Another multiplier (world yearly extractions/reserves) should be included, but the available data was insufficient to do so. Different scarcities are added (fossil fuels, ores etc.). The quality of the indicator is poor. The depletion of biotic resources is also based on a yearly extractions to reserves and mixes plants and animals. This mixed indicator also poorly represents the real value of different biotic resources.

Mechanism oriented impacts are expressed in relation to a reference substance, like CO_2 for Global-Warming. The Global Warming Potential indicator is well developed and so is the indicator for Ozone Depletion.

With effect oriented impacts like human toxicity, the potential damage is considered. Human toxicity is measured in kg body-weight burdened up to a critical value, meaning after intake of a certain amount of the toxic substance, a certain body mass will be exposed to a critical concentration. These masses can be added for different toxins. The model assumes in an extremely simplified manner that the emissions are dispersed in the world air volume and that they are not removed over time. The indicator therefore received a (-) for the quality. Ecotoxicity does not include emissions into air. As the toxic impact on millions of species has to be considered, the lowest critical value for the most sensitive species is taken. The summation of critical volumes/masses that have been derived from critical values for species as different as a salmon and a coral, is a problematic point of the method.

Photosmog, the formation of O_3 from VOCs and NO_x is a non-linear effect. For the determination of the weighting factors, it is linearized. The generic approach that is taken does not allow different background data to be taken into account, as would be needed for Acidification and Nutrification (Eutrophication).

Waste heat released into surface waters is considered harmful. No threshold or local importance is taken into account. The accuracy of the indicator in terms of MJ is high, but the usefulness low.

The threshold of human reception of an odor is taken as critical value to calculate the m^3 of air polluted for the odor indicator. No qualitative criteria of the smell are included. For the Noise indicator, emitted acoustical energy is summed over all sources. This model does not take into account the properties of the receptor and should not be applied.

The indicator for Damage to Ecosystem distinguishes five classes of land use between natural land and a fully sealed surface. The unit is surface times time. Time is the time of existence of the precedent state. This concept is somehow unclear and the passage from one state to the other has equal weights.

More information on the impacts and their indicators can be found in chapter 6 and Appendix B.

Table 3.1 Impacts considered in the [CML 1992] system, its unit, and overall quality of the indicator (- poor, + ok)

Impact	**unit**	**quality**
Depletion of abiotic resources	-	-
Depletion of biotic resources	-	-
Global Warming GWP	CO_2 equivalents	+
Ozone Depletion ODP	CFC-11 equivalents	+
Human Toxicity	kg human weight	-
Terrestrial Ecotoxicity ECT	kg soil	-
Aquatic Ecotoxicity ECA	m^3 water	-
Photosmog	Ethylene equivalents	0
Acidification	SO_2 equivalents	0
Nutrification	PO_4 equivalents	- / 0
Waste heat	MJ	0
Odour	m^3 air	- / 0
Noise		-
Damage to Ecosystem (land use)	m^2*year	0 / -
Victims		-

The next step in the CML methodology is normalization. Every effect score is divided by its estimated score for the total worldwide emissions. The normalized effect scores give a better indication on where a certain product causes a relatively high impact on the environment. The authors clearly state that the normalized effect scores must not be added. No model has been developed for a valuation of the impacts.

In most applications of the CML method the discussion is limited on which impacts should be included and how to valuate them to aggregate them into one index. It is often neglected that the effect score for some poorly developed impacts only badly indicates the 'real' impact. The error from a weak model can be larger than the one from 'wrong' weighting.

CML together with other institutions and experts is working on a major update of this method at the moment. If the major flaws of some impacts can be overcome it might stay the leading valuation system, that tries to be at the same time complete and based on a systematic scientific background.

The Environmental Scarcity or Ecopoint method

The Swiss Ecopoint method is the first method to apply the 'distance to target' principle. Its roots go back to 1978. Different authors have improved it over time. Similar methods are applied in different countries. Environmental policy publications like emission standards have been considered for deriving critical flows. Where those values do not exist, other sources had to be taken into account.

Eco-factors have been derived for only about 20 emissions and energy consumptions. The use of other raw materials has been considered as dispersion rather than final consumption and as not important. 20 eco-factors might seem too few, but they cover to a large extent the effects considered in the CML method as has been shown in a comparative study.

It is a one step method. The weights or "eco-factors" are based on annual flows relative to critical flows for the same area; usually a country. The Eco-factor is calculated as:

Eco-factor = (1Ecopint/Critical Flow)*(actual flow per year/critical flow)
unit: [Ecopoints / emission or resource use]

The method is in widespread use in Switzerland. One of the reasons certainly is the simplicity of its application in calculating just one environmental index.

Ecopoints suffers from the weaknesses of all one step methods using legislation as a basis to derive target values. The Ecopoints in today's form contains the implicit assumption that all intervention flow targets are of equal importance. Users not familiar with the background and limitations of the Ecopoint method most probably will overestimate the quality of the result.

The Critical Volumes Method

The Critical Volumes method allows aggregating different emissions into each environmental compartment (air, water, and soil). The emissions are simply divided by their limit value found in immission standards. The results are m^3 of air, litres of water and kilograms of soil spoiled up to the limit level. These values can be added in each compartment.

The Critical Volumes method is simple to apply and therefore one of the most popular methods used today. But it completely neglects fate and exposure of the emissions. It also includes the weak points of all other methods relying on environmental legislation as reference values.

The "Concept of **Quality-target Relations**" of Schaltegger and Sturm shows many similarities to the critical volume method. By expressing critical flows in molar concentrations, it is possible to aggregate effects from different compartments. But the method also does not take into account fate and exposure. Some impacts like use of resources and land are not included [Schaltegeger 1992].

The Eco-indicator 95 / 99

The Dutch Eco-indicator 95 is the most complete but still ready to use impact assessment method for practitioners [Goedkoop 1995]. It is a multi step weighting method. The emissions are translated into effects similar to the ones defined by CML (see above) on a scientific background. The effects are then translated into damage on the safeguard subjects, based on a distance to target approach, trying to use scientific target values. A subjective procedure including expert interviews is used to value these damages and aggregate them into one indicator, or index using the term defined earlier in this report. Every one of these steps contains assumptions and simplified models. Translating Global Warming into eco-system impairment for example involves high uncertainties. Also problems inherent in the CML methodology are included in the Eco-indicator. Many important environmental impacts like habitat loss and resource consumption are not covered. Although the method still shows deficiencies, it is a clear advancement compared to other methods. It operates within the SETAC framework and is coordinated with the CML concept. The method is only valid for Europe at the moment, but it should be possible to transfer it to other regions relatively easily.

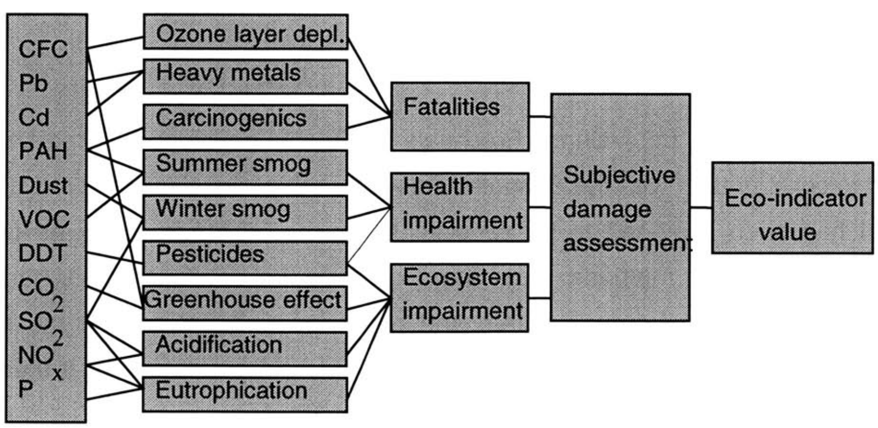


Figure 3.7 Weighting procedure for the Eco-indicator 95 (source: [Goedkoop 1996])

An updated version probably called Eco-indicator 99 should be released soon [Goedkoop 1998]. The three safeguard subjects in the updated version are resources, eco-system health and human health.

EPS

EPS (Environmental Priority Strategies) is a system for a one-step, quantitative environmental valuation. It has been developed in collaboration with the Swedish Industry. EPS takes into account five so called safeguard subjects (things we care about): human health, biodiversity, production of biomass, resources and aesthetic values. The valuation of impacts onto those subjects is based on a willingness to pay approach.

In order to create a relation between environmental emissions/extractions and the effects on the safeguard subjects, the SETAC-concept of classification / characterization is used where possible.

In contrast to many other methods, where the depletion of minerals is even not included for different reasons, EPS gives a very high weight to the depletion of minerals. [IWÖ 1994]

Critical Surface-Time

The Critical Surface-Time method of Jolliet [Jolliet 1997] takes fate and exposure into account including inter-media processes. All damages are expressed in an equivalent polluted or used land area during one year (in m^2/y). The method is focused on ecotoxicity and human toxicity for the moment. Resources are characterized by the energy required to close the production cycle and are finally expressed in terms of land use.

The Critical Surface-Time method presents a promising framework for impact assessment but is still under development.

Human Toxic Equivalency Potentials

The method of human Toxic Equivalency Potentials (TEP) was developed by the US Environmental Defense Fund in collaboration with the School of Public Health at the University of California Berkeley [EDF 1999]. It has been designed to be consistent with the LCA framework as described in this chapter. Like other similar methods, e.g. the European Union System for the Evaluation of Substances, it utilizes an environmental fate and exposure model to predict the dose organisms receive after a toxic chemical is released into an environmental compartment. It then compares this dose with indicators of chemical toxicity to produce a risk index.

CalTox, the integrated environmental fate and exposure model used in TEP, predicts the concentrations of a chemical in seven compartments (air, plants, surface water etc.) after being released into air or water. 23 different exposure pathways (inhalation, ingestion through milk etc.) are modeled to quantify the dose a human will be exposed to.

The dose is then multiplied by route specific risk assessment values (RAVs). RAVs basically show the relative toxicity of a chemical. They are derived from dose response data obtained from human or animal studies. RAV from several public agencies had to be taken into account. Some RAVs had to be fixed by extrapolation and similarity considerations.

The TEP is then expressed as benzene equivalents for carcinogens and toluene equivalents for chemicals with non-cancer health effects. The TEPs from different chemicals can be added within the two categories.

There are still a large number of chemicals that could not be included yet due to data gaps in some of the necessary parameters for the TEP model. Certainly every step in deriving TEPs includes an error. But compared to the early models presented above, which don't take into account fate and exposure, this type of models represents great progress.

TEP has been developed on the background of the US Toxic Release Inventory, which includes emissions of more than 650 chemicals from large polluters. In other countries, or for smaller scale polluters it will be difficult to establish the necessary inventory data with hundreds of chemicals.

According to EDF work is ongoing and more chemicals will be included. EDF also intends to develop TEP that address ecological effects and indirect environmental effects (Acidification and tropospheric ozone formation potential). The Minnesota Toxicity Index only focuses on emissions into air but already includes ecotoxicology. It also aggregates cancer and non-cancer effects into one indicator.

A sensitivity analysis showed that the TEPs did not change much after changing the landscape parameters from Californian to National averages. The human dose response should be the same anywhere. Probably an internationally accepted standard can therefore be established in the future.

Mass Intensity per Service Unit MIPS

MIPS was a proposal for a 'zero' step weighting method [Schmidt-Bleek 1993]. To simplify the LCA procedure, all emissions and extractions are directly added on the basis of their weight. The correlation of mass and environmental impact is not expected to be sufficient to support this model. Considering that the inventory is as tedious for MIPS as for other LCA methods and the limiting information of the MIPS result, the MIPS approach is not expected to take the role of a summary indicator in the future. It might be used as a simple indicator for resource use based solely on mass aggregation or in some popular examples of LCA.

Cumulative Energy Demand

The calculation of cumulative or cumulated-both words are in use- (primary) energy demand (CED) or embodied energy is older than LCA. CED 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. Also CED is not directly an environmental impact, CED still is used quite often. Some arguments supporting the use of CED are:

- CED has existed for a longer time than full LCA and there are more data available.
- CED is the only energy parameter that allows aggregating all forms of energy.
- CED is directly derived from the inventory and does not involve the uncertainties and weighting related to impact assessment. It has therefore a higher accuracy.
- Its simplicity, accuracy and long term establishment makes it easier to communicate.

Arguments against the use of CED are

- How should renewable energies be treated? A CED for all non-renewable energies and a separate one for all renewable energies should be calculated.
- Even if renewable and non-renewable energy are kept apart, it is assumed that the impact of 1MJ primary energy used for electricity in a coal power station is equivalent to 1MJ primary energy in a nuclear power station.
- 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.
- If CED is presented together with other indicators that represent pollution and resource depletion, we have a double counting of energy related impacts.
- The accuracy is not very good. How is nuclear energy to be treated? The energy used in today's power stations is much less than the principal formula given by Einstein. One possibility is the general use of waste heat instead of primary energy content of the resources. How should spills and energetic waste in the exploitation of energy resources be treated?

CED has its role as long as impact assessment methods are not developed enough to take into account all energy related environmental impacts. But it is a very diffuse and not clearly defined aggregate indicator with no clear definitions of what the safeguard subject is.

Monetization

In the context of LCA mostly two step approaches to monetization have to be applied. That means that first a 'dose-response' relationship between a pollutant and an effect is established. The damaging effect then is monetized. Some of the effects like damages to buildings from acid precipitation, or reduced agricultural productivity due to photosmog can be quantified based on real market values. Human health can be quantified by using increased health care costs due to the damage. Instead of quantifying the damage, it is also possible to quantify the hypothetical cost for technical means of preventing the damage.

Not all impacts can be quantified on the bases of real world market values. An other approach therefore looks at the willingness to pay (WTP) to secure a benefit or to prevent a loss, and the willingness to accept (WTA) to forego a benefit or to tolerate a loss. This could be the willingness to pay for better air quality or the amount that an individual expects to be paid in order to support degradation in air quality. WTP and WTA approaches can also be used to quantify existence values for a landscape or species. Empirical studies showed that WTP and WTA can lead to very different results. Also, economic theory indicates that they should not differ very much.

Dollar value can create the illusion of scientific or rather actuarial precision. But depending on the model chosen for monetization, the outcome can be quite different. It is important to have a consistent model and communicate it clearly to the user.

In a two step approach, attempts to predict societal costs of an environmental effect are limited by the same problems that also go along with other environmental indicators presented above. On top of estimating the physical damage there follows an estimate of the economic value of that damage. They are therefore prone to an even bigger error.

The advantages are

- the possibility to add any kind of impacts of very different nature. It also allows adding costs from reduced productivity due to bad indoor air quality to the cost of external damages.
- easy communication, as the units are familiar
- The monetized damage can be added to direct building costs. In this one-dimensional model, trade-off calculations are easier.

Panel Methods / Multicriteria analysis

Panel methods can be applied on different levels. They can be integrated in methods like the one of CML for the step of valuation.

Weighting by panels uses different methods of multicriteria analysis. In the simplest method, the weighting can be based on a negotiated consensus. Voting is another method for ranking different effects according to their importance. In multi-voting, panel members can allocate a certain amount of votes among the problem areas. An upper limit can be set on how many votes can be assigned to a single problem.

In a more sophisticated approach the criteria for evaluating the overall importance of an effect are defined in a first step. Each criterion is assigned a weight. Then every impact is scored for each criterion. The criteria scores are multiplied with the weights and summed for every effect.

In an analytic hierarchy process (AHP), the participants have to make decisions on priority effects based on a paired comparison. In the simple case of three effects this includes three comparisons:

A<->B, A<->C, B<->C

It is easier to decide about which effect is more important on a one to one basis then to assign weights to a whole list of effects. AHP provides the means to derive an overall ranking from the paired comparison.

An example for an attempt of defining weights, with a panel method, for different impacts has been done with 22 Dutch experts from research, industry, government, consultants, and environmental organizations [Kortman 1994, as mentioned in IWÖ 1994]. Table 3.2 presents the result. The weights the individual experts assigned to the impacts varied a lot.

Table 3.2 Weight of different environmental impacts according to a Dutch panel.

Global Warming	24%
Ozone Depletion	23%
Nutrification	22%
Acidification	18%
Human Toxicity	13%

In general one can expect widely varying results from a panel depending on the background of the members (profession, personality, nationality etc.), information provided to the panel, and the way questions are asked. If a panel method is applied, it should include a sufficient number of persons to result in 'average' weights.

Red Flag Methods

In a red flag method certain emissions e.g. of CFCs are red flagged if they occur in the inventory table. The product or process should then not be used. If the setting of a flag is independent of the quantity of environmental intervention, the method very quickly can become unworkable. In a detailed LCA flags will show up everywhere due to the long process chains. Nevertheless the method has a certain potential if thresholds are set for setting a flag. The advantage is that no impact assessment is necessary at all. It can be combined with other methods.

3.4.7 Comparison

In [IWÖ 1994] some of the above mentioned methods were applied to a global ecobalance. The functional unit was all known emissions and extractions from industrial processes. The individual weights of emissions/extractions vary strongly from method to method. The main reason lies in the fundamentally different approach towards impact assessment in some methods. Another, probably less important reason, is the different background data that were used for the methods, as some of them have been developed in different countries.

Some people conclude from this and similar studies that no valuation should be done. This is wrong. No valuation means that equal weights or fully subjective weights, based on intuition will be applied. In this case an arbitrary large 'error' must be expected.

The result of the comparative study is that

- In all compared methods, few impacts make up for most of the total impact score: In order to describe 95% of global impact scores, CML, Ecoscarcity, Critical Volumes, EPS and Eco-Indicator all only need between 15 and 30 emission and resource uses.
- Many methods (e.g. CML-based valuations, Ecoscarcity of Switzerland and Holland, Critical volumes, Quality-goal-relations) give high priority to the main acids (NO_x, SO_x).
- Many methods give high priority to 'global warmers' (CO_2 and CH_4 and others)
- Many methods give high priority to ozone layer depletors
- Many methods give relatively small priority to land uses
- Energy consumption and its emissions usually make up an important share of the total impact (or effect) scores.
- No method can formally integrate landscape aesthetics and radiation.

[IWÖ 1996, p.7]

3.5 Summary on LCA Indicators

The tendency in the LCA Community is towards multi-step explicit impact assessment as proposed by SETAC. The first steps in a multi-step method are based on a scientific background and the weighting in the last step is based on sociopolitical sciences and panel weightings. Eco-indicator is the method that has taken this approach the farthest so far but still leaves a lot of room for improvement. The availability of national or international goals for the individual impacts can help in the last weighting step.

Pollution and waste

- **Air**

For the important impacts of Global Warming and Ozone Depletion we have acceptable models available to derive indicators. The impact for Acidification as developed by CML needs improvement, which should be feasible. The severity of Winter- and Photosmog due to a certain amount of emissions depends on local conditions. More location specific models are therefore needed.

- **Water**

The emissions into water can contribute to Toxicity, Eutrophication, Chemical Oxygen Demand (COD) or Waste Heat. Indicators of toxic effects of emissions into water are described under 'Toxicity' below.

Nutrification is to a large extent due to Phosphorous from agriculture and wastewater. The sources for nitrogen are more diffuse if we take into account deposition from the atmosphere. It might make sense to neglect Nutrification in LCAs that do not depend strongly on agriculture or wastewater. CML developed an indicator that takes into account the Nutrification and COD by a simple aggregation method [CML 1992]. The damage from heat released into surface water is very local and difficult to be aggregated with the other effects.

- **Land / ground**

The direct emissions into ground are not part of today's indicator methods. Probably this is due to the fact that direct releases into ground are usually not allowed by environmental regulations. Accidental and unlawful releases are not included in LCA inventories. Also the damage is very local and depends on specific conditions. Emissions into the ground are often due to waste disposal (see below).

There seems to be a long term problem emerging with persisting chemicals and heavy metals that build up very slowly in the ground after being deposited from the atmosphere or being transferred into the ground by hydrological processes. An indicator that can track this phenomenon is needed. Probably the sources are very specific and a red flag method would be sufficient.

- **Toxicity**

As it has been shown above with the example of human Toxic Equivalency Potentials, there are indicators available that allow aggregating many chemicals in terms of their toxicity. For screening level LCAs, a single indicator that includes cancer and non-cancer effects and human as well as ecotoxicological effects is helpful. The problem with some of the toxic emissions into air or water is that they are not included in many of the LCA inventories. Many of the available inventories include sum parameters for classes of chemicals. A mean TEP should then be defined, although this might include a large error. Also a minimal set of critical chemicals, which should be included in any LCA, should be established.

- **Occupational Health**

Most LCA based indicators in use today do not include occupational health. Many substances are harmful if they occur in high concentrations or over long periods of time, as can happen at workplaces. If the same substances are diluted in the atmosphere they are no longer harmful. These substances are usually not included in LCA. In this study, Occupational Health did not get adequate attention. It should be further explored. Research on the inclusion of occupational health in LCA is going on. There also exist ideas to apply models similar to the ones presented on human toxicity, for indoor exposure to toxic substances. The main parameters are pollutant source, ventilation rate and toxicity of the pollutant.

- **Waste**

Waste is not an impact by itself but a predecessor for different forms of environmental impacts. Depending on the chosen way of disposal (dilution, combustion, dumping etc.) the impact can be very different. Even if the way of disposal is known, the impact will depend on local conditions. After the fate of different pollutants contained in waste has been modeled, we still need to identify its damage potential in terms of different impacts mentioned above. The prediction of damage from waste disposal therefore is difficult to integrate into LCA. Probably the most complete attempt in establishing a full down-stream inventory for waste disposal can be found in [Zimmermann 1996].

A more pragmatic approach simply sums the weight of waste and uses it as an indicator. In that case waste should at least be weighted according to different categories like inert waste, household waste, hazardous waste. Another pragmatic approach, taken for example by Norris, is to add disposal costs, which give some indication on how hazardous a certain waste type is [Norris 1998].

Resources

- **Land Use / habitat loss**

Land use takes a very special role among the resources that serve as input into our economy. The impacts from land-use are manifold. It includes the loss of arable land, habitat loss and landscape degradation in terms of aesthetics. Simply adding the surface can represent the first type. Habitat loss is much more difficult to quantify, as it also has to include a qualitative aspect of land use. The quantification of aesthetics is difficult. An attempt can be found in [Knoepfel 1995]. The CML indicator "Damage to Ecosystems" [CML 1992] is based on five different classes ranging from natural to fully sealed surfaces. A similar approach is taken in [Frischknecht 1996] where the unit of the indicator is m^2*year. The years are derived from the time it takes to bring land from one state to the next closer to the natural state.

It is important to improve the indicators for land use taking into account the resource, ecological, and aesthetic value of land. It is quite probably the difficulty in deriving such an indicator that led to the weak representation and general low weight of land use in indicator systems up to now. The Scientific workshop on Sustainable Development Indicators (Wuppertal, Germany) also identified a need for further research on 'space indicators', that take into account ecological implications and intensity of use of the space [SCOPE 1997, p. 390].

- **Minerals and energetic resources**

The development of characterization and valuation methods for resource depletion finds itself still in a preliminary phase. Most scientists see an inherent value in abiotic resources and 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. In the CML methodology scarcities for different materials are simply added. A Swedish method also takes into account a "Development Indicator", which takes into account the change of the rate of consumption for a resource over time. A high increase of use shows an increasing importance of a resource and it should therefore have more weight [Glaumann 1997].

The available data should allow deriving estimated use-to-stock ratios for most resources. The problem is rather the agreement on a methodology that is to be applied to derive an aggregated indicator.

Probably approaches of the economists in evaluating resource consumption in monetary terms should be reviewed. Economists have been working on this issue longer than the LCA community. They have developed different models in the context of national resource accounting.

As energy has a very special role, it seems reasonable to aggregate non-energy resources and energy resources separately. In an additional step sociopolitical or economic weighting could aggregate the two indicators.

- **Water use**

Water use shows up in some LCAs as a separate category. The weight of water use must be based on the local background data. In regions where it is abundant there is not need to show it explicitly. Impacts related to water use, like the energy used for pumping should be expressed in the according impact indicators.

- **Biotic resources**

No satisfactory indicator for biotic resource depletion is available at the moment. The linear combination of different scarcities of plants, animals etc. as it is done in [CML 1992] is not acceptable. Considering that the biotic resource consumption is of concern for a quite limited number of species and processes, a project specific indicator is probably more useful. For many typical LCAs biotic resource depletion might be negligible.

So far biodiversity indicators are limited to lists of endangered species, statistics on the amount of wilderness area etc. There is a lack of a practical indicator that measures the pressure on ecosystems from human activity. There seems to be an inherent problem in this task as it is highly complex and very difficult to generalize, as is required for LCA. In the context of LCA, the loss of biodiversity is basically entirely due to habitat loss. It seems therefore more reasonable to measure habitat loss than loss of biodiversity. Land use and pollution of air, land and water already cover to some extent habitat loss.

3.6 Conclusions on LCA Indicator

Some of the impact assessment and aggregation methods presented are better than others are, as was indicated. But not a single method is the correct one. The choice of the aggregation method depends on the application of the indicators.

A fully aggregated index like the Eco-indicator can be very useful for fast screening purposes. Necessarily different assumptions and simplified models have to be used in order to be able to aggregate quite different impacts. Certain important impacts may not be included at all due to the limits of certain aggregation methods. Different methods therefore come up with quite different results based on the same inventory. In a direct comparison, a product can only be considered as being superior if the difference is very significant.

In order to overcome the arbitrariness brought into the result by the choice of the aggregation method, some tools recommend using several aggregation methods in parallel. In the best case, the ranking of product choices does not change with the different methods, but this is not always the case. This procedure of comparing several highly aggregated indicators is contradicting the goal of aggregation.

The importance of certain impacts is case specific. It might be appropriate to neglect certain minor impacts in some cases. A normalization step shows the importance of an impact relative to the total in a reference area. It is very helpful to identify these minor impacts. Other impacts have a quite concentrated source and a red flag method can be sufficient to address the issue. Both procedures help to reduce the number of impacts that need to be weighted. For the remaining important impacts we should use the best available indicators. For some of them, like Global Warming Potential, there exist reasonably accurate indicators that aggregate emissions contributing to this effect. These well-developed indicators should not be watered down for the sake of a full but weak aggregation method. For some important impacts, good indicators are missing yet.

A full aggregation of this reduced set of indicators can be done by means of weighting by a panel. The panel should be well informed and use reference values, like national policy goals, where available. The final user of the method can also be involved in the last aggregation step. This last step is very transparent. The results of a product comparison on this aggregated level might be significant. Otherwise a more informed decision can be taken on the level of the individual impacts.

The possible framework as was outlined in this conclusion is in line with the "Bellagio Principles" presented above. It is an explicit organizing framework, with a limited number of key issues. It uses standardized measurements and reference values for weighting. The assumptions are explicit and the data can be made accessible to all. It is designed to serve a specific audience and it aims for simplicity in structure and use of clear language.

4 Buildings and Sustainability

Buildings have a major impact on many issues of sustainability. On a global level buildings account for one-sixth of the world's fresh water withdrawals, one-quarter of its wood harvest, and two-fifths of its material and energy flows. People spend 90% of their time indoors. But 30% of new and renovated buildings suffer from 'sick building syndrome' [Roodman 1995]. In the first part of this chapter we will look at the impact of different life cycle stages, different building systems, and different materials constituting a building. The second part considers emissions, material and energy flows through the whole economic system and the relative contribution of buildings. The aim of this chapter is to find orders of magnitude for the impacts and flows mentioned. For a particular case the exact figures can vary considerably from the following general numbers.

4.1 The Contribution of Different Life Cycle Stages

Figure 4.1 shows a building's life cycle. It begins with the extraction of raw materials. The mined raw materials have to be transferred into commercial materials and products. Between most stages, materials are transported. So-called final energy or site energy (electricity, fuel), which is necessary in all stages, undergoes a 'production' process as well. In the construction phase, building materials and products are assembled into a building. A similar process continues for the maintenance and renovation of the building over its useful lifetime. All these processes that occur before the building is used, are called upstream processes in terms of life cycle assessment. The operation phase represents the time where the building performs its service. At the end of its lifetime, the building is demolished, or better deconstructed and the materials salvaged, recycled, recovered, or disposed. These last stages are called downstream processes.

The main question to be answered is: What are the technical and achievable opportunities to reduce the impacts of the upstream processes relative to those opportunities for building operation? Achievable are those technically feasible opportunities that are viable in the market. In order to compare the different life cycle stages, we have to make an assumption on the duration of the operation of the building. In the following a useful lifetime of 50 years is assumed in accordance with most authors. In Europe, houses tend to have a longer lifetime than in the United States. Some authors therefore use a lifetime of 80 years. Those data have been adjusted to a 50 years lifetime, to make them comparable. Individual components can have a shorter lifetime and are replaced several times in over the full building's lifetime.

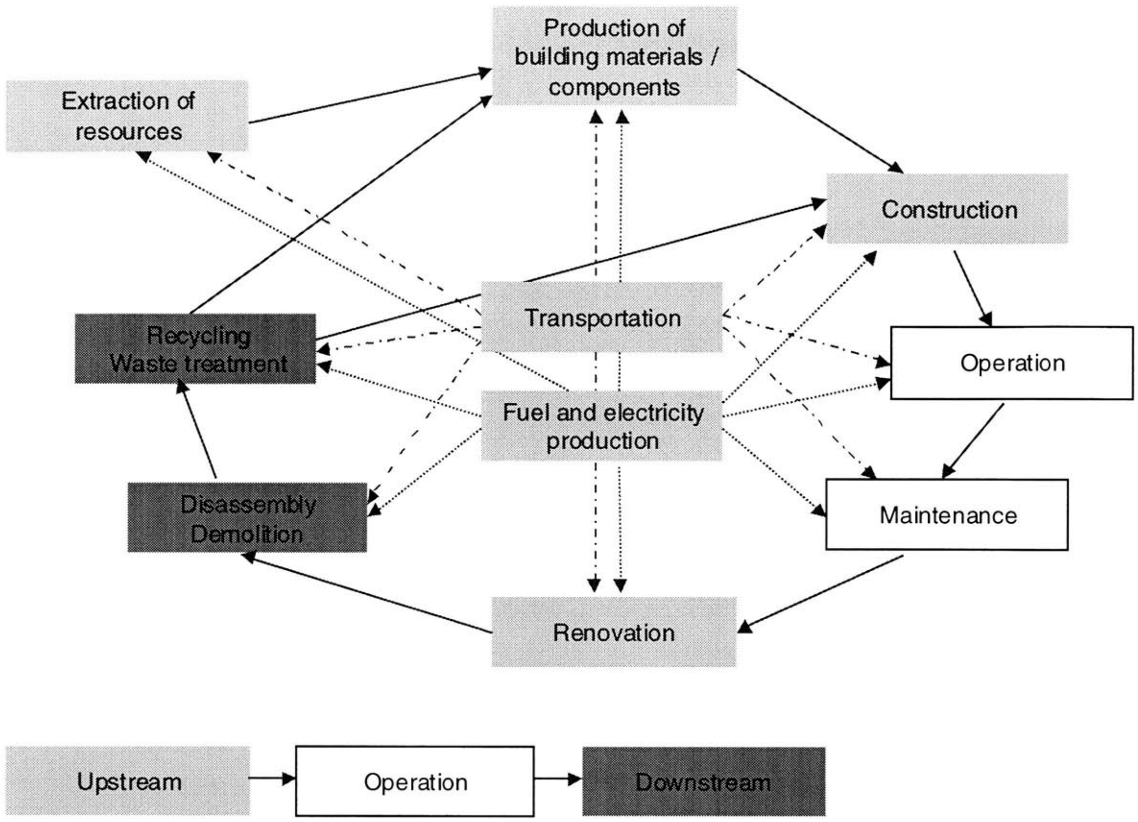


Figure 4.1 Life cycle stages of a building

For the upstream impact, the necessary renovations are added to the initial construction. Operational energy is summed up over 50 years. Another methodology would be to express the years necessary until the energy for building operation equals the energy embodied in building materials.

Most data available only consider direct and indirect use of energy. Not very many data are available on other emissions that would allow considering other emissions. As embodied energy has a relatively high correlation with other environmental impacts, it is used here to estimate the orders of magnitude of different life cycle stages, material groups and building systems. All energy is expressed in terms of primary energy. Not all sources make an explicit distinction between renewable and non-renewable resources. Where such information was available, only non-renewable energy was included. In particular for wood this means that only the energy necessary for wood harvesting, processing and transportation is included, but not the energetic value of wood itself. In countries with a high amount of electricity from hydro, numbers will in general be lower.

4.1.1 Embodied Energy in New Construction and Renovation

The upstream processes-extraction of resources, production of materials and energy, transport, and construction-represent the embodied energy. The numbers in Table 4.1 vary not only due to different building technologies, but also due to different definitions of the system boundaries for LCA. Not all of the data entries include infrastructure for manufacturing (machines and buildings) and transportation (roads and trucks), manpower, transportation (direct energy use for transportation), construction process (energy used on the construction site) and mechanical and electrical systems installations and finishes.

Many sources do include the transportation of materials to the construction site, but not the energy used on the construction site. In one of our earlier studies at EPF Lausanne, Switzerland, we estimated the primary energy for electricity used on site for the construction of a multi family unit [Gay 1997]. It turned out to be less than 2 percent of the total upstream energy consumption. This number can certainly change under particular conditions.

The energy for material processing in production of more complex building components is often neglected due to the lack of detailed data. This means a boiler would simply be represented by the mass of steel, plastic etc. but all the energy used in manufacturing and waste produced is neglected. This is more true of mechanical and electrical systems, where the processing energy is higher per unit mass than in the structural elements of a building. As structural elements are much less diverse, for most of them data are available.

Finishes and mechanical and electrical systems can account for around 2 GJ/m2 of floor area in a residential building [Gay 1997]. Neglecting them will therefore produce significantly lower results.

Another major difference stems from the definition of floor area, which is not explicitly cited in some studies. Whereas some count gross floor area, in other studies it is limited to net area, excluding storage rooms, corridors and garages. In our earlier study, which serves as base case, we counted net floor area, but measured from the exterior perimeter of the building, i.e. wall cross section around useful floor area is included [Gay 1997].

Most of the studies cited in Table4.1 do not include the service sector of the economy. This includes all kinds of services like financial institutions that serve industry in general, but also the services of architects and engineers for a building in particular. As Norris showed on an input output-based LCA approach, this can increase the values significantly [Norris 1998].

The data in [Gay 1997] are based on a very detailed upstream inventory for building materials and for the process energy necessary to extract, transport and manufacture them. Not included are the inputs associated with the service sector and labor. The building is heavy; walls and facades are mainly made of concrete.

The numbers of [Buchanan 1993] are significantly lower; obviously there are differences in defining the functional unit and boundary conditions. Nevertheless, Buchanan's study gives a general indication on how much a 'good' building can differ from a 'bad' building in terms of embodied energy. This difference is more than 3GJ/m^2.

Table 4.1 Energy embodied in initial building construction per m^2 of floor area

~8 GJ/m²	Average residential, Germany	[Geiger 1993]
7.7 GJ/m²	Multi family, concrete structure and walls, 1,870kg/m², Switzerland	[Gay 1997]
5.0 GJ/m²	Multi family, Germany	[Feist 1996]
4.1 GJ/m²	Single family, lumber construction walls, concrete basement, ~1,300kg/m², Michigan, US	[Blanchard 1998]
3.6 GJ/m²	Single family, light structure, Sweden	[Adalberth 1996]
5.5 GJ/m²	Single family, concrete floor, brick walls, steel framing, aluminum windows, no interiors, New Zealand	[Buchanan 1993]
2.3 GJ/m²	Single family, timber floor, weatherboard walls, timber framing, wood windows, no interiors, New Zealand	[Buchanan 1993]
3-5 GJ/m²	Different Indian houses	[Debnath 1995]
3.7-5.6 GJ/m²	Five-story office, lower bound: timber structure, upper bound concrete structure, New Zealand	[Buchanan 1993]
8-12 GJ/m²	Offices, ~1,000kg/m² (mixed structure) to ~2,200kg/m² (mainly reinforced concrete structure), input-output based data, Japan	[Tatsuo 1993]

Tatsuo's study is done on six different office buildings. The total weight of the lightest building with a steel structure is around 1,000kg/m². The heaviest with a large amount of reinforced concrete weighs about 2,200kg/m². The most efficient in terms of embodied energy is not the lightest building, but the one which scores relatively low in embodied energy in structure, very low in finishes and average in mechanical and electrical systems. The generally high numbers might be due to higher investments in finishes compared to residential buildings, but probably mainly due to the input-output approach that is taken. Input-output tables include all economic activities, including services, that go into a sector and are therefore more complete than a bottom up process chain analysis, where services are usually neglected.

Including structural elements, mechanical and electrical systems, and finishes, the bounds for a typical light weight building using materials with low embodied energy (timber frame, and wood windows, low energy finishes etc.) seems to be around 4 GJ of embodied energy per square meter. For a heavier building, using for example reinforced concrete, steel and fired clay bricks for the building structure, aluminum windows etc., the embodied energy is around 7.5 GJ/m². Extremes that pass these boundaries do certainly exist. If the service sector and labor is included, these numbers will be higher.

Major Building Systems

A building is made of different functional elements. The three main constituents are structure of the building, interior and exterior finishes, and mechanical and electrical systems. The structural part can be very different depending on local construction types. This is in particular true for residential buildings. In Switzerland, a residential building is often made of a double fired clay brick wall with insulation in the cavity. Timber based structures and single brick walls with exterior insulation and siding are common too. In the United States most houses are based on 2 by 4 studs with insulation between the studs, exterior siding and plasterboard inside. In China until recently most external walls in urban areas were uninsulated 24cm or 36cm solid fired clay brick. Today one of the construction types is made of one foot thick solid concrete walls. The impact of the building structure on the life-cycle energy can therefore vary a lot. With a heavy concrete or steel structure, the contribution of the building structure tends to be more important than mechanical and electrical systems, and finishes for the initial construction [Gay 1997, Feist 1996]. For a timber frame building, the structure tends to be less important than mechanical and electrical systems and finishes at initial construction.

Kohler concluded from his study of different types of buildings that no simple dependence between the type of structural materials and the total environmental impact exists [Kohler 1994]. It can not be said for example that a wood structure always will perform better than a concrete structure building. Reducing mass, and improvements in recyclability and durability can all help to keep the environmental impact low for both building types.

Over the lifetime of the building, most of the mechanical and electrical systems, and finishes are replaced or renewed during **maintenance and renovation**, some of them several times. For academic laboratory buildings in the United States, the first renovations usually occur within the first five years of occupancy, sometimes even *before* owner occupancy. Finishes therefore gain more weight compared to the building structure. In the study by Blanchard and Reppe, polyamide in carpets became the most important single material contributing to embodied energy due to its replacement every eight years [Blanchard 1998]. Similar results were found by the study of the Swiss multi residence home. Considering the embodied energy over the whole lifetime, floor and wall coverings became very significant. In both studies renovation and maintenance contributed about an additional 60 to 70% of the initial embodied energy over 50 years. Some other studies assumed lower values for the embodied energy due to renovation, others calculated up to 100% of the initial embodied energy for renovation in 50 years.

Building Construction Materials

The impact of a building can also be sorted by building materials, as has been done by different authors. Table 4.2 shows the composition of a typical German single family residential unit. In terms of mass; stone, gravel, and sand are dominant. But these materials are low in embodied energy. Due to their large mass, transportation can become an important factor, if they are transported over large distances. The material data in Table 4.2 include transportation only from 'cradle to gate', meaning that the last transportation step to the construction site is not included.

Fired clay bricks can have a significant impact if they are used in large quantities. Concrete Blocks have a lower embodied energy.

Steel is the non-mineral material used in the biggest quantities in construction. Depending if it is reinforcement bar made from recycled steel or high quality structural steel, the embodied energy varies about between 13 and 38 MJ/kg.

The rest of the materials are used in small quantities relative to the total mass of the building. On the other hand they can have a very high content of embodied energy. A piece of machined virgin aluminum has an embodied energy of about 400MJ/kg. This specific embodied energy is nearly ten times as high as the specific energy of fossil fuel.

Insulation usually does not have a critical impact. It is low in weight and has a medium energy content.

Paint, caulks and sealants, adhesives and many specialty materials do not have a high contribution to the embodied energy of a building. But even though used in relatively small quantities, they are often the source of other toxicity related problems. Often their quantity is not well known. More and more traditional building materials and even more so compound materials contain different chemical additives unknown to the builder and even less to the building owner.

Dividing the total building mass by the total embodied energy we get an average embodied energy for the materials. In [Blanchard 1998] and [Gay 1997] the average energy content is about 3-4MJ/kg.

Table 4.2 Typical composition of a German single family residential building [Enquete 1998, p.140] and embodied energy of materials [Weibel 1995]

Weight [metric tons]	Material	Embodied energy [MJ/kg]
190 t	Stone, Gravel, Sand	0.09-0.3
100 t	Blocks, Bricks	0.8 - 2.7 (concrete block - fired clay)
29 t	Cement	5.2
20 t	Steel	13.0-38.5 (reinforcement bar - structural)
10 t	Wood	3.6-6.5
1.2 t	Aluminum Copper Plastic Glass	400 (structural, not recycled) 100 80-140 15
<1 t	Insulation Paint, Caulks and Sealant, Adhesive etc.	18-95

We can see that the weight of the used material is about inverse to the content of embodied energy. We have high masses with low energy and low mass with high energy. The result is a distribution of the embodied energy over many materials and many building elements.

In general we will not have a single source that is dominant. But all types of materials -large quantity / low embodied energy; medium quantity / medium embodied energy, and low quantity / high embodied energy-have the potential of playing an important role.

The building is the sum of many small elements. If we want to lower the embodied energy, we have to carefully choose the elements and materials in every design decision.

Norris came to a similar conclusion by an input-output based life cycle analysis [Norris 1998]. From the 400 inputs into his case study building, no single input dominated the upstream burden for any of the environmental indicators studied. The indicators included emissions of VOCs, NOx, CO, SO_2, PM_{10}, CO_2, Toxics included in the Toxics Release Inventory, and Waste. Top ranking inputs accounted for between 4% and 6.7% of total upstream burdens only. On the other hand he showed that the top 25 inputs together account for roughly half and the top 50 inputs together account for about 70% of the total upstream burden.

Manufacturing, Transportation and Construction Processes

In many studies, the building LCA is limited to a summation of the environmental impacts from the material masses. Manufacturing, transportation and the construction process are neglected.

In the study for a residential building in Switzerland, transportation of the building materials from the material suppliers' depot to the building site added only about 4% on top of the materials environmental impact. But transportation distances in Switzerland are relatively small compared to countries like the United States, where transportation distances are much higher. Not included in the Swiss study was the transportation of the workforce. The inclusion of construction site activities was limited to electricity consumption on the site. This only added about 1.6% on top of the materials impact.

Neglecting manufacturing will underestimate the embodied energy in particular for any equipment used in mechanical and electrical building services. This is also true of more highly processed materials.

Infrastructure

Little data is available on the impact of infrastructure. Cretton compared the infrastructure for the old central part of a Swiss village, which has a density of 32 persons per hectare, with a neighborhood built in the late 70s. This has a density of 17 persons per ha [Cretton 1997].

Roads consumed half of the embodied energy of all infrastructures. Regional roads that serve the village are included pro rata of usage. All other systems are only included in the perimeter of the village. The water supply system consumed about a quarter of the embodied energy at the time of construction. Sewage system, electricity supply, and natural gas share the rest. All systems are run underground. Taking into account the lifetime of the different systems, the construction of the infrastructure for the village center consumes about 100MJ per square meter of floor area served and year. For the less dense neighborhood this value was about 160MJ/ (m^2*year), which is 60% higher.

The operation and maintenance of infrastructure also requires direct and embodied energy. The consumption of electricity is dominant. Electricity is mainly used for the lighting of streets, pumps in the water supply systems, and wastewater treatment. Also included in this calculation are transmission losses in lines and transformers in the considered perimeter. They account for about 30MJ/(m2*year). The total operational energy nearly doubles the total primary energy consumption of the infrastructure. It is about 190 MJ/(m2*year) for the village center and about 300MJ/(m^2*year) for the less dense neighborhood. In Figure 4.2 the energy necessary for the construction and operation of the infrastructure is summed over 50 years and compared with the embodied energy for the construction and renovation, of a building. Building operation is not included and will be presented in the section below. As we can see, in the neighborhood with 17 persons per hectare, the energy for the construction, renovation, and operation of the infrastructure is higher than for the construction and renovation of the building.

Taking into account overland transportation of water, electricity and gas, infrastructure will factor in even more.

A Japanese study of the urban area of the Kanto region got similar results [Tagashira 1997]. The whole Kanto region has a population density of about 12 persons per hectare. But it also includes highly populated areas like Tokyo, where infrastructure can be used much more efficiently. The CO_2 emissions of infrastructure systems, which included roads, electricity supply, gas supply, and water supply, were compared to buildings. Construction, maintenance, and dismantling, but not the energy for operation, were considered. Roads dominated for infrastructure, causing 65% of the infrastructure related CO_2 emissions. Buildings incorporated about 40% more of CO_2 emissions than the whole infrastructure. These ratios are quite similar to the results of Cretton's results before taking into account the operation of infrastructure.

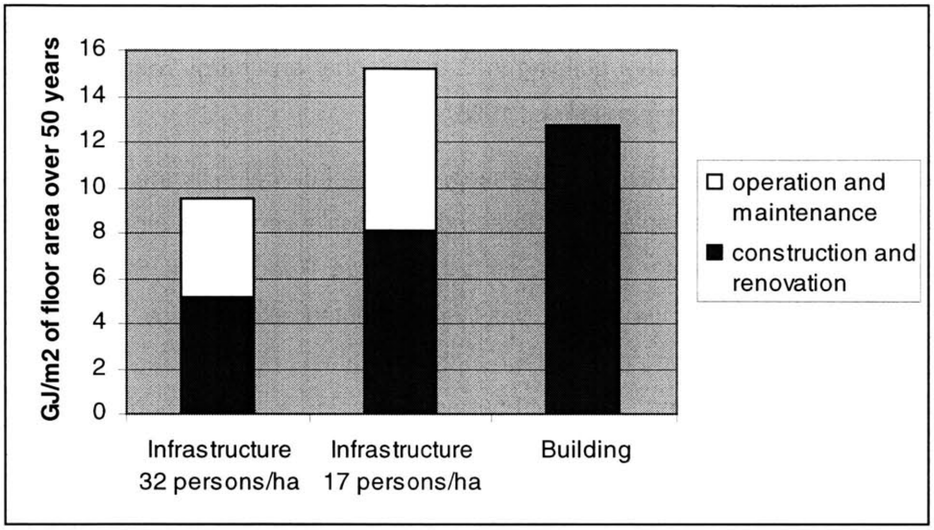


Figure 4.2 Embodied energy for the construction, renovation, and operation of infrastructure compared to the embodied energy of building construction and renovation over 50 years. Infrastructure includes roads, water, electricity and natural gas supply (data from [Cretton 1997]).

4.1.2 Operation

The energy used for heating and cooling of a building will depend on the climate. The following examples are for a climate that corresponds more or less to the 'climatic region II', as can be found for example in Boston. Heating is dominant and temperatures below freezing are common during the winter months. In summer temperatures above 30ºC will only occur on some days in the summer.

The second major parameter is the quality of the building envelope and the ventilation system. The energy requirement for a typical existing building in New England is about 1,023 MJ/m^2 of floor area. This corresponds to about 1,100MJ/m^2 (100,000Btu/ft^2) of site energy, representing the fuel that is delivered to the building. To calculate the site energy, we have to take into account losses of the heating system. An assumed boiler efficiency of 90% adds 11% on top of the basic energy requirement of the building. For older houses this is an optimistic assumption and does not reflect the large potential in energy savings by using more efficient boilers.

The Swiss or German average house is built a bit more airtight and has better windows. The energy requirement is about 888 to 1,110 MJ/m^2. These values are about four times as much as the new German building code obligates. Good insulation, good windows and reasonable airtightness can achieve this requirement.

To lower the energy consumption in a cold climate even further, requires controlled ventilation with heat recovery. With 160 MJ/m^2 the Swiss 'Minergie" label sets the threshold at half the value required by code. Feist demonstrated in a passive building in Germany that an energy requirement as low as 54 MJ/m^2 can be achieved by simple means [Feist 1996].

There are two basic strategies for a zero heating energy building in a cold climate. In most cases the necessary solar heat is harvested by solar collectors and stored in a very large storage tank to bridge the coldest days with no sun in winter. In a building by Andrea Rüedi in the Swiss Alps only the building mass serves as the storage device for passively collected solar energy. This was possible because long periods without sunshine are rare high in the mountains on the slope where the building is located. For the worst case of several days without any sunshine a small wood stove can provide the little heat necessary [Notter 1995].

The values presented in column 1 of Table 4.3 present the energy requirement of the building not taking into account losses by the heating system. Column 2 shows site-energy. Taking into account the upstream process chain until the fuel is in the house adds about another 15% for fuel oil [Frischknecht 1996]. This value was used to calculate the third column of primary energy.

Table 4.3 Final energy demand for heating of residential buildings per m^2 of floor area

Building Load	Site-energy	Primary energy	Location / Type
1023 MJ/m^2	1,135 MJ/m^2	1,305 MJ/m^2	Typical New England existing
800-1000 MJ/m^2	888-1,110 MJ/m^2	1,000-1,250 MJ/m^2	Swiss / German average
252 MJ/m^2	280 MJ/m^2	315 MJ/m^2	New German building code
160 MJ/m^2	178 MJ/m^2	200 MJ/m^2	Swiss 'energy-star' (Minergie)
54 MJ/m^2	60 MJ/m^2	67.5 MJ/m^2	Passive house by Feist in Germany

The energy required for hot water is small compared to the energy for heating in an average building. In an energy efficient home however, they can be of the same order. The standard value for energy calculations in Switzerland is 80 MJ/m^2. The spread of real values can be very large depending on the floor space per person and user behavior. For the conversion into primary energy 25% are added. If the water is heated by electricity, a factor of three for the conversion has to be applied. The energy consumption for hot water can be met by using solar energy. Standardized systems allow harvesting half or more of the required energy with solar collectors for modest extra costs. An installation that covers 100% of the hot water requirements will become much more expensive as the collector and storage tank have to be much bigger.

Table 4.4 Energy for hot water in residential buildings per year

Site-energy	Primary energy	Location / Source
90 MJ/m^2	100 MJ/m^2	Swiss standard calculation (SIA 380/1)
115 MJ/m^2	144	Average of all US Households [EIA 1995]
~120 MJ/m^2	150	'standard home' [Blanchard 1998]

The electrical consumption of a building can vary a lot depending on the type of appliances installed. The 90 MJ/m^2 for typical Swiss and German residential buildings in Table 4.5 are the case where electricity is used for cooking, but not for hot water and air-conditioning. The European average efficiency for electricity production and delivery is about 33%, meaning two thirds of the energy contained in the fuel that goes into the power station are lost due to power station limitations and losses in the distribution network [Frischknecht 1996]. The efficiency has been calculated on the basis of waste heat, as the specific energy of nuclear fuel depends on definition. In other countries with a large fraction of fossil and nuclear thermal electricity, the efficiency is similar. A factor of three is therefore applied for the conversion of final to primary energy.

The average US household consumes 63.4% of its electricity for appliances (lighting 9.4%, TVs 7.4%, clothes dryer 5%, freezer 4.2%, range/ovens 2.8%, others 20.7%) and refrigerators (13.9%). With a total electricity consumption of 962 billion kWh and a total floor area of 181.2 billion sq. ft. this equals 129 MJ/ m^2 [EIA 1995].

Table 4.5 Electricity in residential buildings for appliances and refrigerator per year

Site-energy	Primary energy	Location / Source
100 MJ/m^2	300 MJ/m^2	Typical Swiss and German residential
129 MJ/m^2	387 MJ/m^2	Average of all US Households [EIA 1995]

Commercial Buildings in the United States for a comparison have an average site-energy consumption of about 1,020MJ/(m^2*year); most of it if for space heating, followed by lighting, water heating, cooling, office equipment and others. Converting electricity consumption into primary energy triples these values. The total primary energy consumption per square meter is about 1900MJ/(m^2*year). Lighting then ranks first, requiring nearly twice as much energy as space heating. Cooling and Office equipment rank third and fourth in terms of primary energy [EIA 1998].

4.1.3 Demolition / Disassembly

Different studies, for example [EQUER 1997, p.91], show in general a relatively small impact of the demolition activity for regional and global issues. Only if masses are large and transport distances to treatment sites long, does transport have a significant impact. This is in principal due to a small energy consumption of the necessary machinery and transportation vehicles in a typical case relative to the lifetime impact.

The values found in different studies vary between less than 1% [Blanchard 1998] to around 10% of the initial embodied energy. The values will depend a lot on the scenario for the building demolition or disassembly assumed.

On a local level the disturbance due to dust, noise and effects of transportation can be high, but they are limited in time.

Depending on the system boundary definitions for the life cycle analysis, material salvage for reuse can be accounted for as downstream expenditures of the house being disassembled (waste) or as upstream expenditures of the building where it is going to be reused (product). The criteria often applied to draw the line between 'waste' and a 'product' for reuse is the state in which a material's economic value is zero. This means a third person is willing to pick up the material without getting paid any disposal fees. As it has been shown in different studies, e.g. [Yost 1997], the added labor cost can be offset by avoided disposal cost and the value of salvaged materials. The additional cost/gains depend on the local cost for landfill, labor, transportation and the availability of local recycling outlets. Landfill costs generally tend to increase while more deconstruction with reuse of materials, closed loop recycling (e.g. steel), and open loop recycling or downcycling (e.g. concrete) can be expected in the future.

4.1.4 Overview Over the Whole Building Life Cycle

Figure 4.3 integrates the results presented above. All energy usage is summed over 50 years. For the embodied energy, the Swiss building from [Gay 1997] with an embodied energy of 7.7MJ/m^2 has been taken as base case. For the embodied energy of the New England Building, the data from the Michigan house with 4.1MJ/m^2 has been used. To achieve this difference of 3.6MJ/m^2 a much lighter structure and generally lower material energy intensity at the time of construction would be necessary.

Renovation over the fifty years has been fixed in general by 70% of the initial embodied energy. For the New England house, the same quantity for renovation is used as for the Swiss building. It was assumed that the lighter and probably less durable construction of the Michigan house will not result in lower renovation expenditures than the more solidly built house, in fact even the contrary might be true.

Demolition has been fixed to 10% of the embodied energy of construction and renovation. Hot water is based on 90MJ/m^2 of site energy. Electricity was fixed at 100MJ/m^2 of site energy for the base cases.

The first building, presented in column 3, is the case of a typical New England building. The 50 year lifetime primary energy consumption is close to 100 GJ per square meter of floor area. This equals the energy contents of 3150 liters of fossil fuel (77.4Gallons/ft^2). That amount of energy would just about fit into the building if it were filled to the roof with fuel oil!

If we multiply that quantity with the average U.S. residential floor area per person of 52m^2 and use it as car fuel, we could drive 44 miles a day with it. The fuel efficiency of the car has been assumed to be 8.6l/100km (27.5mpg). The primary energy content of the car fuel takes into account exploration, refinery, transport from the oil field to filling station etc. and is 60MJ per kg of fuel [Frischknecht 1996]. As we can see, the location of a building, access to public transport, and mobility behavior of the inhabitants is very important. Taking car fuel into account, a low energy building set somewhere in a remote area whose owners commute to work every day with their private cars can have a higher environmental impact than an average building located in walking distance of daily commuting points or with access to public transport.

The second column shows the primary energy needs for the construction, maintenance, and operation of the necessary infrastructure for a population density of 25 persons per ha. It is about of the same order as the energy embodied in the construction and renovation of a building. Again the location of the building proves to be important. If the buildings are connected to the main infrastructure systems, the investments in infrastructure will surpass those for the buildings in low-density areas.

Column 4 and 5 show a Swiss average building and one built to actual code. We can see that a building that follows actual building codes will already have a significantly lower lifetime energy consumption.

The Swiss 'energy star' (Minergie) building consumes about 25% of the energy for heating of an average building and half the energy of a building built to code. Electricity consumption has been assumed to be 30% lower by using more efficient appliances. A high estimate of 0.5GJ/m^2 for additional initial investment in energy reduction measures has been taken into account. This increase in embodied energy does not have to be. The energy efficient building in [Blanchard 1998] corresponds about to the Swiss 'energy star'. By choosing low energy materials, Blanchard and Reppe were able to lower the energy for building operation by 67% and at the same time the embodied energy by 4% compared to the standard building.

The Minergie label is a voluntary program. The new compulsory building code in Germany will achieve a similar reduction by a factor of four compared to average buildings; where the average consumption in Germany is about 30% higher than in Switzerland.

The next step is a passive house, which is a building with a heat requirement so low, that no separate heating system is necessary. The supply air can distribute the little heat required. This is achieved with very good thermal insulation (U-value <0.15 W/m2K), high airtightness (n50-values <0.6h-1), superglazing (U-value <0.8 W/m2K), solar transmittance >50% and a ventilation system with high efficiency heat recovery [Feist 1996]. As Feist showed, by careful design the embodied energy in such a building can even be lower than in a standard building. Some of the additional measures are also offset by the gains in the avoided heating system. This is true for embodied energy as well as for costs. For our comparison in Figure 4.3 the embodied energy in the construction was elevated by 0.7GJ/m2 compared to the prior building, assuming the installation of a grid connected PV system that cuts the net electricity consumption from the grid in half.

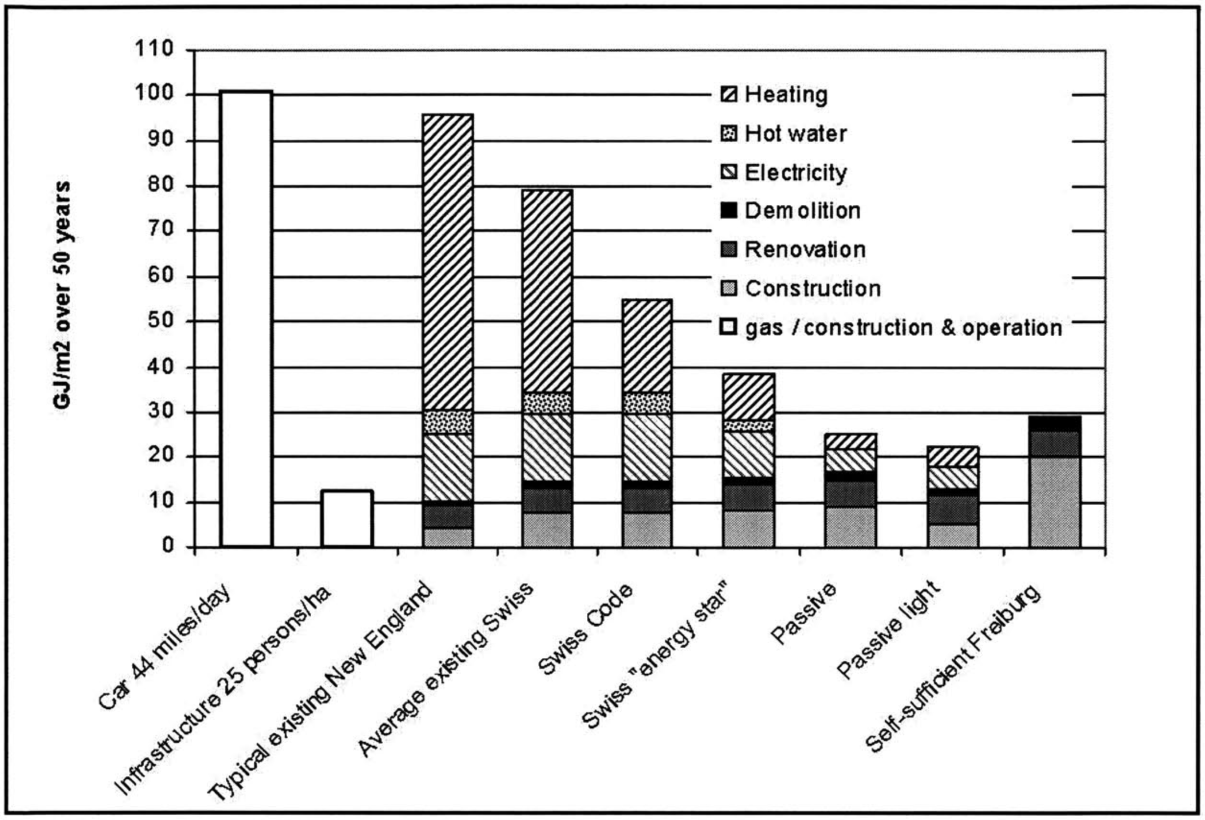


Figure 4.3 Primary energy consumption of residential buildings over 50 years.

The first passive building presented is a heavy construction with some energy intensive materials. A more careful choice of the building materials should allow reducing the embodied energy by the 3.6GJ/m2 that were the difference between the llight American versus the heavy Swiss building. Again no credit was given for the renovation inputs compared to the normal passive building. Energy requirements for heating have been increased by 25%, as a low-mass passive building can not make use of solar energy as well.

The last column shows an energetically self-sufficient house in Freiburg, Germany. The data reported by Geiger show an increase in lifetime energy for the step from a passive low energy house to a fully energy self-sufficient building [Geiger 1993]. This is due to the large storage devices -tanks for thermal energy and batteries or hydrogen generators and fuel cells for electricity - to bridge the periods of low solar irradiation.

The economic optimum of direct costs depends on local fuel prices and would probably be around the Swiss code or Swiss 'energy star' building. If we also take into account external costs for different environmental and human health impacts, the optimum can be expected to be much closer to a passive building.

For the Untied States offices tend to be more energy intensive than lightweight residential buildings at the time of their construction. Taking into account the higher turnover rate for the interiors and renovations, offices will have significantly higher lifetime embodied energy than residential buildings. For operation they also have a higher electricity consumption than residential buildings, which results in a high primary energy consumption.

All the examples presented were based on primary energy, since this data is most readily available. If we look at other environmental effects, the relative importance of embodied impacts can be much higher. The Swiss residential building presented above was heated by natural gas, which is low in emissions that contribute to Acidification. Electrical conversion into primary energy and emissions was based on a European average. In terms of embodied energy, building construction and renovation accounted for 16% of lifetime energy consumption. But the embodied emissions contributing to Acidification represented 40% of the lifetime emissions. The importance of embodied versus operational had been increased by a factor of two and a half looking at emissions of Acidification instead of embodied energy [Gay 1997].

4.1.5 Conclusion

The location of a building can have a more important impact on lifetime energy than the building design itself, if transportation and infrastructure are taken into account

Embodied energy in infrastructure is of the same order of magnitude as the embodied energy in the building construction and renovation.

For an average existing home, the energy embodied in materials and construction processes including renovations is small (10%) compared to operational energy over 50 years.

For an energy efficient home, with a lifetime primary energy demand of less than 50 GJ, embodied energy contributes about 20% or more of the total.

In a highly efficient passive house with very low operational energy of around 60MJ/(m^2*year), embodied energy can account for more than half the total lifetime energy demand.

In a specific case a particular building system can be dominant. The building structure can make an important contribution at the time of construction, but finishes and mechanical and electrical systems are replaced several times over a building's lifetime and gain therefore importance in a lifetime view. But no building system or construction material tends to be always dominant. It is the sum of many small elements that make the lifetime-embodied energy of a building.

Considering effects like human toxicity or Acidification can significantly increase the relative importance of the impacts embodied in material and construction processes for all types of buildings.

To achieve a sustainable state of the building stock, we have to take into account the slow renewal rate of buildings. A new building should therefore be four to ten times as efficient as an existing average building in lifetime energy consumption and emissions. In such a building the embodied impacts are important or even dominant.

4.2 Buildings, Pollution, and Waste

In the chapter above, we have seen the relative importance of different life cycle stages. But how do the building related emissions compare to the overall emissions? In a German study, which was based on sectors input-output tables, the following percentage of emissions relative to the overall national emissions was calculated for the building construction industry and its supply sectors: CO_2 5.7%, SO_2 6.2%, NO_x 7%, particles 7.4%, CO 4,4%, CH_4 2.4% and non-methane-VOCs 21%. This compares with 5% of the primary energy used in the same sector [Achternbosch 1998]. These emissions occur mostly at building material manufacturers and some on the construction site. Not included is the operation of buildings.

Norris did a similar calculation for the U.S. He identified the upstream CO_2 emissions for each of the 500 sectors in the U.S. economy [Norris 1998b]. Upstream emissions for the building sector were roughly 82 million metric tons of carbon equivalents, which is also 5.7% of the countries total CO_2 emissions.

In Table 4.6 those 5.7% are spread over 'Industrial' and 'Transportation fuel'. Some is also included in 'Commercial' buildings, for the buildings in which services for the building industry are provided. In addition to these emissions by the building industry, there is a much larger percentage of direct emissions from operating the buildings. As we can see the operation of residential and commercial buildings is responsible for a total of 36% of the U.S. CO_2 emissions.

Table 4.6 CO_2 emissions in the United States 1996 in Million Metric Tons of Carbon Equivalents [EPA 1999]*

Sector	MMTCE	%
Residential [1)]	286	20
Commercial [1)]	229	16
Transportation Fuel	477	33
Industrial	445	31
Total	1437	100

* emissions from fossil fuel combustion by electric utilities are allocated based on electricity consumption by each end-use sector. Excluding US territories.

[1)] Operation only, construction and materials are included in 'industrial' and 'transportation'.

The share of the building materials and construction sectors can be much higher in emerging countries like China. Cement manufacturing accounts for less than 1% of the total CO_2 emissions in the United States, and for 2.3% in Europe, but for 5.6% in China.

Besides these emissions which occur upstream of the building construction and during the operation of a building, there are also toxins that are contained in building materials. They include two important groups: organic substances and heavy metals. Heavy metals usually only represent an immediate threat to workers and inhabitants in the form of wood treatment. They are very persistent and can still be found in demolition waste. They are a hazard for people and the environment if washed out during the use phase of the building, if emitted in form of particles during demolition or if released into the atmosphere by construction waste combustion. If materials are recycled, heavy metals are carried along in the same cycle. Organic materials are typically less persistent but they represent a bigger hazard to workers and inhabitants. Substances with a low boiling point tend to be a hazard for the worker, substances with a higher boiling point a hazard for the inhabitants [Achernbosch 1998].

4.2.1 Waste

By far the world's largest amounts of waste in terms of mass are mining residues. This includes the top layers of soil and rocks that have to be removed to access the ores, tailings from mining, and the metallurgical waste after the metals have been extracted from ores. As we will see below, construction is responsible for a large fraction of the mining activities and therefore also for its wastes.

In Germany about 50% of all waste comes from construction sites and demolition, i.e. it equals the total of the other waste streams. Construction and demolition waste is equal to municipal garbage in the United States. Municipal solid waste was 188 million tons in 1993, or 725kg per capita in the United States [Wernick 1996].

These huge waste streams could be largely avoided for both the construction and the demolition phase of a building. In a project for a commercial building waste sent to landfill during construction was reduced by 75%, compared to traditional ways of disposal [Schurke 1997]. Similar numbers have been reported for the demolition of buildings. In the deconstruction of an ordinary home, 70% by volume of all materials from the building were salvaged or recycled [Yost 1997].

1,200 of Fort Ord's 7,000 buildings have to be torn down because they do not meet building codes and contain hazardous materials. Facing demolition and disposal costs of over $100 millions they decided to dismantle the buildings. Salvagers reclaimed up to 90% of the materials. If recovery went down to 75%, the costs for deconstruction would only have been half as much [Block 1997].

From the three examples above, we can expect that around three-quarters of construction waste can be salvaged with little extra costs, by disassembling buildings.

4.3 Buildings and Environmental Resources

4.3.1 Energy

The pattern of energy use in the United States in the mid 1990s is shown in Table 4.7. Buildings consume more than one-third of the total U.S. primary energy and almost two thirds of electricity. The pattern is broadly similar in other industrialized countries and urban areas of developing countries. In 1992 buildings consumed 34% of the total energy in the world. Even with the actually low energy prices in the US the average household spends almost $1,300 per year on energy [EIA 1995].

Besides this direct consumption, the manufacturing and transportation of building materials consumes about another 9% of the total United States energy consumption [Roodman 1995,p.24]. Direct and indirect consumption add up to more than 40% of the total energy consumption that are building related.

In Germany the energy consumption for the construction industry and its supply sectors is about 5% of the total according to Achternbosch et al. [Achternbosch 1998]. Germany is a country with a mature economy and a relatively stable population. As the construction of new buildings compared to demolition is much higher in emerging countries, the fraction of the construction related energy consumed can be significantly higher than the 5%. In China 7% of the electricity and 21% of fuel were consumed in the manufacturing of building materials in 1992 [SSB 1992].

Table 4.7 Primary energy uses in the US Mid 1990s [Committee 1997]

Sector and Energy Service	% of primary energy use
Residential Buildings	**12**
Space heating	50
Water heating	20
Air conditioning	5
appliances	25
Commercial Buildings	**24**
Space heating	35
Lighting	21
Water heating	16
Air conditioning	8
others	20
Transportation Fuel	**26**
Industry and Agriculture	**38**

4.3.2 Non-energy Material Consumption

Excluding the energy materials and food, the US material flows amounted to 2.8 billion metric tons in 1995 or about 10t per person (28kg per day). If we also count the material that is moved in mining to access ores or the ores themselves, the amount is nearly four times as high, at about 101kg per person per day [Gardner 1998]. Construction minerals dominate with about 70% of apparent consumption. A very similar pattern is true on a worldwide level, with a total consumption of about 10 billion tons in 1995 as shown in Figure 4.4. With less than 5% of the world's population, the US today accounts for nearly 30% of the world's material consumption.

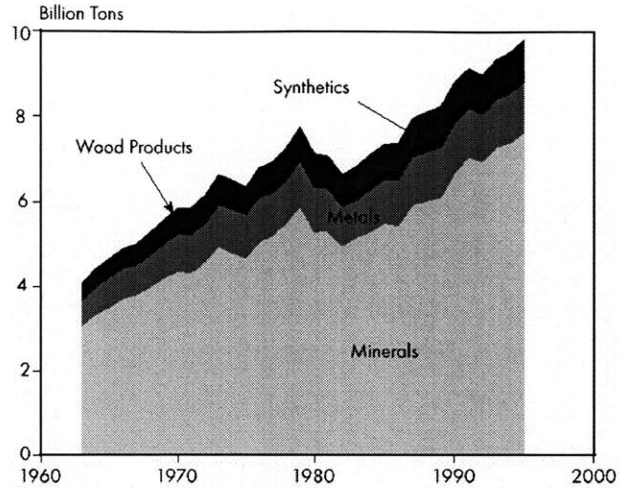


Figure 4.4 Non-Fuel Materials Flows in the world 1963-95 [Gardner 1998]

As we can see in Table 4.8, construction minerals alone account for more than two thirds of the material flows in the U.S. Construction of infrastructure is included as well. A large fraction of metals, plastics and wood is also used in the construction sector. A German study compared the flux of materials into the building sector with the construction materials disposed after demolition [Achternbosch 1998]. The flux into the building stock was about ten times higher than the flux coming out. In the United Stated for every six houses constructed only one is destroyed. There is a huge amount of materials that are accumulated in the building stock that future generations will have to deal with. In Switzerland this building stock is about 100 tons per capita [Kytzia 1998], if we also include infrastructure this number is more than twice as high. By using wood from sustained forestry, this accumulation of a material stock has a positive aspect. In this case, it represents a significant CO_2 deposit. The building stock can also be seen as a resource stock of which materials for new buildings and products can be drawn in the future.

Table 4.8 Non-Fuel Materials Flows in the United States 1990 [Wernick 1996]

Material Group	**Apparent Consumption (106 metric tons)**	**%**	**Recycled Quantity %**
Construction Minerals	1,746	68	8
Industrial Minerals	330	13	8
Metals	112	4	55
Nonrenewable Organics (e.g. plastics)	112	4	2
Renewable Organics (e.g. forest products)	231	9	8
Animal Products (e.g. hides)	2	0	1

The total materials intensity per dollar of GDP has been nearly stable for decades after 1950 and has been going down slowly since 1970 in the United States. But individual materials show a very different behavior. It is interesting to look at how the importance of different materials has changed over time in terms of kg/$GDP. This is shown in Figure 4.5. Plastic is the only material that keeps increasing. This is also true for construction, where the use of plastic per invested dollar keeps going up. As we could see in Table 4.8, plastics is a material group with a low recycling rate. Plastic products in any application need to be designed for better recyclability. Steel is one of the many materials that have been steadily going down in use since the forties. Timber has also been decreasing steadily. Initially wood was mainly used for construction and fuel, today about 25% is used for pulp and paper. On a worldwide level about 25% of wood is used for construction and 55% is burned to cook food and heat homes. Aluminum is one of the materials whose consumption kept increasing for a long time but reached its maximum around 1980. Although the average material intensity is going down slowly, it must not be forgotten that the absolute material consumption is still going up steadily. It has about increased fivefold in the US since 1940, the normalization point in Figure 4.5. To achieve a sustainable state we need an absolute decline of material consumption.

Not shown in Figure 4.5 are many materials that are only used in relatively small quantities. Many of them have not been used at all for a long time. Around the turn of the century, people made use of about 20 elements of the periodic table. Today all naturally occurring elements are actively exploited. Some of these elements and in particular their chemical compounds are often toxic.

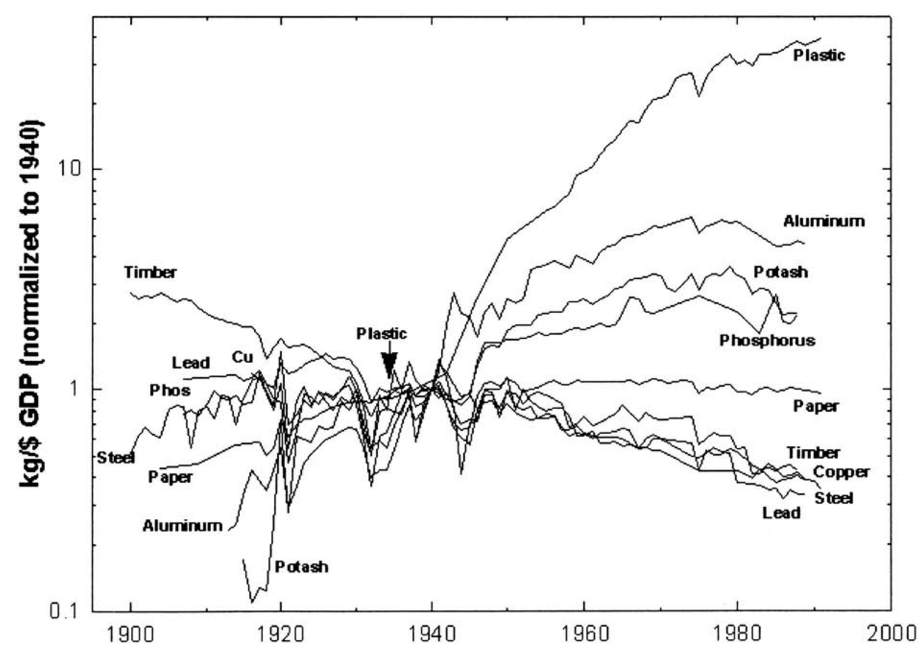


Figure 4.5 US Materials Intensity of Use in kg/$_{1987}$GDP normalized to 1940 and corrected for inflation [Wernick 1996]

4.4 Buildings and Land Use

The emissions and resource consumption presented above are not very visible in our daily life. Our perception rarely detects or recognizes it as a particular problem. On the other hand, another big building related problem is so much part of our daily life that we also tend to ignore it. It is the sheer occupation of space by buildings and related activities.

In Switzerland 375 square meters per person or 5.9% of the whole territory are covered with buildings and infrastructure [OFS 1997]. In Germany 4.7% of the total area are covered with transportation infrastructure alone.

The outward sprawl of American metropolitan areas has consumed more than 19 million acres of rural land between 1970 and 1990. Every year 400,000 acres are being bulldozed under. The Livable Communities Agenda recently announced by Al Gore wants to put a halt, or at least slow down this trend.

An advisory committee on sustainability to the German government considered better land use management as a key element for buildings in a sustainable future. They recommend reducing the rate of conversion of unbuilt to built surface to 10% of the value from the mid nineties. In a longer-term view stabilization has to be achieved.

Land use starts at the very bottom of the process chain of a building. In Germany 0.5% of total surfaces are actively used for resource extraction. On top of that comes the statistically unknown number of mines that were abandoned after they were exploited. Once the topsoil is removed, the ground looses its principal ecological functions. Deeper excavations interfere with the aquifer. At the end of a building's useful life once more the huge waste streams from building demolition occupy large surface areas.

Besides the direct impacts on the ecosphere in the form of habitat destruction, sprawl results in many other impacts on society: increased traffic congestion, longer commutes, increased dependence on fossil fuels, worsening air pollution, lost open space, higher taxes and abandoned city centers etc.

Figure 4.6 illustrates the results of a study by Newman and Kenworthy on the relation of urban density and automobile fuel consumption [Newman 1989]. Newman and Kenworthy distinguish cities with an urban density of 10-30 person per ha, which they call automobile cities; cities with 30-130 person per ha, which they call public transport cities; and cities with 130-400 person per ha, which are walking cities. The difference in fuel consumption is an order of magnitude between American automobile cities and Asian walking cities. Cities from developing countries are not included, they would rank at the bottom line.

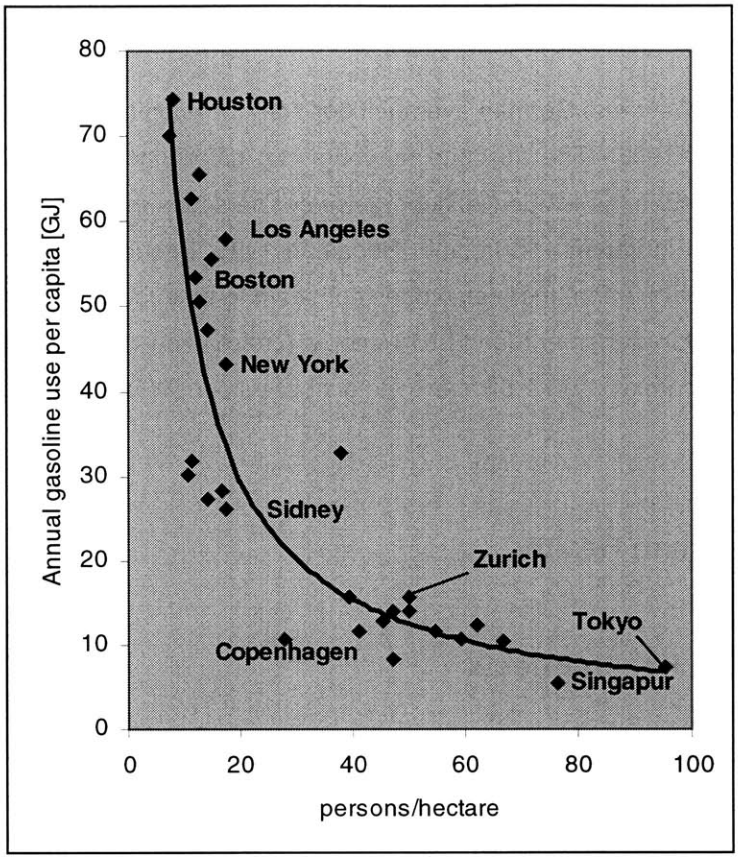


Figure 4.6 Urban population density and gasoline use per person in 1980 [Newman 1989]

Land Occupation and Floor Area

Sprawl is fuelled by an increasing demand for floor area per person. 65% of the total floor area in the United States are single family buildings. The average number of persons residing in an occupied house in the US has been going down very steadily. In Austin, Texas, for example, the number dropped from about five in 1890 to fewer than three today. In parallel the floor area of new buildings has increased. Since the early 70s, the average size of a new home has grown from 148m^2 (1600ft^2) to 195m^2 (2100 ft^2). As a result the floor area per person has almost doubled in the last forty-five years [Wernick 1996, p.14ff, Roodman 1995].

In Switzerland the number of households is growing much faster than the population. The percentage of single person households has increased from only 12% in 1950 to 32% in 1990. At the same time demand for comfort has increased. In 1960 only half of the residential buildings were equipped with a central heating system. It was not unusual only to heat the kitchen and the living room. In 1990 more then 90% of all residential buildings had central heating systems, which usually heat the whole building. The heated floor area per person has therefore increased even faster than the floor area only [OFS 1997].

Other countries show similar patterns. German average floor area for living in the fifties was $15m^2$ per person, now it is $37m^2$ [Pott 1996]. The absolute numbers can differ significantly. Whereas in the United States and also in Sweden the residential floor space per person in the early 90s was about 52 m^2, it was only half as much in Japan and Ireland [Roodman 1995, Enquete 1998]. As there is no upper limit on the floor area per person, there also does not seem to be a lower one. In Delhi, India, a case study of a typical two-story tenement found 518 people (constituting 106 separate households) living in 49 rooms, allowing approximately 1.5 square meters per person [WRI 1996].

4.5 Buildings and Human Health

4.5.1 Building Related Health Effects

In a study of 1984 by the world health organization it was estimated that "**sick building syndrome**" occurs in about 30% of new and renovated buildings. The costs for productivity losses and medical costs are estimated to be in the order of tens of billions of dollars each year worldwide. [Roodman 1995, p.25]. Sick building syndrome is not a particular illness. It is expressed in the form of dry or burning mucous membranes in the nose, eyes, and throat; sneezing; stuffy or runny nose; fatigue or lethargy; headache; dizziness; nausea; irritability and forgetfulness. There are multiple varying causes. A primary factor is bad indoor air quality (IAQ). Air quality results from the combination of air change rate and source emission rate. Bad indoor air quality can therefore be based on inefficient ventilation or high sources of pollutants.

Besides bad IAQ there are also factors like poor lighting, noise, vibration, thermal discomfort, and psychological stress that may also cause, or contribute to, the symptoms of "sick building syndrome

There are also other **building related illnesses** with a more or less known cause and effect relationship. Some of these health effects caused by bad IAQ show up immediately, for example asthma. Asthma has increased dramatically over the last ten years and now affects nearly 15 million Americans [ASHRAE 1998]. Other health effects will only show up after a long exposure time, sometimes only after many years. They include respiratory diseases, heart disease, and cancer.

The contaminants contributing to bad IAQ include volatile organic compounds (VOCs), which outgas from carpets, paints, furniture and other building materials and cleaning products. Other major sources of contaminants are any open combustion processes in a building like gas cooking, tobacco smoke or kerosene heating. They emit pollutants like CO, CO_2, NO_x, particulates and unburned hydrocarbons.

Molds, dust, bacteria and Human generated pathogens (e.g. viruses and bacteria) are another category of pollutants found indoors. Under certain geological conditions, natural radon can occur in very high concentrations and special measures are necessary to prevent it from entering into the building or to flush it out if it does enter.

The limitation of sources for bad indoor air quality has to be the first step in addressing building related illnesses. A paper by Hal Levin outlines a strategy for achieving high indoor air quality [Levin 1997].

4.5.2 Economic Impact of Comfort and Indoor Air Quality

The average cost for office building heating and cooling in the US is about $2 per square foot per year. Employees get paid $200 per square foot per year. Office cleaning costs are only $1.38 to $2.32 per square foot per year. Increased worker productivity can therefore have a much higher impact on the economics of a building than energy savings. The thirty year life-cycle costs of an office building are typically [Romm 1994]:

- Initial cost (including land and construction)	2%
- Operation and maintenance (incl. energy and cleaning)	6%
- Personnel costs	92%

If costs are discounted to the time of construction, demolition costs will virtually disappear as a cost factor.

In 1986 a building of the main post office in Reno, Nevada, housing two sorting machines underwent a renovation. A lower and sloped ceiling was installed to reduce energy costs for heating and cooling, and to improve lighting and acoustical conditions. A mock up was installed over one of the machines. Nothing else had changed and there was no unusual interaction between workers and the supervisors. The productivity of the people working in the renovated area shot up 8% and stabilized at 6%. At the same time the error rate dropped to 0.1%, the lowest in the western region. The improved lighting conditions were considered as the main factor. Combined, the energy and the maintenance savings were worth about $50,000 per year. With an initial investment of $300,000 this comes to a payback time of six years. But the productivity gains were worth about $300,000 to $400,000 a year, representing a payback time of less than a year. Similar results have been found in several other buildings [Romm 1994].

4.5.3 Occupational and Industrial Health

Progress has been made over the last years to improve worker protection. However employers still reported 6.3 million work injuries and 515,000 cases of occupational illnesses in 1994. In 1995, occupational injuries alone cost $119 billion in lost wages and lost productivity, administrative expenses, health care, and other costs. Not included in this figure are the costs of occupational diseases [NIOSH 1998].

The sectors involved in the upstream chain for buildings include many professions with a high degree of exposure to health hazards. Many of the professions with a high risk for direct victims are also in the supply chain of buildings.

This starts with people working in the mining process for the many resources that go into a building. Material and component manufacturing can expose workers to a high level of chemical health hazards. A very high health risk is also present for workers on the construction site. This includes injuries, and exposure to particulates (e.g. fibers from glass wool insulation), chemicals (e.g. adhesives for floor tiles) and noise.

4.6 Construction and Economy

The building sector, which includes new construction and renovation as well as material and equipment suppliers, is valued at more than $800 billion per year in the United States. This equals almost 13 percent of GDP. The value of construction put in place in 1997 was $618 billions. The sector employs more than 5.1 million workers, which is about 10% of the US labor force. In Switzerland the whole building sector - including also architects, engineers, and employees of add-on industries - employs about 20% of the total workforce.

A country's building stock and transportation infrastructure is a huge asset. To rebuild the Swiss building stock would cost about $ 180,000.- per capita. Another $50,000 would have to be spent on transport related infrastructure. About 2% of these values are spent every year for the maintenance and renovation of the buildings and infrastructure [Infras 1996].

The full costs of ownership and operation of a building are often only very roughly estimated or not even calculated at all. But just doing these calculations often would support more investment in sustainable building. Many investments in energy efficiency and more durable materials are economically practical. It is often the lack of knowledge about the operating costs that prevents people from making these investments.

5 Design of Sustainable Buildings

5.1 The Need for Tools and Sustainability Indicators

Designing a building is a highly complex task. The number of possible designs is infinite. The number of good designs is still a big number. We will never have -and do not want to have- an indicator that allows an optimization function to come up with 'one solution'. Human beings are unique in their ability to design, taking into account at the same time objective and more intuitive criteria.

But 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 in a life cycle approach they also stem from processes that can be remote from our immediate environment. Who can tell by intuition what the Global Warming Potential of a Brick is? And still, by our design choices we are deciding what will be the impacts of our building on the environment. In chapter 3 it has been shown that LCA is a methodology that is suited in providing such information. A similar problem is given for the emission of toxics from building materials. First of all the designer needs to know what chemicals are included and secondly he needs to be informed of any potential health effects. Tools are necessary to inform the designer about the link between his design decisions and environmental and human health impacts.

Designing a sustainable building is not simply a question of picking the materials and systems with the lowest environmental impact. The elements forming a building are related to each other and to the building requirements. It is up to the designers to coordinate the different elements. The feed back from LCA tools has to be fast and simple in order to integrate this knowledge into the design process along with all the other information the designer has to consider.

Although the focus in this paper is on LCA, it must be realized that LCA is not the only instrument and not a sufficient instrument for sustainable design. For example it does not address indoor air quality. Also all qualitative topics can not be addressed. But LCA is an instrument, which is probably capable of covering more aspects in a quantitative manner than any other method.

Two different types of tools will be discussed in this chapter and chapter 6. The first ones are LCA based manuals and software that help the designer in choosing a certain wall, floor, or structural system over another. These LCA based software tools have only appeared recently and most of them are at a prototype level. The choice of indicators that are included has been driven more by the availability of data than by needs. The second set of tools presented is general building assessment methods, which are much broader in scope. They have to give different weights to different performance criteria of buildings. LCA based elements begin to appear in some of them. Chapter 6 will take a look at the environmental and human impacts and the corresponding indicators that should be included in the different sustainability tools, based on the findings presented in the chapters above.

Building codes and other mechanisms of building policy are based on certain goals. Two of the major goals of zoning and building codes have always been the protection of the local environment and the protection of the inhabitants of buildings. Under the light of sustainability, building codes should be reviewed. Taking a local viewpoint only may result in non-optimal solution from a whole society's or environment's point of view. A life cycle view needs to be taken. All dimensions of Sustainability in the context of buildings need to be explored. A similar approach needs to be taken in developing design guidelines for sustainable buildings. Chapter 7 presents a case study for Chinese buildings, which explores some of these dimensions.

5.2 A Building Model for Sustainable Design Tools

Any quantitative method that assists sustainable design needs a consistent framework and systems limitation. The building needs to be structured in **life cycle stages** as it has been shown in Figure 4.1: Extraction of resources, fuel and electricity production, transportation, production of building materials, manufacturing of components, construction, operation, maintenance, renovation, demolition / disassembly, and recycling / waste treatment / disposal, have been distinguished.

The building itself needs to be structured into its major **systems**. A hierarchical object oriented model represents the building. In a Swiss tool, a building model that was developed for cost estimation has been found to be very useful also for life cycle assessment of the building. It is the 'Cost Classification by Elements' as it is shown in Table 5.1 [CRB 1991]. For each element there exists a reference unit that is used for cost, or in the case of LCA impact, estimation. For walls this reference unit would be surface area, for other elements it can be a count of quantity.

Table 5.1 Building model used in the Cost Classification by Elements CCE [CRB 1991]

D Building substructure	
	D0 Mass excavation
	D1 Filling
	D2 Foundations and lowest floor slab
	D3 Drainage (structure)
E Building superstructure	
	E0 Upper floors stairs and balconies
	E1 Roofs
	E2 Columns
	E3 External walls below ground level

	E4 External walls above ground level
	E5 Windows and external doors
	E6 Internal walls
I Mechanical and electrical services	
	I0 Electric power and lighting
	I1 Telecommunications and security
	I2 Heating installations
	I3 Ventilation and air conditioning
	I4 water and waste services
	I5 Special Installations
	I6 Lifts, escalators...
M Finishing work to buildings	
	M0 General finishing work
	M1 Partitions and internal doors
	M2 Protective elements
	M3 Floor finishes
	M4 Wall finishes
	M5 Ceiling finishes
	M6 Fittings and garden works inside the building
	M7 Household kitchens and kitchenettes

Most building models have been developed on a national level. There are necessarily many similarities between them. Two efforts are currently underway trying to find an international consensus on such a building model. One is the 'STEP' model of ISO. The other effort is 'Industry Foundation Classes' (IFC) as defined by the 'International Alliance for Interoperability. The second version has been released. Both models are much broader in scope than the simple model presented above. Both models are pushed by industry, researchers, and CAD companies that want to facilitate the data exchange in the design and manufacturing process. The feasibility of such a linkage of different databases to promote sustainable design has been shown with the 'Building Design Advisor', which is based on IFCs [Papamichael 1997].

5.3 Sustainability in the Design Process

During the whole design process, decisions are made that affect the sustainability of a building. The design process is understood here in a very broad sense. Each stage involves different actors. Very general questions need to be answered at the beginning, with the advancement of the design, more precise questions need to be answered [Gay 1998]. The aim of the present paper has not been to establish design guidelines. However the most important principles of sustainable design from the authors point of view are summarized in Box 5.1.

- **Initial Choices / Programming**

It is at an early stage where fundamental decisions with a large impact are taken:

Should we build a new building or transform an existing one?
Should we stay or relocate?
Where should we locate the new building?
How much should we build and for how long?

Usually these decisions are primarily taken on an economic background. They should also include criteria of sustainability. A life cycle viewpoint does not necessarily mean a detailed study. Rules of thumb can be sufficient. Mean or typical values for buildings can be applied at this stage, as the design is not known yet. In chapter 4, orders of magnitude for the impact of a building versus infrastructure and mobility have been given. Such rules should be developed systematically.

If a site has to be chosen, it should at least include the ecological value of the potential site, micro-climate, the existing infrastructure, and impacts on transportation.

- **Architectural Design (concept design phase, schematic design phase)**

The site has been chosen. Different principal building options are explored at an early design phase. A comprehensive view of all building systems is necessary. A variety of specialists need to be brought into the design team at an early stage. The building shape and orientation will have a large impact on the energy consumption, ventilation, and daylighting of the building. Different simulation programs can help in the design process. This can include energy simulation and CFD studies for airflow around the building.

The spatial arrangement of the rooms and layout of the floor plan dictate the potential for the building to adapt to changing needs over time. A long-term perspective and assumptions about the future of the building are necessary.

LCA based case studies can serve as a reference to give the design team a general feeling what a certain basic shape and structural system mean in terms of environmental and human impacts. In the same way that an experienced designer knows about the economic impact of his decisions, he can also develop a design experience for sustainability.

- **Technical Choices, Construction Details, Materials- and Product Selection (design development phase, construction drawings phase)**

It is in this stage that LCA based manuals and tools can guide the designer in choosing certain types of systems over others. Systems with low embodied impacts but comparable performance should be favored. The choices have to reflect the assumptions about the use and assumed lifetime of the building.

The construction details of the building envelope, windows, ventilation-, heating- and cooling system, determine the environmental impact of the building during its operation. Again, simulation software and the know-how of specialists can be helpful.

As we have seen in chapter 4.1.1 it is the sum of many small elements that reduce the embodied impact of a building. For every decision the incremental contribution to the buildings life cycle impact needs to be considered. Object oriented CAD programs linked to materials databases will be very helpful with this in the future. Standards will be required so that industry-wide data will be comparable.

The lifetime of different systems has to correspond to the long-term scenario for the building. The whole building needs to be seen in different layers. Short-lived layers or systems have to be easy replaceable.

The design of the ventilation system and the choice of materials will decide on the indoor air quality of the building. It is important to have clear information on the materials and products that are used in construction. A standardized 'materials declaration' form has been developed in Switzerland [SIA 1993]. Whereas information on LCA tells us about remote impact on the environment and on human health, a 'materials declaration' gives detailed information on the composition of a product as arriving on the building site. Hazardous chemicals that are often used for bonding and surface treatment of floor and wall coverings, panels etc. are explicitly stated. This prevents sources for problematic indoor air quality at the design stage.

- **Bidding**

The detailed conditions and descriptions in the building specifications are one more important step towards a sustainable building. Conditions on minimal contents of recycled materials, requirements on material suppliers, waste management on the construction site etc. can be included. Up-to-date Information will need to be available to the designer so that the specification will properly reflect market availability. In this way, the design specification will inform the marketplace what to strive for in its production.

- **Construction**

The construction site management is responsible for minimizing the local impact of the construction site on nature and neighbors, and for minimizing construction waste with its associated source reduction and landfill reduction.

- **Operation**

The responsibility of the design team does not end with the end of construction. A very important aspect is the commissioning of the building.

Materials and systems have been chosen with a certain intention on their maintenance. Technical systems have a certain intended mode of operation. The client needs a detailed introduction and documentation on these design intentions. Monitoring of energy consumption for the different technical systems and materials flows for maintenance of the building can help detecting faults in operation and show potentials for optimization of the buildings operation. They also serve as feedback for future projects.

- **Demolition / Disassembly**

The demolition or disassembly strategies of an existing building can be integrated in the design of the new building. Parts of the building might be reused or materials salvaged.

The new building needs to be designed for disassembly and demolition. Any building designed today should not end up as landfill but as resource for a new building at the end of its useful lifetime. Methods will need to be developed that balance ‘permanence’ and re-use.

5.4 Existing Tools for Sustainable Buildings

Some of the needed tools that can help the designers have been mentioned above. They include many of the 'traditional' simulation and design tools already in use. The available tools that address sustainability or 'green building' explicitly vary in their objective and scope.

The HOK Sustainable Design Group identified six generic types of design guides, which serve distinctive purposes [HOK 1997]:

Inspirational
e.g. "Hannnover Principles" or "Natural Step" are very broad in visions and call the designer for action, but lack specifics.

Resource Guides
e.g. "AIA Environmental Resource Guide" or "USGBC Sustainable Design Technical Manuals" serve as general technical reference by summarizing large bodies of information.

Process Oriented
e.g. "HOK Sustainable Design Guide" or "Green Building Advisor" have design integration and implementation as their primary focus. Key issues are addressed at specific points in the design process.

Action Oriented
e.g. "US Postal Service Green Guidelines", "US National Parks Service, Guiding Principles of Sustainable Design" or "Handbook of Sustainable Building" organize the information by topic instead of by process. The process is secondary to the content.

Assessment method

e.g. "BREEAM", "LEED", "Austin Green Builder" or "GBC" define goals and provide benchmarks to improved performance. They vary in breath of issues addressed and scientific grounding of the benchmarks. They are discussed below.

Building Specific

e.g. "Greening of the White House" are limited to a specific building and usually serve educational purposes.

The shortcomings of some existing tools are that they omit important aspects, or that they overflow the designer with information. Some are subjective in the way they compare and balance different impacts against each other. This can lead to implicit trade-offs; improving the building in one environmental aspect, but possibly doing much more damage in terms of other impacts. Most guides could be improved and would gain credibility if they were based on more quantitative scientific background data resulting from LCA.

5.4.1 LCA Based Tools

Manuals

The "Handbook of Sustainable Building" [Anink 1996], takes an interesting approach in selecting preferred materials. It uses the Dutch "Environmental Preference Method". It is related to LCA in the sense that the whole lifecycle of building materials is considered. In a qualitative, or if data is available in a quantitative way, the materials are screened for the most important environment related problems. A matrix with different criteria like energy use, material use, emissions etc. is filled with 0, + , -, or x for specially bad. The weighting of the criteria is subjective by the authors. The disadvantages of subjectivity and neglecting certain effects are obvious. The big advantage lies in the possibility to include information from very different sources, including qualitative information.

Chapter 6 will present a proposal for a new LCA based manual.

Software for the selection of building materials and assemblies

All available software tools are at prototype levels or only the first version has been released. Most of them include only a small number of assemblies of products. The integration into the design process has to be improved. The advancement of general building models that allow linking different design tools should be helpful to achieve this.

None of the tools is satisfactory yet in handling the impact assessment. This is not only a problem of these building oriented LCA tools, but much more reflects the ongoing discussion and development of better impact assessment systems among the LCA community.

Athena

Athena has been released in a beta version and should be available to the public in the near future. Athena follows LCA principles to assess the performance of buildings or their components. There is a number of predefined 'assemblies' that the user can adjust to his current project. The systems and materials included will be extended and the data differentiated to represent different North American regions. There are background reports available that document the inventories for the material life cycles.

The following impacts are included in the current beta version: Primary energy consumption, air toxicity, water toxicity, solid waste, Global Warming Potential, and consumption of resources.

Global Warming Potential and primary energy consumption are calculated following standard procedures as they have been presented in chapter 3. Waste is simply accumulated on a mass basis. For the extraction of resources, the authors of Athena developed their own weighting system based on subjective scores of a panel for the relative effects of different resource extraction activities. Air and water toxicity are based on the Critical Volume method. The advantages and disadvantages of this simple method have been presented. The authors of Athena point out that some of the indices included in the beta version are still under development [Athena 1999].

OGIP

OGIP has been developed with the aim of taking environmental issues into an integrated design process. It is supported by the Swiss Federal Office of Construction and the Swiss Research Center for Rationalization in Building and Civil Engineering (CRB).

The inventories for the building materials have been established by the Swiss Federal Institute of Technology and are well documented [Frischknecht 1996] [Weibel 1995].

OGIP can be used in the stages from conceptual design to detailed design with construction drawings. OGIP uses the same element based building model that CRB developed for cost estimation (see Table 5.1). As in Athena, different predefined assemblies are available. The software is capable of simultaneous estimation of building construction cost and environmental impact based on life cycle assessment. An integrated simulation tool calculates energy requirements for the operation of the building according to a Swiss building energy code. The software will be released during summer 1999.

The input of data is alphanumeric over the keyboard. In a later stage it is hoped to link the tool to object oriented CAD software.

The software allows for different LCA assessment schemes for the environmental impacts, as they were described in chapter 3. It is up to the user to decide which weighting principals he wants to use. The typical user will not be aware of the shortcomings of the different methods.

BEES

BEES is the only LCA based building design tool developed in the United States at the moment. Like OGIP it intends to estimate cost and environmental impact in parallel. Compared to Athena and OGIP it is more product and not assembly oriented. This makes it probably more useful in a later design stage only. A small number of materials is included in the current version and the inventory reports contain little quantitative data.

The impacts considered include Global Warming Potential, Acidification and Nutrification using the CML valuation method that has been presented in chapter 3. Natural resource depletion is calculated taking into account the current production and reserves of a material. The solid waste inventory includes non-recyclable solid waste resulting from the installation, replacement, and disposal of each building product. Waste is accumulated on a volume basis.

A particularity of BEES is the inclusion of the impact on indoor air quality of some materials. A simple model that considers VOC emissions of the product itself, amount of adhesive use, and floor waxing for interior surface finishes approximates the impact on indoor air quality.

A simplistic form of normalization is performed by dividing each product's impacts by the highest measure for a product in a certain impact. The user can than use weighting schemes from different expert panels or apply his own weights to the normalized impacts in order to calculate an aggregated index. The use of weighting schemes, which have been elaborated for emissions on a national level, in the context of this simplified normalization method is questionable [BEES 1998].

Others

Among the others tools available in a final or prototype version is Eco-Quantum from the Netherlands. Together with Athena and OGIP it is one of the most advanced tools that can assist the designer in taking into account LCA considerations in the design process. Other tools include 'Team for buildings' and a tool by the Danish Building Research Institute.

5.4.2 Assessment methods

Building assessment methods are used to rate buildings according to their impact on the environment and the human health. Depending on the performance, the building receives a number of stars; silver, gold, platinum or a similar distinction. The market value of the distinction is the principle driving force encouraging a client to require an assessment. Out of ten or more methods that have been developed, BREEAM, LEED, and GBC 98 are the three systems that are discussed here briefly [BREEAM 1998] [LEED 1999] [GBC 1998].

All methods are organized in a checklist style, giving away scores in different performance categories. High performance, usually meaning a low impact, results in a better score. All include sections on material and energy use, local site issues and indoor air quality and comfort.

BREEAM is the oldest of the three methods. It has been developed in the UK, where today about 30% of new offices are assessed by the method. Supermarkets, industrial and residential buildings can also be assessed. It has been adapted to other countries and a version for North America is also available. The assessment is organized by the main sections of global, local and indoor issues.

LEED is developed and promoted by the US Green Building Council, a nonprofit consensus coalition of the building industry.

For most issues addressed by a checklist, BREEAM and LEED give away one credit. For some issues, like the energy consumption for building operation, the credits received can vary. This equal weighting of many issues is not acceptable from an LCA standpoint. For example in LEEDS, 1 credit is given for using materials that have been manufactured within 300-miles of the building site for 20% of all building materials. Another credit is given for using salvaged or refurbished materials for 5% of total building materials. On the other hand a reduction of the energy consumption by 20% compared to ASHRAE standard 90.1-1989 also only results in 2 credits. But as we have seen in 4, the reduction in energy consumption of a standard building will result in a much higher reduction of environmental impact than using local or refurbished materials of a small fraction of all materials.

Any certified architect or engineer can sign a LEED rating application. The system therefore had to be kept simple. BREEAM is a third party rating. The credit system in BREEAM can therefore be more sophisticated. More important issues cover a wider range of potential credits. Still, BREEAM also shares the problem with LEED that the credits do not reflect the absolute environmental or human health impacts.

This arbitrary or equal weighting of issues over a large range of impact is the biggest shortcoming of LEED and BREEAM.

Recognizing this problem, the 'Green Building Challenge' (GBC) '98, a two-year international effort to develop a new generation assessment method, was initiated. It addresses a large field of issues and is based on a multi-layer weighting procedure. Although the procedure is quite elaborate and complex, it still includes a large amount of subjectivity of the authors, which can adjust the weighting for each country.

The GBC '98 ended in a conference in Canada. In a review many participants found the system to be too complex and missing objectivity. The new version, called GBC 2000, is intended to improve some of these deficiencies.

LCA based elements are included in the GBC '98 and the new BREEAM. Due to a lack of data, most participants did not calculate airborne emissions embodied in the building structure as required in GBC '98. A manual accompanying the BREEAM method rates certain assemblies based on LCA.

Any assessment method has to find a balance between simplicity, comprehensiveness and objectivity. Although LEED shows many weak points from a scientific point of view, it might result in the highest overall environmental improvement for the whole program, as its simplicity facilitates market penetration.

Chapter 6 will present some ideas on how LCA based data could improve the credibility of the assessment methods.

5.5 LCA Data Availability and Data Quality

Throughout this report the case is made for the application of LCA data in the design of buildings. So far the availability of these data has been considered as given. But as we could see in the examples of existing LCA software, they only include a limited amount of materials.

For the time being there is a lack of LCA inventory data in many countries. Switzerland, Canada, the Netherlands, and Scandinavian countries have taken a leading role in establishing databases that are available to the public for a moderate price. The Swiss database is particularly transparent and all assumptions are documented. But none of these databases is complete in the field of building materials. Due to a lack of data many other countries use data gathered for other countries. This is appropriate if similar technology and energy systems apply in both countries.

Another problem is that the inventory for some of the data is based on one or a small number of manufacturers of a certain product. But differences between manufacturers of similar products that are produced by different processing technologies can sometimes be larger than the difference between different product types created for the same application. This could be true for example in a comparison of glass-wool versus slag-wool insulation. The larger the number of companies included in the data survey the better. The effort involved in raising inventory data puts limits to this.

In the future it can be hoped that the effort to establish an LCA can be lowered with the proliferation of the ISO 14000 system. So far one of the main problems was the very cumbersome process of collecting data in the companies. ISO standard 14031 specifies the Environmental Performance Evaluation (EPE) of companies. The environmental damaging effects of a company are collected and analyzed systematically. These data can be used for an LCA of products as described in ISO 14040ff.

In general data is available for the building superstructure and some of the major insulation types and finishes. There is a big data gap for mechanical building systems and some of the interior finishes. By nature, data is usually missing for any newly invented product or products with a small market penetration. On the other hand quite often it can be these marginal materials that present an environmental friendly alternative to dominating materials.

The overall error and data gaps of a building inventory can have several reasons:

- The data for a material or product is not available.
- The data has been raised in a different geographical region.
- The data has been raised in the context of a different production technology.
- The data are based on one or a small number of samples.
- The data is outdated.
- The quantity of material used and wasted for the building is unknown, this in true in particular for many ancillary materials.
- The transport distances are not known.
- The onsite processes are not known.

As we have to deal with a large number of independent errors and many building elements, the error for the whole building is smaller than for some materials or products with a poor inventory. For the inventory of the construction and renovation of the Swiss multi residential building presented in chapter 4.1, the overall standard deviation was estimated to be about 11% [Freitas 1997].

However during the design process we are interested in the performance of a certain system or component compared to an alternative choice. On this level the error margins are larger.

On top of the error of the inventory comes the systematic error of the impact assessment methods. It is not possible to quantify an 'error' in the classical sense for the weighting procedure. In general it is recommended to look at relative values of comparable technical solutions for the same application rather than absolute values, e.g. the performance of one roofing system compared to other roofing systems.

Depending on the quality of the data, a difference can only be considered significant if it is more than 10% for good, or around 30% for poorer databases.

BOX 5.1: Principles for sustainable design

- Minimize new construction: Explore options for using and renovating existing buildings. Redevelop Brownfields. Respect local ecological conditions. Opt for compact and clustered development in favor of detached buildings and sprawl. Be moderate in the required floor area per person or workplace.
- Consider implications on transportation and integration in the community when choosing and designing a site (availability of: infrastructure, public transport, cycle and walk paths, mixed zones, short daily trips to markets, etc., recreational areas)
- Design for a high level of health and comfort considering (day-) lighting, (natural-) ventilation, and acoustic environment. Limit sources of indoor air pollution.
- Minimize energy consumption for the operation of the building: Design with the climate, high performance envelope and windows, efficient heating-, cooling- and ventilation strategies and systems. Use efficient lighting system and appliances. Use renewable energies.
- Minimize the impact embodied in materials:
  Chose materials with a low embodied impact and use them efficiently.
  Use recycled materials.
  Use materials like unfired clay bricks to provide mass where required.
  Only use high impact materials like aluminum where appropriate
  Take into account the transportation of high mass materials and production energy for highly processed materials.
- Design for durability, flexibility and adaptability of the building.
- Chose durable low-maintenance materials for exposed surfaces. Chose materials that can be maintained with non-toxic methods.
- Separate different layers with different lifetimes.
- Design for disassembly, material salvage, recycling and disposal. Keep materials that undergo different cycles of reuse or decomposition separable. Avoid cross contamination of materials with substances that hinder a reuse, recycling or environmental friendly way of disposal.
- Minimize construction waste. Provide recycling facilities for the building users.
- Develop and follow a strategy for quality management in the design and construction process.

6 Sustainability Indicators for Buildings

6.1 Assumptions

In the preceding chapters, sustainability has been defined, the methods for calculating sustainability indicators have been shown, the impact of buildings has been demonstrated, and the need for quantitative tools has been shown. Now we have to select those topics of sustainability which are the most important ones in the context of buildings and those indicators which can measure the impacts. Again the focus of this chapter is on quantifiable impacts on the environment and on human health. Some qualitative issues will also be addressed. To achieve sustainability, the social and economic dimensions will have to be considered too in some form.

It is assumed here that the LCA inventories for building materials are available. The challenge is to simplify and aggregate individual emissions and resource consumption for ease of communication to a small number of impacts, and at the same time be scientifically correct. Depending on the application e.g. comparative analysis of assemblies or products, assessment method, or building policy, the balance between comprehensiveness and practicability will result in a more extensive or compact set of indicators. The set of indicators should be revised regularly in order to integrate new knowledge about emerging or solved problems. To achieve a minimal set of indicators, the following assumptions are made:

- An indicator represents other related impacts in the same dimension.

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

There is no need to inventory all potential impacts. This assumption is the most important one. 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. 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 the 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.

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

There is therefore no need to establish an indicator for that impact. This corresponds to so called 'red flag' methods. An example would be CFCs, which were primarily used in HVAC-systems and as an expansion gas in certain types of insulation.

- Aggregation based on scientific reasoning can be done for similar types of emissions, resource consumption etc. At a certain level, fundamentally different indicators can only be weighted by societal value setting.

This procedure has been presented in chapter 3. The societal value setting must be transparent. Depending on the application, the user of the method has to be able to set the weight for different impacts himself.

The indicators, as outlined in this project, are primarily thought for urban areas in industrialized and developing countries. Some criteria receive different weights depending on the regional context. By the turn of this century, almost half of the population will live in urban centers and the trend in urbanization is expected to continue. Problems related to traditional rural housing can be considered in the same general framework of indicators (indoor air quality, stress on local environment etc.) but the assessment and the means to improve the situation are different.

As we have seen in chapter 3, indicators are used to assess status, document trends, act as an early warning and diagnose cause and effect. The indicators we are looking for here are based on the assumption that the status of different problem fields is assessed and the warnings have been understood. It is mostly state indicators that serve this purpose. State indicators are also a means in defining weights for different impacts. It is assumed that cause and effect are understood in detail or at least in principle. The task that our building related indicators have to fulfill is to link design decisions with the identified fields of concern. The indicators we need for that purpose correspond to pressure indicators. They answer the question on the incremental change of the state of the environment or human health that our decisions imply.

6.2 Setting Priorities

6.2.1 Range of Impacts

Many publications list what are believed to be the most important threats to a sustainable way of living. Initially it was intended to compare the impact from different sources in a tabular format. This proved to be difficult as different authors use a different delimitation of the impacts. The problems can be identified at different stages along the damage chain ranging from the release of pollutants or resource consumption to the damage on the safeguard subjects (ecosystem- and human health, resources). Many of the impacts are partially overlapping. Table 6.1 gives an overview of the most urgent problems identified to impact environment and human health by a number of sources. The impacts are explained in Appendix B.

The list needs to be reviewed periodically to incorporate new findings on impacts. Potential issues of high future importance are for example the global change in the chemical composition of the atmosphere with different persistent substances and the exposure to substances that trigger hormone like activities in humans and animals. Nonylphenolethoxylat for example is used for cleaning in the industry and shows oestrogenic activity.

Table 6.1 Impacts on the Environment and Human Health

Pollution and Waste	
Global	Global Warming / Climate Change / Greenhouse Effect Ozone Depletion
Regional and Local	Acidification Human Toxicity Ecotoxicity Carcinogenic Substances Heavy metals Pesticides / Herbicides Toxic and micro-biological pollution of surfacewater Soil and groundwater pollution Photosmog / Troposhperic Ozone Wintersmog General Urban Air Pollution Radiation Eutrophication / Nutrification Construction waste Industrial waste Municipal waste Hazardous waste Nuclear waste Aesthetics / Landscape degradation Visibility Waste heat Habitat alteration and destruction Ecosystem health Land use Soil erosion
Immediate environment / indoor	Occupational and Industrial Health Direct casualties / accidental releases Noise Odor

	Visual comfort Thermal comfort Indoor Air Quality Asbestos Radon
Resources	
	Non-renewable energy (fossil, nuclear) depletion Abiotic resources (minerals and ores) depletion Biotic resources depletion Loss of biodiversity Deforestation Fresh Water Ground water

6.2.2 Different Strategies for Different Applications

The following three applications must be kept in mind for the discussion on which impacts should be included and with which indicator they should be measured.

- A manual in paper or electronic format that helps the designer to choose between different wall- and floor assemblies (see chapter 6.5). The aim is to keep the number of indicators as small as only possible.
- A building assessment method (see chapters 5 and 6.6)
- General building policy and development of building codes (see chapter 7 for a case study in China).

For all three applications the steps listed below will be followed in order to reduce the number of indicators to a manageable set.

1. Identify the most important impacts
2. Eliminate overlapping impacts
3. Eliminate impacts on which buildings have only a minor impact
4. Use red flags where appropriate (banning impacts by addressing specific critical sources)
5. Define regional issues, which might be important locally

The impacts are discussed in detail in Appendix B. Only a summary is shown below. The presented classification into impacts of high, medium or low importance is based on a consultation of several sources but finally represents the personal opinion of the author. It is based on the criteria that have been introduced in chapter 2 and that were also used for the definition of an ideal impact assessment method in chapter 3. It must not be forgotten that all impacts presented in Table 6.1 are real and serious problems. A classification into 'low importance', means a low importance relative to the other even bigger problems.

An impact was considered as to be more severe:

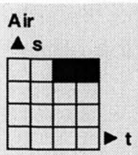
- If the extent of damage done to the system is large.
- If it acts on a large scale and affects whole entities.
- If human health is affected.
- If the damage shows up with a time lag or is irreversible.
- If the momentum driving the impact is large. This is measured by the rate of change of the emissions or resource consumption. The supporting 'lobby' that resists a reduction is also included in qualitative terms for momentum.
- If we have no or little technical or political means to control the impact.
- If there is a high uncertainty on the mechanisms and damage involved. Taking a no-regret approach, the upper scale of potential damageis considered.

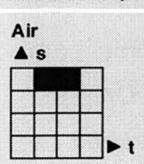
These criteria can be defended from a rationalist's point of view. They simply aim at an optimal path for the conservation of the living and non-living nature on which mankind is depending. Only the human health criterion includes an ethical element. The health of the individual is considered as important, although it does not affect mankind as a whole.

The correlation between indicators mentioned below are derived from expectations and will need to be confirmed in some cases.

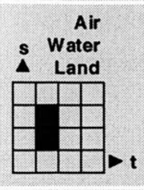
Most of the reasoning on the impacts and the choice of indicators presented below, could be used in applications other than buildings. However the final selection was made with the three building related applications presented above in mind. The presented list is therefore valid in the context of buildings only.

For the discussion of the impacts and indicators, the building's life cycle is divided into the three major phases of 'upstream', 'operation', and 'downstream'. Upstream includes everything necessary for the construction and renovation of the building. Operation is the useful time of the building. Of primary concern are the energy consumption of the building and the impact on the occupants. Upstream processes for the production of site energy as it is used during operation are dealt with in the 'operation' phase. Downstream includes impacts associated with the disassembly or demolition of the building and waste disposal.

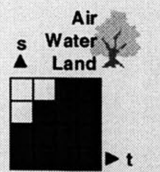
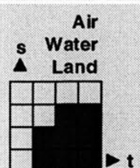
Global Warming	
	Global Warming has an infinite damage potential, it acts on a global scale and is irreversible. The momentum that drives Greenhouse gas emissions is very high. The uncertainty about the absolute temperature increase and the resulting damage is high. Means to get Greenhouse gas emissions under control would be available. The impact has **high importance**.
Buildings	With a total of about 40% of the CO_2 emissions, the share of building related emissions is large in the upstream and building operation phase (see chapter 4 and Appendix B). In an energy efficient building, upstream can be as important as operation. Downstream processes are less important.
Indicator	Global Warming Potential (GWP) measured in [kg CO_2 equivalents] is a well-developed indicator. The indicator is not location specific. As most of the emissions stem from fossil fuels, the indicator will show a high correlation with non-renewable energy. The indicators for Global Warming and non-renewable energy need to be coordinated.
Application	Global Warming should be included in a quantitative manner in all indicator applications.

Ozone Depletion	
	The damage would be very high to infinite for a further depletion of the ozone layer. It affects primarily Polar Regions but would have extended to other regions too. The effect is reversible within decades. The emissions of the major sources have been reduced significantly. The physical and chemical mechanisms of Ozone Depletion are understood. This impact had high priority a few years ago, but is now 'under control' -> **low importance**.
Buildings	Upstream/Operation: The share of building related emissions is large. CFCs were used in HVAC systems (emissions during operation) and as foaming agent in insulation materials (slow release over building lifetime). Downstream: The CFCs contained in old HVAC equipment need to be disposed properly. In developed countries CFCs are nearly phased out. China is the country with the world's highest production of CFCs remaining but will also phase out CFCs in some years.
Indicator	Red Flag, banning specific materials and equipment Ozone Depletion Potential (ODP) measured in [CFC-11 equivalents] if a quantification is necessary. The indicator is well developed. The indicator is not location specific.

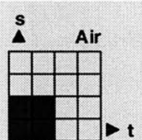
Application	In countries where CFCs are still used, materials and equipment containing CFCs or whose production process involves CFCs should be avoided. This should be a basic requirement in any application in countries where CFCs are still used, but usually will not need not to be quantified.

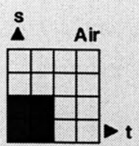
Acidification	
	Acidification has a medium damage potential, which will occur on a regional level, the damage is mostly reversible. Technical means to control acidification are available and in many countries the emissions causing Acidification have been reduced significantly. The **importance** depends on the local background conditions and varies between **low to medium**.
Buildings	Upstream: Many building materials embody high emissions related to Acidification. Operation: The impact depends on the power stations for electricity production and on the heating system of the building. If coal fired heating systems are used like in China, the impact can be high. Many developed countries limit the sulfur content of fuel oil. Downstream: negligible, besides acidification from operation of demolition machinery and transportation.
Indicator	[CML 1992]: The different emissions are weighted according to their stoichiometric increase of H+. Buffering and place of deposition (land or water) is not taken into account. This is a relatively simple model. The effect-score is expressed in SO_2 equivalents. Acidification will show a high correlation with electricity production for countries with a high share of coal power stations. The indicator should take into account local background conditions.
Application	Manual: the indicator will not need to be included as there is a correlation with non-renewable energy, Global Warming and Toxicity. Eventually Red Flag for process in materials manufacturing with high emissions contributing to Acidification. Assessment method: The weighting of the indicator should take into account local background conditions. In certain regions it might be neglected. If Acidification is a local problem, it should be taken into account at least in the 'operation' phase. Policy: Importance depends on local background conditions. A further reduction of Acidification still is a goal of most developed and developing countries.

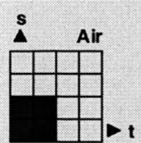
Toxicity	
	Toxicity is an aggregate for a large range of toxicity related impacts. "Adding up" the importance of all the individual toxicity related impacts will result in a **medium to high importance**
indicator	A general Toxicity indicator could be made up by the aggregation of a Human and a Eco Toxicity indicator. See chapter 3.4.6 Toxic Equivalency Potentials (TEP) for more information on the aggregation of toxic chemicals. Toxicity would cover a very large field of impacts on human and environmental health that are not covered and not highly correlated by other major indicators like Global Warming and Resource consumption. It is very important that the indicator takes into account fate and exposure. It then can also include effects like the long term poisoning of soil by heavy metals, airborne particulates etc.
Application	The indicator covers a very broad spectrum and could represent all toxicity related effects in all three considered applications.
Human Toxicity	
	The damage from disperse intake of toxics by the whole population is expected to be quite high. On the level of the individual it can be fatal. The spatial range and persistence varies strongly depending on the specific chemical. Existing and new control strategies have to address many sources and will have to take a long time perspective. The problem is considered to be of **medium** importance in general, but can have a **high** importance in locations with high exposure to toxins.
Buildings	Upstream: toxic releases from production of building materials and components, exposure of workers to chemicals on the construction site. Operation: Toxic releases from combustion processes of building operation into environment, exposure of occupants to toxic releases of building materials and materials used for building maintenance. Downstream: Waste streams from building demolition can contain persistent organic toxics and heavy metals, although usually not in very high concentrations.
Indicator	The human Toxic Equivalency Potentials developed in the USA is based on a sophisticated fate and exposure model. The TEP is expressed as benzene equivalents for carcinogens and toluene equivalents for chemicals with non-carcinogenic health effects. The TEPs from different chemicals can be added within the two categories for carcinogens non- carcinogens.
Application	See Toxicity

	Ecotoxicity
	Ecotoxicity includes all toxic impacts on the living nature. Many chemicals that show a high Human Toxicity will also show a high Ecotoxicity. But some of the exposure roots are different and some chemicals that are not toxic for humans, can have toxic effects on other species.
Buildings	Upstream: toxic releases from production of building materials and components Operation: Toxic releases from combustion processes of building operation into environment Downstream: Waste streams from building demolition can contain persistent organic toxics and heavy metals, although usually not in very high concentrations.
Indicator	[CML 1992]: Aquatic (ECA) and Terrestrial (ECT) Ecotoxicity are differentiated. Emissions into air are neglected. m^3 of water or kg of soil loaded up to a critical value are calculated. As the toxic impact on millions of species has to be considered, the lowest critical value for the most sensitive species is taken. The summation of critical volumes/masses that have been derived from critical values for species as different as a salmon and a coral, is a controversial point of the method. Other indicators exist, but have not been further investigated in this study.
Application	See Toxicity
	Carcinogenic Substances → **Toxicity**
	Heavy Metals → **Toxicity**
	The damage from heavy metals at current ambient concentrations is not very high in countries where leaded fuel is banned. Individual buildings, which contain lead paint, can cause a severe damage to individuals. Heavy metals in the soil are very persistent. Long term accumulation in soil could present a severe, nearly irreversible problem. Technically a control would be possible. Overall the problem is of **medium** priority.
Buildings	Upstream: Heavy metal releases from manufacturing processes Operation: Heavy metal releases of power stations. Paint containing lead is still a big problem for contamination of occupants. Copper and Zinc used in construction can be released in significant amounts, in particular if exposed to Acid Rain.
Indicator	Amount of individual heavy metals released. Aggregation on the basis of toxicity taking into account exposure root. Red Flag for materials containing heavy metals or releasing heavy metals during manufacturing.
Application	Manual: include in Toxicity Assessment method: included in Toxicity, Follow Red Flags to prevent acute intoxication.

	Policy: avoid heavy metal releases in building industry.
	Pesticides/Herbicides → **Toxicity**
	The building related use of pesticides and herbicides is minor.
Indicator	Red Flag Pesticides that are problematic for indoor air quality must be banned in construction materials as well as in the operation phase. Problematic Herbicides for landscaping should be avoided.
Application	General Guidelines, building construction and maintenance specifications
	Toxic and microbiological pollution of surface waters → **Ecotoxicity**
	Soil and Groundwater Pollution → **Toxicity, Heavy Metals**

Photosmog	
	There is a medium damage potential, that will be confined to local or regional levels and is reversible within hours. The impact strongly depends on local conditions, and can have a **low to medium** importance.
Buildings	Upstream: VOC releases from paint and other solvents on the construction site. Operation: NO_x from heating system based on combustion. Downstream: No relevant emissions of NO_x or VOC.
Indicator	[CML 1992]: Emissions are transferred into an effect score of Ethylene equivalents. The formation of O_3 from VOCs and NO_x is a non-linear effect. For the determination of the weighting factors, it is linearized. Quality: (0) Low NO_x emissions will also be required by indicators addressing Human Toxicity and Acidification. Photosmog could eventually be integrated into a Toxicity indicator.
Application	A manual based on generic data can not take into account Photosmog in an appropriate way. Eventually Red Flag for process in materials manufactured with high emissions contributing to Photosmog. An assessment method should require low VOC emissions during building construction and low : NO_x during building operation. Policy: Photosmog is a problem that has to be solved on a regional level and is an example of an impact that only can be solved by an integrated approach, addressing different sources of VOC and NO_x.

Wintersmog	
	Nowadays this type of smog is mainly limited to Eastern European cities. The major sources, like particulates and SO_2, will have to be reduced anyway because of their toxic effect and they are taken care of in other indicators. In general the effect will not be relevant for us. -> **low importance**
Application	Policy: Cities where Smog still occurs will have to address the problem.

General Urban Air Pollution	→ **Photosmog, Wintersmog, Acidification, Human Toxicity**
	This includes bad air quality in urban areas due to high concentrations of primarily: ozone (O_3), carbon monoxide (CO), suspended particulate matter (SPM), sulfur-dioxide (SO_2), nitrous oxides (NO_x), and Heavy metals. Many cities have a baseline problem in particular with NO_x and O_3. In some megacities, Urban Air Pollution is a very severe problem. The damage on human health can be very high locally, but conditions are reversible once emissions are under control. The impact strongly depends on local conditions, and can have a **low to high** importance.
Buildings	Upstream: If manufacturers of building materials are located in an urban area, they can contribute to the problem. Operation: The building operation can contribute significantly to urban air pollution, mostly from combustion processes for heating. Particularly damaging is the burning of dirty coal in bad stoves, as it still is often the case in China. In urban areas with high urban air pollution, a different technology has to be chosen to limit emissions locally. Downstream: Small contribution.
Indicator	Emissions of the main pollutants listed above. If Aggregation is necessary, it could be done on the basis of Toxicity equivalents
Application	Manual: A manual based on generic data can not take into account General Urban Air pollution in an appropriate way. However, the emissions will be covered already by Toxicity. Assessment method: The choice of the heating system should respect local conditions. Policy: Urban Air Pollution is a problem that needs a comprehensive approach to be solved.

Radiation	→ **Nuclear Waste, Radon**

Eutrophication	
Buildings	Excluding the use of washing powder etc. from our system boundaries, the building related emissions contributing to Eutrophication are minor. The impact needs not further consideration.

Waste	
	There is a wide range of waste qualities ranging from stone-like and inert waste from building demolition to highly reactive hazardous waste. Whereas the first tends to be problematic in terms of volume, the problem with the latter is its toxicity.
Indicator	There are two principle approaches in deriving waste indicators: The first approach models the whole downstream process of waste and the related pollutant released from the disposal sites or waste combustion. The impact of waste is translated into other impacts of pollution. See chapter 3.5. In the second approach, waste is summed up on the basis of mass or volume within one waste category. An indicator for Hazardous waste should take toxicity into account.
Application	Manual: Qualitative indication of waste at time of construction and of possibilities of recycling and disassembly could be included. Assessment method: Difficult to integrate. Strategies for recyclability could be required. Policy: Minimization of waste is a major issue of environmental policy.
	Construction Waste
	See chapter 4
Buildings	By definition all building related.
Indicator	Mass or volume of waste.
	Industrial Waste
Buildings	Upstream: from building material manufacturing.
	Hazardous Waste
Buildings	Upstream: from building material manufacturing.
Indicator	Should take into account toxicity.
	Nuclear Waste
	The final disposal of nuclear waste is still an unsolved problem for most countries. Nuclear waste is very concentrated but has a very long persistence. → **Low to medium importance**
Application	No new nuclear power station is planned to be built in developed western countries at the moment. Existing nuclear power stations will continue to be used independent of our design decision. The indicator on non-renewable energy requires a reduction of the consumption of electricity, including nuclear power, already. -> no need for particular consideration in the context of buildings.
	Waste Heat

	Into water: from thermal power stations. Release into the air increases the heat island effect in cities, which has a positive aspect in winter, but increases cooling loads in summer.
Municipal Waste	
	Is outside of our system's delimitation for building impacts. An assessment method might require recycling facilities to reduce municipal waste.

Aesthetics/ Landscape degradation	
	Landscape degradation and aesthetics are a problem. However, they do not have an influence on Sustainability in a narrow definition, which considers only the physical well being of nature and human beings. The quantification is difficult. → **Low to medium importance**
Buildings	Buildings can have a major impact on aesthetics and landscape degradation.
Indicator	Difficult to quantify
Application	Not part of Sustainability as defined in this study

Visibility	
	The impacts of reduced Visibility due to air pollution is similar to landscape degradation and aesthetics but can be measured and quantified. → **Low importance**
Application	Not part of Sustainability as defined in this study

Occupational and Industrial Health	
Buildings	See chapter 4.5.3
Indicator	No indicator is currently available that would aggregate different impacts on Occupational Health. Red Flags can mark particularly problematic processes.
Application	Manual: Red Flag. Assessment method: requirements on building construction. Policy: Occupational Health is a problem that has to be solved on a socio-political level.

Direct Casualties / Accidential Releases	
Indicator	LCA based indicators do not include accidental releases and direct casualties.
Application	Policy: Risk assessment and management are necessary to recognize and avoid accidental releases and direct casualties.

Noise	
Buildings	Upstream: Construction can have a local high impact on neighborhoods and workers (occupational health). Overall building related noise is relatively small. Building occupants are subject of noise, but not source.
Application	Not included in any application under consideration.

Odor	
	Not building related

Visual and Thermal Comfort	
Indicator	Following standards guarantees a high level of comfort.
Application	Not to be included in manual Assessment method: Minimal requirements on comfort. Policy: Setting of standards.

Indoor Air Qualtiy	
	See chapter 4.5
Indicator	No indicator exists currently that aggregates different pollutants contributing to bad IAQ. Proposals for such an aggregated indicator exist [Takemasa 1998]. There should be no need for such an indicator. High indoor air quality can be achieved anyway with proper design and construction. Red Flags can ban critical materials. Thresholds for maximum releases for materials can be fixed to ensure no negative impact on IAQ. E.g. CO_2 1000ppm, small particulate matter: 0.15mg/m3 [Takemasa 1997].

Application	Manual: ban critical materials by Red Flags. Require 'Materials Declaration' that state chemicals included and their emission rate. Assessment Method: Has to look at the whole concept on how IAQ is addressed, including source control and ventilation efficiency. A report could be required that states strategy and measures taken. Policy: Standards on maximum indoor concentrations for certain pollutants. Standards on ventilation Standards on maximum releases

Asbestos	
Indicator	Red Flag, materials containing asbestos have to be banned.

Radon	
	Can have a high importance locally under certain conditions.
Buildings	Radon problem only occurs indoors.
Indicator	Concentration of radon.
Application	Manual: not included. Assessment method: Require check for risk of Radon at certain site and necessary countermeasures.

Non-renewable Energy	
	Non-renewable Energy is a basic input of our economy's activities as fuel energy and also as feedstock energy. It is irreversibly lost. → **High importance.**
Buildings	High share of building operation and upstream processes of buildings, see chapter 4.
Indicator	The indicator for non-renewable energy will show a very high correlation with Global Warming. Considering only the resource aspect of non-renewable energy the indicator is 'Energy' with the unit [Joule] (see chapter 3.4.5 for further discussion on the energy content of nuclear energy).
Application	In general non-renewable energy should be included in any application, however it might be covered sufficiently by Global Warming in most cases. Manual: Global Warming covers aspect of energy. Add non-renewable energy possibly as additional information. Assessment method: similar to manual.

	Policy: The reduction of the consumption of non-renewable energy still must receive high priority in building related policy. Although in the future it might be more effects like Global Warming that are the driving forces behind this attempt.

Abitotic Resources	
	There are different viewpoints on the importance of resource depletion, for which the importance varies between **low and high**.
Buildings	Very high share of buildings during upstream processes.
Indicator	[CML 1992]: effect score = Extractions * (1/reserves) Another multiplier (world yearly extractions/reserves) should be included, but the available data was insufficient to do so. Different scarcities are added (fossil fuels, ores etc.).
Application	Manual: should be included if considered as of high importance.

Biotic Resource Depletion	**→ Deforestation**
Buildings	The only biotic resource that is depleted in the context of buildings are forests.

Loss of Biodiversity	**→ Habitat Loss**

Deforestation	
	Loss of virgin forests is considered a major impact.
Buildings	Wood is used in large amounts for building construction and operation.
Indicator	Red Flag / Requirement No old growth, only wood from proven sustainable forestry. If possible labelled like for example by "Forest Stewardship Council (FSC)".
Application	Include in all applications.

Fresh Water	
	Very location specific. Importance ranges from no problem to locally very high importance, increasing importance in the future for some regions. The depletion of ground water and the continuous lowering of the groundwater table is specifically problematic and has to be avoided.
Buildings	A high share of water is used in building operation.

Indicator	Has to take into account local conditions.
Application	Manual: neglect. Building assessment: Include for operation, weight depending on local conditions. Policy: depending on local conditions.

Ground Water	**→ Fresh Water**

The following tables give a summary on the impacts that are considered as being the most important and for which buildings have a major share. The impacts marked in bold letters in Table 6.2 are supposed to cover the major dimensions of building related impacts. Also shown are 'subindicators' which are covered as well by the indicator. The here listed impacts should be considered in some form in any application of building related sustainability tools, be it the manual, a building assessment method or general building policy.

Land use will be difficult to consider for the manual, as indicators that encompass different forms of land use are poorly developed for the moment. More important is the land use of the building itself, which has to be a fundamental or an essential section in the assessment method.

Table 6.2 Impacts that should be considered in all applications

Pollution and Waste	
Global	**Global Warming**
Regional and Local	**Toxicity** Human Toxicity Ecotoxicity covers among others: Carcinogenic Substances Heavy metals **Waste** Construction waste Industrial waste Hazardous waste **Land use** covering: Habitat Alteration and Destruction Loss of Biodiversity Land as resource
Indoor	**Indoor Air Quality**
Resources	
	Resource consumption Non-renewable energy (fossil, nuclear) Abiotic resources (minerals and ores)

Table 6.3 presents impacts, which can be of high importance regionally or locally. Whether they need to be considered depends on the local conditions. A manual using generic environmental data for the choice of different assemblies will not be able to take these impacts into account.

An assessment method should take these effects into account for the operation phase of the building. Different heating systems might get different weight depending on different local conditions for example.

All the effects of Table 6.3 need to be tackled by a comprehensive approach in regional environmental policy.

Table 6.3 Impacts which can be important locally/regionally

Pollution and Waste	
Regional and Local	General Urban Air Pollution Acidification Photosmog Visibility
Resources	
	Fresh Water

As mentioned before, banning very specific materials can control some impacts. These impacts are listed in Table 6.4.

Table 6.4 Impacts, which can be addressed by specific measures, and 'Red Flags'

Pollution and Waste	
Global	Ozone Depletion
Regional and Local	Pesticides / Herbicides
Immediate environment / indoor	Occupational and Industrial Health Indoor Air Quality Asbestos Radon
Resources	
	Deforestation

6.3 Building Indicators and Time

Due to the long lifetime of a building, the time aspect needs special consideration: The first and major problem is the lifetime itself, which is usually unknown. But the functional unit for the services that a building is providing should include the time factor. For housing the functional unit can be "1m^2 of housing for one year". In order to get the total impact from construction and operation of the building, the initial impacts from the construction of the building are divided by the lifetime and the yearly impacts of operation are added

In [SIA 1995] and other studies, a pragmatic approach is taken by fixing the lifetime to a typical value. This approach seems reasonable as a building's lifetime is often rather limited by external factors than by degradation of materials. In the Swiss manual which will be presented below, the total lifetime is assumed to be 80 years. The US method BEES 1.0 [BEES 1998] and many other studies use50 years for their life-cycle considerations.

For elements that suffer from material degradation - like paint, carpets, or window sashes — the most appropriate lifetime based on experience has to be used. The Swiss government's Office for Construction published a list that is used for maintenance cost calculations. Large professional building owners also have such data.

The second problem with the long lifetime of buildings concerns the fact that some emissions will only occur after many years. They would have to be weighted by background data that is not known yet. Again it is proposed to take a pragmatic approach, which treats all emissions occurring over time in the same way. The projection of an increasing or decreasing importance of a certain impact can be included in the choice of the set of indicators and in the weighting factors.

A third problem is the change of technology over time. How should we treat disassembly, the phase which is the most distant in time? It would be possible to assume today's average, today's best available technology or a projection of expected deconstruction technology and processes as they might be used in some decades. The real situation can not be predicted. However, as we have seen in chapter 4, the impact from demolition is rather small, and the trend towards disassembly will even lower the impact from demolition. Under this viewpoint quantification of demolition impact becomes secondary. As an alternative it would also be possible to quantify deconstruction/disassembly in intermediate terms like 'mass to be disposed'.

For the operation of the building a pragmatic approach is to assume today's technology over the whole lifetime, unless a strong argument for a different technology in the future has to be considered. To minimize the error from the use of generic data, the most recent data available should be used.

6.4 Weighting of Building Indicators

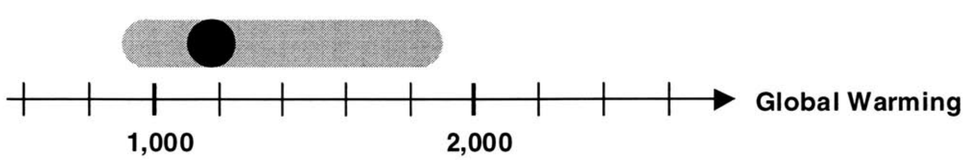
We have reduced the amount of indicators to a small number, as presented in Table 6.2. These indicators are already aggregated using some of the methods presented. For specific or individual applications there might be no need for a further aggregation. If some of the regional indicators are also included, a further aggregation might be necessary.

- Wherever 'Red Flags' were used, or a threshold was set, no weighting is necessary.

- For full weighting, **normalization** is an essential step. Normalized impacts will be easier to interpret. Normalizing also helps in error checking. Normalization was explained in chapter 3. Dividing each impact by the total impact of a country is one possibility for normalization. . In the case of absence of national reference data, global emission data could be used. Normalization only shows which effects are large or small relative to the total effect in the reference area. It does not give any information on the absolute significance of the effect.
- Normalization is followed by **weighting**. Sometimes normalized impact scores are added directly, without further weighting, which leads to wrong results. Depending on the application, the weighting can be done by a panel, e.g. determined by the developers of the assessment method, or the client. The Science Advisory Board of the EPA also recommended that "subjective values always will - and should - influence the ranking of relative risks, no matter how sophisticated the technical and analytical tools become" [EPA 1994b]. This can also mean involving the population.

6.5 The Manual

The goal of the manual is to guide the designer towards a choice that results in a minimal impact under the given conditions of a certain project. A manual has to 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 materials contained in the assembly are listed. The impacts are then summed up for the whole assembly. Each impact of the assembly considered (black dot in Figure 6.1) is represented graphically in a range, which is defined by all available alternative assemblies (gray bar in Figure 6.1). [SIA 1995] is limited to the presentation of Global Warming and Acidification. All assemblies are calculated for a functional unit of one square meter. The presentation of the impacts relative to comparable assemblies is much more important than the absolute values. First of all hardly anybody has a feeling for those absolute values and secondly the designer has to choose one of the available



alternatives. His goal must be to keep the impact low for a certain assembly relative to alternative choices.

Figure 6.1 Graphical representation of the impact of an assembly relative to comparable assemblies

The major critics with respect to the Swiss handbook are the represented indicators. Many agreed on taking Global Warming as one indicator. Less consent was on Acidification only as 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.

In the 'Handbook of Sustainable Building' products like floor finishes are ranked by 'preference 1', 'preference 2', 'preference 3' and 'not recommended'. In addition limited qualitative information is given that justifies the ranking.

In this study the following strategy is taken: It is assumed that a designer that uses such a handbook is interested in sustainable building and prefers to make an informed decision if the required information is easily accessible. A fully aggregated indicator that includes environmental, human health and resource impacts is not transparent enough to serve this purpose.

A minimal set of indicators that will result in a reduction of all impacts could be 'Global Warming', 'Toxicity' and 'Resource Consumption'. These indicators could be presented in a similar way as shown in Figure 6.1 with three graphs.

It is not always guaranteed that the (sub-) impacts that are not explicitly shown will follow the pattern of the three indicators represented. Some particular process in the life cycle of one or more materials might result in a certain high impact, although all those represented graphically are much lower. A threshold for such an outlier could be to rank more than 30% higher for a certain impact in the ranking of all compared assemblies. In that case an additional graph could show that impact.

Additional information on occupational health, disposal, durability etc. could be included.

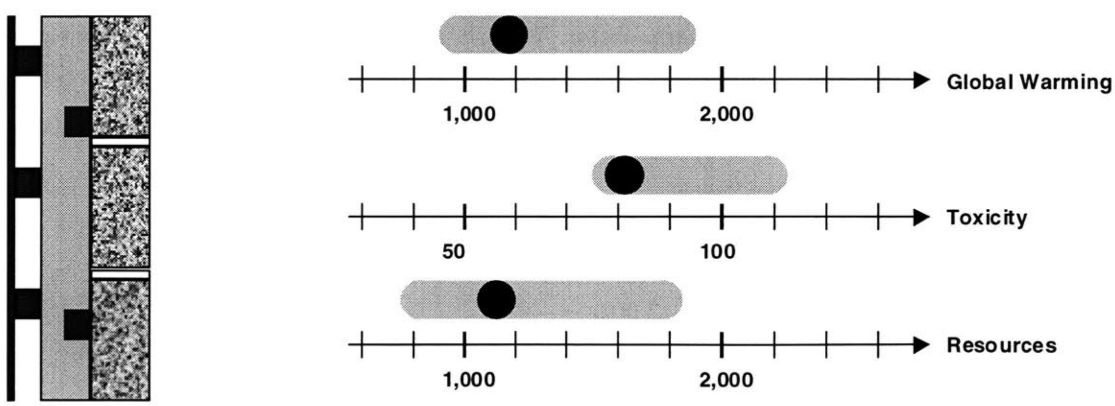


Figure 6.2 Graphical representation of the impacts of a wall assembly relative to comparable assemblies. Global Warming, Toxicity, and Resources cover the major impacts.

In an electronic version of the manual, it would be possible to provide more detailed information if requested. Clicking on Toxicity could for example reveal the different contributions of heavy metals, carcinogenics etc. For an overview showing all assemblies, it can also be envisioned that the three indicators are aggregated into one indicator. The difficulty will be to derive the relative weights. The results then could be presented in a similar way as those above. A range instead of a dot could graphically incorporate the high uncertainty related to a fully aggregated indicator. One assembly should only be considered favorable over another, if the difference is significant.

6.6 Assessment Method

Some of the existing assessment methods have been presented in chapter 5. As mentioned before, the major shortcoming of many methods is the arbitrary or equal weighting of topics with different impacts.

An LCA based approach would help in making assessment methods more objective and at the same time help to solve environmental problems more effective. If the credits are given following the real impacts, the available resources will be invested there, where they lower impacts in the most efficiently.

Ideally an assessment system should be based on a small number of indicators. The rating body or any other panel could weight the different indicators against each other in order to achieve a single index that serves as parameter for the scoring of different measures taken and the performance of the buildings assessed.

Any measure like the provision of bicycle racks would not just receive an arbitrary score, but a scenario would be made of car miles that are not driven thanks to the bike racks. The emission reduction resulting from the reduction in driven miles by car defines the score. Certainly a high error is involved in such scenarios, but such scenarios are also implicitly made by the existing methods and the arbitrariness there is much higher.

Another big advantage of such an approach is the principal openness of the method. Existing systems tend to be closed in the form of their checklist. Some credits are given away or are limited to the application of very specific technical solutions. This is counterproductive to an active involvement of the designer and does not encourage innovation. A fully performance based approach would allow to give credits for any system for which a reduction of impacts can be demonstrated in a credible manner by the design team.

Today's building labeling systems are applied on a voluntary basis. If the labeling system has a scientifically sound basis and is robust enough so that a majority can agree on it, it might even be used as benchmark for tax or other economic incentives in order to promote sustainable buildings.

7 Buildings in China and Sustainability

7.1 China's Challenge for Sustainability

Chinas has a population of 1.2 billion people, one fifth of the world. The problem is that at the same China has a much smaller share of the world's resources (see Table 8.1). The average consumption per capita of energy and other resources as well as emissions are far below western averages. If each of the expected 1.4 billion Chinese in 2010 were to consume and emit as much as an average American, it would not only bring to a collapse China itself, but also have serious implications on a global level.

Table 8.1 China's share of world population, economic output, natural resources and selected pollutants, circa 1990 (source: [Starke 1995], [BP1999])

Category	Share of World Total
Population	22
Economic Output	7
Crop Land	7
Irrigated Land	19
Forests and Woodlands	3
Protected Land	4
Roundwood Production	8
Fresh Water	7
Carbon Emissions	11
Sulfur Emissions	16
Oil Reserves	2.3
Natural Gas Reserves	0.8
Coal Reserves	11.1

China's is probably more challenged in achieving sustainability than any other country. Considering China's global impact on sustainability, it is in the self-interest of the developed countries to support China in this effort as much as possible.

China was one of the earliest countries to apply Sustainable Development as a guideline on the level of government. As early as 1983, China put forth the principle of concurrent planning. The national development policy priorities are as follows [Xiaomin 1997]: development of the economy, management of seven per cent of the world's cultivated land, and at the same time, China intends to make a sustainable use of natural resources, reduce energy consumption and control pollution.

This official policy is not easily translated into practice. Below, some topics of China's challenge for sustainability are discussed following the framework as it has been developed in the chapters above. The main problems arise from the inherent contradiction of economic development sustainability. Economic development seemingly inevitably translates into increased energy, materials, and pollutant fluxes for a nation evolving from a developing to a developed country.

The focus will be on housing related problems in urban areas. According to numbers from the United Nations Population Division and the United Nations Development program, the percentage of Urban population in China will increase from 30% in 1995 to 55% in 2025 [WRI 1996, p.151].

Global Warming

Already regularly plagued by natural disasters, and with large populations living at low-lying coastal plains, China quite probably would be one of the countries suffering the most from an increase of the world's atmosphere temperature.

After the United States, and the former USSR, China is the third largest emitter of carbon dioxide. Per capita CO2 emissions from China were 0.6 tons of carbon, compared with 5.3 tons per capita in the United States and 2.3 tons per capita in Japan [NEPA 1994]. Efficiency improvements helped to translate an exponential growth of the GDP into just a linear growth of carbon emissions. China's carbon emissions have nearly quadrupled over the last twenty years. Relying on coal as its major energy source and with a fast growing economy, China is expected to become the world's largest emitter of greenhouse gases by 2020 [Starke 1995].

Energy consumption is by far the largest contributor of greenhouse gas emissions, accounting for more than 80% of total emissions. Manufacturing of 210 million tons of cement added 4% to the total greenhouse gas emissions in 1990. In comparison, in the US cement only accounts for 1% of CO_2 emissions. With 14 percent of the CO_2 emissions, the share of the residential sector is the same as its share of energy consumption [NEPA 1994].

Urban Air Quality

The air quality in many Chinese cities is much worse than recommended by the World Health Organization. A few of the cities are shown in Table 8.2. The high concentrations of suspended particulate matter and sulfur dioxide are the gravest concern. Acute and chronic respiratory illnesses are responsible for 17% of deaths in Chinese urban areas, compared to 7% in the U.S. [Sinton 1996].

Most of the sulfur dioxide is emitted from the many coal fired oil boilers and stoves. Most of the coal is not washed and stack removal of sulfur dioxide is uncommon in China. Although the sulfur dioxide emissions are higher than in Southern China, the damage from acidification is smaller, as some of the acid is neutralized by natural alkaline dust.

The single largest emitter of particulates is the building materials industry with a share of 24%. Power plants follow with 18% and the ferrous industry with 8%. Non-industrial users, mainly household contribute over a quarter [Sinton 1996].

Table 8.2 Urban air quality in Chinese cities, New York and Vancouver (source: World Health Organization and the Nations Environment Programme, [WRI 1996])

	Suspended Particulate Matter [μg/m³]	**Sulfur Dioxide [μg/m³]**
Beijing	362.7	88.6
Guangzhou	169.7	45.5
Shanghai	225.2	63.3
Shenyang	356.9	131.5
Xian	444.9	50.0
New York	61.6	37.5
Vancouver	34.9	17.1
WHO *)	60-90	40-60

*) recommended by the World Health Organization

Land use

Land use management is one of the top priorities for China. With 7% of the world's cropland, China has to feed 22% of the world's population. The population density is about four and a half times higher than in the US.

The urban per capita living floor space was only 7.9m^2 per person in 1995, the official goal is to achieve 9m^2 in 2000 [Xiaomin 1997]. This is still 2-4 times less than in western countries. The floor space not only keeps increasing per person, but the urban population itself is also increasing. This puts a constant pressure on the surrounding lands that are also needed to feed China's population. The contradiction of economic growth and urbanization versus land use for farming was probably more apparent in Shanghai than anywhere else during the big building boom in the nineties. A law was instituted which halted the conversion of agricultural land into built surface to protect farmland from being built over. According to official numbers, 15 million hectares of arable land were converted to other uses over the last three decades in China [Starke 1995].

Another form of pressure on arable land by urbanization is the use of soil for brick manufacturing. In Beijing the construction with clay bricks has been forbidden after brick manufacturing used up too much of the soil that is already scarce for agriculture. The 450 billion bricks produced in China in 1990 consumed about 640 million cubic meters of clay in 1990 [Liu 1994].

Renewable resources

The numbers on the area of forests are very contradicting from different sources. What is true in anyway is that China can not meet its demand for wood. In spite the ongoing forestation efforts, large amounts of timber must be imported. Wood therefor does not present an alternative for other building materials on a large scale.

China's seven per cent share of the world's freshwater are unevenly distributed with most water available in the South. Many cities suffer from a constant water shortage. In Beijing for example, the groundwater table keeps dropping constantly. Still, demand is expected to increase heavily, when more and more people get connected to fresh water supply and sanitation systems. Some of the shortage could be overcome by reducing losses in the distribution systems and using water more efficiently. As with energy, Chinese industry is also much less efficient in the use of water.

Non Renewable Energy

A reduction in energy consumption is practically impossible. China was very successful in reducing energy consumption and emissions per economic output, but the economy was growing much faster.

The primary energy consumption has risen from 637.3Mtcoe in 1980 to 1,039Mtcoe in 1990 and 1,164.7Mtcoe in 1994. It has doubled within less than 20 years. An even faster growing industry, building stock, and transportation sector offset the large progress made in energy efficiency. 74% of this demand is met by coal and 18% by crude oil. Natural gas only provided 1.9% and hydro electricity 5.6% of primary energy in 1994 [Sinton 1996].

The oil reserves of China are small compared to its population. After exporting oil for many years, in 1993 China for the first time became a net importer of oil. Imports for oil are expected to increase steadily. If China does not want to fall into a complete dependence on foreign countries for oil supply, oil is not an alternative as a large scale energy source. The use of oil should be limited for transportation and as feedstock energy for China's industry.

The use of natural gas has increased strongly. Still, with only 0.8 percent of the world's gas reserves, China's domestic natural gas reserves are expected to last for about fifty years at the current use rate [BP 1998]. With increasing demand this number will drop. Although not a major source of energy, natural gas has improved indoor air conditions for many homes where it replaced the use of coal in open fires for cooking.

The residential sector accounts for about 14 percent of commercial energy consumption. This does not include the massive use of biomass in rural areas where most of the population lives. This would just about double the share of residential energy consumption. Household's commercial site energy consumption has been growing fast until the late 1980s and peaked in 1988. Since 1992 it has actually been falling [Sinton 1996]. This drop was achieved by a penetration of coal briquettes and more efficient stoves, electrical heating and cooking appliances and increased availability of gas. The share of coal for total direct end use in households dropped from 90% to 72% within a dozen years. At the same time the shares of electricity (4.6 to 17.6%), district heating (1.7 to 2.7%) and LPG (0.8 to 2.8%), natural gas (0.3 to 1.9%) and town gas (0.9 to 2.2%) have risen. This fourfold increase in the share of electricity means an absolute increase of the electricity consumed by households by more than a factor eight between 1980 and 1994 [Sinton 1996]. This goes in parallel with a massive increase of electric household appliances. In Shanghai for example, besides many other appliances, there now are 113 TV sets, 101 refrigerators, 82 washing machines and 50 air conditioners per 100 households.

Renewable Energy

Hydro-, wind-, and solar energy are the only domestic energy sources available for a long term sustainable energy path. A study on a large scale wind farm in inner Mongolia and a 500km long-distance transmissions line to Beijing, came to the conclusion that the electricity from wind is close to being cost competitive with coal power [Lew 1996]. Other studies concluded that most of the alternative energy sources that can be developed on a large scale in China over the next twenty-five years are more costly than coal. The same report suggests that by 2020 China could meet 20% of its energy and 40% of its electricity demand by alternative energy sources [NEPA 1994].

Building materials industry

The output of major construction materials tripled within a decade after the 1970s. By the late 1980s, China led the world in the production of cement, lime, bricks and flat glass [Liu 1994]. The building material industry was China's largest industrial energy consumer with 15% of the country's total energy consumption in 1990. Cement, brick, and lime accounted for 90% of the energy consumption in the sector. Small-scale cement plants and non-state-owned brick plants consume 80 to 90% of total energy demand in their industries respectively [Zhiping 1994].

China has had great success since the eighties in improving the energy efficiency of the industry. Between 1985 and 1990 the physical energy efficiency of cement production was increased at an average rate of 4.5% per year. The ferrous metal industry, another important supply sector for the building industry, also improved its energy efficiency, also not at the same rate as the building materials industry. The energy efficiency of most processes in steel production lags 5% to 40% behind standards of developed countries [Zhiping 1994]. Overall, modern Chinese steel plants have an energy efficiency which lagged about 20% behind U.S. average in 1990 [Ross 1991].

In 1990 the fuel consumption for clinker production varied between 165 and 205 kgce/ton of clinker, and the average was 180 kgce/ton (5,274MJ/ton) as compared with 157 kgce/ton in the United States and 110 kgce/ton (3,223MJ/ton) in Japanese plants [Liu 1994].

Bricks used to be the dominant wall construction material in China. Most of the bricks are produced in thousands of small enterprises with an inefficient outdated technology. The energy consumption for brick varies between 110kgce/1000 piece in the few large enterprises using tunnel kilns and 150 to 400kgce/1000 piece in smaller enterprises and rural primitive kilns. The energy consumption of the large modern enterprises seems to be comparable with Australian energy consumption for brick production on a volume basis [Liu 1994].

This lag in modern technology is supposed to decrease according to official policy: "China intends to accelerate development in the area of science and technology and actively develop new and higher forms of technology. It is anticipated that the level of technology in the main industries will be close to or at an advanced international level by the year 2000" [Xiaomin 1997].

Beijing Case Study

Until the 1980s, the large majority of residential buildings in Beijing cities were five to seven story apartment blocks. The walls of these buildings are uninsulated and made of solid brick. The diameter of external walls is either 24 or 36cm. Floors and roofs are made of prefabricated hollow-core concrete elements.

Today, most windows are still single glazed and not very airtight. For most buildings shading is poor and the design does not take advantage of potential solar gains. The design is not optimized in respect to natural ventilation. Under these conditions, many people add split units for cooling in summer, which are not very efficient (see Figure 7.1). However, night cooling strategies during the summer could keep indoor temperatures at an acceptable level without air conditioning nearly all year round. These strategies require a design that allows enough wind to pass through the building during nighttime [Da Graca 1999].

Fig. 7.1 Typical multi-apartment building in Beijing. No insulation, single glazed windows, and poor shading / passive solar design result in high heat losses in winter and overheating in summer.

IAQ

One of the major sources of poor indoor air quality is the cooking over coal-fired stoves. With the higher penetration of gas and electricity in urban households this problem could be reduced in many households. The rate of urban household gas use was 68% in 1995. The goal is 70% in 2000 [Xiaomin 1997]. Nevertheless cooking over open fire remains a high source of contaminants. Given the Chinese cooking tradition, the easiest way to counteract this problem is an efficient ventilation system that extracts pollutants from the cooking area.

Heating

The heat for most existing urban buildings used to be supplied by individual stoves or central heating systems. The coal fired individual stoves are gradually being replaced. One central boiler system typically serves 5-20 apartment blocks. The manually operated boilers had, and many still have, an efficiency of only around 50% to 60% and distribution adds another 7% of heat losses [Huang 1989]. This compares to 80% to 85% for similar boilers in developed countries. Different measures to improve the efficiency of the boilers resulted in an increase of efficiency by 10% for medium and large boilers [Zhiping 1994][PNL 1995]. The small boilers are being replaced by larger district heating systems. Compared to average energy consumption of decentralized heating systems with small boilers and stoves (28kgce/m2), the average energy consumption of larger district heating systems is 25% lower at 21kgce/m2 [Zhiping 1994]. Some of the small boilers are also replaced by centralized coal fired combined heat power plants. The result is a higher overall efficiency of the system and reduced emissions. Replacing individual stoves and small-scale boilers by a central cogeneration plant, reduced the SO_2 emissions by 32% and the particulate emissions by 48% in the example of the Jingzhou cogeneration plant. Cogeneration provides 11% of the electricity produced by thermal power plants [Yan 1996].

The boilers are operated over a defined period of the year, following a fixed schedule, which lasts from November 12 to March 17 in Beijing. The apartment owners have no means for an active and individual control over the heating of their apartment. Overheating is corrected by opening windows. But much more common is underheating. The indoor temperatures for buildings heated by central systems typically range from 16°C to 18°C. In buildings heated by stoves, the temperature only reaches 10°C to 16°C [Lang 1992]. With simple means, like tape along window frames, people try to counteract part of the large heat losses. The underheating results in significantly lower energy consumption on the cost of low thermal comfort for the inhabitants of the apartments.

The government has mandated a Central Heating Zone for which heating is mandated. This zone basically includes all locations north of the Yellow river and also some cities a bit more south or the yellow river. With about 3000 degree days for a base temperature of 18°C, Beijing has about the average climate within the Central Heating Zone. The average coal consumption for the whole zone, therefore gives an indication for Beijing. It is 30kg coal/m^2 for buildings equipped with central heating and radiators and 18kg coal/ m^2 for buildings equipped with stoves [Tu 1991].

We simulated the energy requirement for a typical building in Beijing with different conservation measures. The results are presented in Table 8.3. The simulations were performed using DOE 2.5. The base case had the typical 36cm solid brick external walls with no insulation. The windows are single glazed and were assumed to be not very airtight. The air change was fixed at 1.5 ACH per hour. This resulted in a heat requirement of 365 MJ/m^2 and year. As we have seen above, the efficiency of the small boilers and the local distribution network can be smaller than 50%. Here it was assumed to be 50%. This results in a site energy consumption of 730 MJ/m^2. This equals 25kg of coal per square meter and year, which corresponds about to typical values for Beijing.

In a first improvement, 5cm of insulation were added. This reduced the energy requirement for heating of the building by one third. Adding another 5cm of insulation and using double glazing reduced the energy consumption by another third. In the next scenario, the air change was reduced from a very leaky 1.5 air changes to 0.5 air changes per hour. This reduced the energy consumption from

155 MJ/m^2 to 53 MJ/m^2. This air change of 0.5 would require a good ventilation system in the kitchen in order to prevent indoor air quality problems. Assuming that the boiler and the heat distribution system have an efficiency of 80% instead of 50%, reduces the site energy from 106 MJ/m^2 to 66 MJ/m^2 (see last line in Table 8.3).

Table 8.3 Energy consumption for heating of residential buildings in Beijing per square meter and year

Building energy	Site-energy	Type
	879 MJ/m^2 (=30kg coal/ m^2)	Average of "Central Heating Zone", buildings with central heating system [Tu 1991]
365 MJ/m^2	730 MJ/m^2 (η=50%)	Base Case, no insulation, single glazing, ACH=1.5
241 MJ/m^2	482 MJ/m^2 (η=50%)	5cm of insulation, single glazing, ACH=1.5
155 MJ/m^2	310 MJ/m^2 (η=50%)	10cm of insulation, double glazing, ACH=1.5
53 MJ/m^2	106 MJ/m^2 (η=50%)	10cm of insulation, double glazing, ACH=0.5
53 MJ/m^2	66 MJ/m^2 (η=80%)	10cm of insulation, double glazing, ACH=0.5, high efficiency boiler

Inventory of the Building Materials

A full inventory for the building materials was not possible in the framework of this study. An inventory of walls and floors was performed. The database that was used is based on European technology [Frischknecht 1996] [Weibel 1995]. Based on the information of the Chinese building industry, 40% of energy consumption were added to the European data for cement, bricks, and steel.

The hollow core prefabricated concrete floor slabs is an efficient system as less mass is required than for solid slabs poured on site. The solid brick walls however, are very intensive in embodied energy. The 36cm solid brick wall has an embodied energy content of about 2,300 MJ per square meter of wall. This means that roughly 80kg of coal are required for one square meter of this wall type. Also including lighter inner walls, floors and roofs; then dividing by the floor area results in 2,300 MJ per square meter of floor area for the whole building structure.

If the same building was based on external walls of about 20cm of reinforced concrete, the embodied energy would be only 1,100 MJ per square meter of wall, or 1,000MJ less per square meter of floor area, compared to the building with the brick wall.

The embodied energy of the added insulation and the extra glass for the double glazing are negligible compared to the overall embodied energy of the building.

Building Life Cycle

Figure 7.2 shows the building life cycle for a typical six story Beijing building similar to Figure 4.3. The electricity requirement was assumed to be 100 MJ/m^2 and year, as Chinese households now nearly have as many electric appliances as households do in western countries. Due to lack of more detailed data, the energy requirements for hot water were also fixed at 100 MJ/m^2 of site energy.

No detailed inventory was performed for the building construction. The buildings are built heavier than typical American residential buildings, however less equipped than the Swiss building, which served as base case in chapter 4. The embodied energy for the construction was therefore fixed at 5.5 GJ/m^2 as a reference. The scenarios for renovation and demolition were the same as in chapter 4. The energy consumption for building heating was presented in Table 8.3.

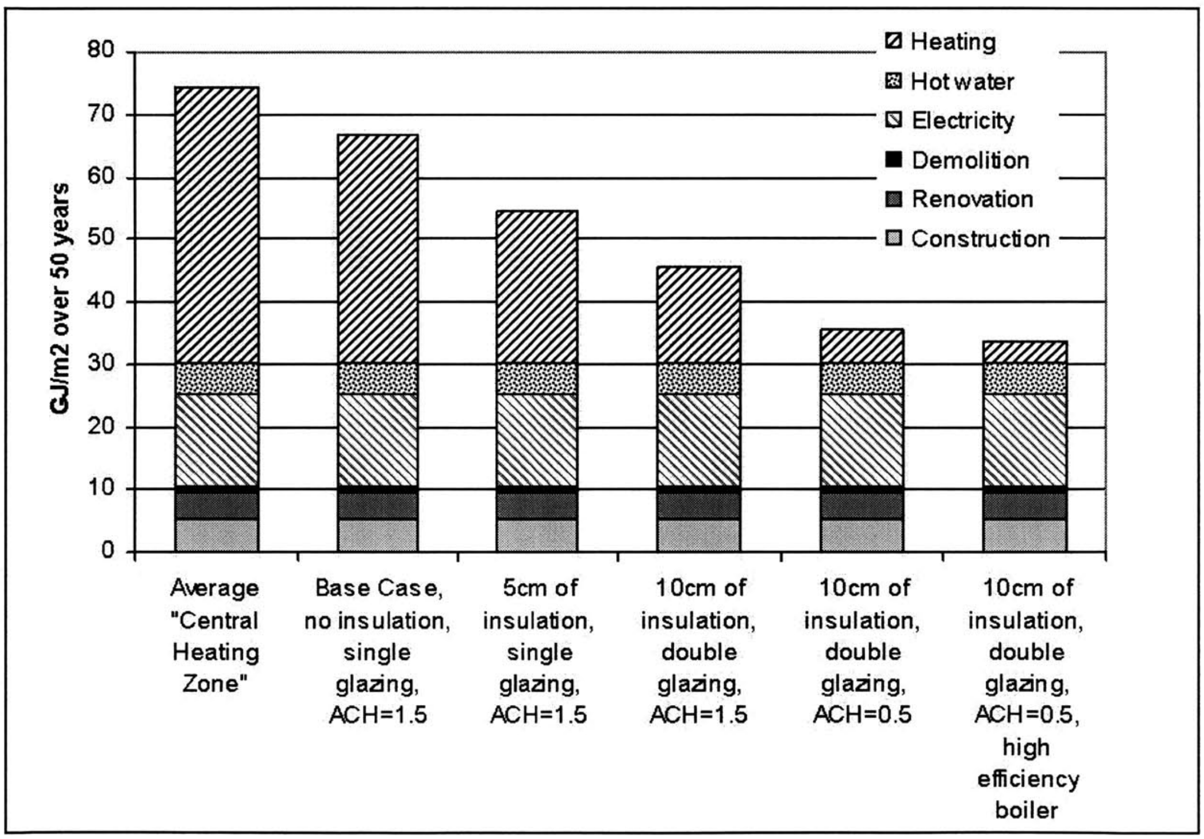


Figure 7.2 Life cycle energy consumption for a multi apartment building in Beijing

Similar to the buildings presented in chapter 4, for the average building, energy embodied in the construction weighs little compared to the energy needed for the building's operation. The energy efficiency measures taken - 10cm of insulation, double glazing, reduced air change, higher efficiency boiler- are all simple and feasible measures. They could reduce the building life cycle energy consumption by a factor of two compared to an average building. From Figure 7.2 it also becomes clear, that the next most important element to improve is primary energy consumption due to electricity consumption.

It must not be forgotten that this data are all based on a reference unit of one square meter. For a comparison with other countries, a comparison on a per capita basis should be done too. The floor area per person in China is two to four times less than in developed countries.

8 Conclusions

A framework that outlines the principles of sustainability has been developed. This framework can be used as a guideline to discuss sustainability in various contexts. Here it has been applied to identify critical issues of sustainability related to buildings. The range of topics to consider varies from indoor to global scale problems; and problems whose impact will be felt immediately to those that will be long lasting. The focus was set on environmental and human health issues. They can be summarized under the headings of pollution (including Global Warming and Toxicity), renewable and non-renewable resources, land development, and destruction of habitat, and indoor air quality. Aspects of general 'well being' of individuals and the community beyond human health are difficult to quantify and integrate into formal design tools like the ones under consideration in this study.

By analyzing a building's life cycle, we have seen that the impact embodied in building materials can be very substantial compared to the impact of the building's operation. Construction and operation of buildings have a substantial share of the whole economy's impact. The source of these buildings' impacts is spread over many components. If we want to direct our design towards minimizing those impacts, we need some metrics - or indicators - that show which path to take. Life cycle assessment has been presented as providing the means for such indicators. Life cycle assessment focuses on those interactions with the natural environment and human health that are not attended to by business today.

A critical step in life cycle assessment and with indicators in general is the aggregation of information about hundreds of interactions with the environment into a few useful indicators. Research in this field is ongoing, but there are methods available today that allow for such an aggregation. By identifying the most important topics, a minimal set of indicators was established that is easy to handle and still covers many dimensions of sustainability. Like for any applied indicators, the chosen indicators have to be appropriate for the audience.

Different applications for the indicators have been presented. One was a manual that helps the designer to make an informed decision on wall assemblies. Another set of tools discussed is building assessment methods.

In a case study for China, the developed framework has been applied to analyze the existing situation of buildings and sustainability and to explore future options. The only non renewable energy resource available in large quantities is coal. Operating the growing building stock in a business-as-usual manner, fueled by coal would create even more sever problems on a local and also on a global level. The first steps to take are energy conservation measures. The impact embodied in insulation is negligible compared to the savings of operational energy.

Comparing the floor area per person from a developed country with the floor area and consequent building related impact of a Chinese person, we can expect a substantial growth in China and other developing countries. We will have to substantially lower the average impact of our building stock in the near future to allow developing countries to come closer to our standard of living.

Considering the slow turn-over rate of buildings, this means that new buildings should probably be at least four times as efficient on a life time basis as existing buildings. In such a building, the impact embodied in construction and renovation is significant or dominant. Every component needs to be chosen carefully during design. Different aspects of sustainability as outlined in this study, covering as much indoor, local, regional and global issues, need to be considered.

It is hoped that this report will contribute to raising awareness about the importance of making the necessary data on building materials available. This includes life cycle assessment based data to quantify global and regional impacts as well as information on the chemicals contained in building materials and their influence on human health.

Bibliography

[Achternbosch 1998] Achternbosch, M. et al.:
Stoffströme und Kosten im Bereich Bauen und Wohnen. ITAS Institut für Technikfolgenabschätzung und Systemanalyse, Karlsruhe, 1998.

[Adalberth 1996] Adalbert, Karin:
Energy Demand During the Life Cycle of a Building. In: CIB W67 Symposium. Wien, August 1996.

[Anink 1996] Anink, David; Boonstra, Chiel and Mak, John:
Handbook of Sustainable Building, An Environmental Preference Method for Selection of Materials for use in Construction and Refurbishment. James and James, London, 1996.

[ASHRAE 1998] Anonymous:
Environmental Health Committee Names Critical Health Issues. *ASHRAE insights*, September 1998.

[Athena 1999] Athena Sustainable Materials Institute:
Athena Beta 1.1 Limited Release. Canada, March 1999.

[Ausubel 1998] Ausubel, Jesse H.:
Resource and Environmental Stresses. White Paper, EPRI Global Energy Strategies Forum, 23-26 April 1998.

[Azar 1995] Azar, Christian; Holmberg, John and Lindgren, Kristian:
Socio-ecological indicators for sustainability. Chalmers University of Technology, Göteborg University, Institute for Resource Theory, January 1995.

[BEES 1998] Lippiatt, Barbara C.:
BEES 1.0, Building for Environmental and Economic Sustainability, Technical Manual and User Guide. National Institute of Standards and Technology, Gaithersburg, Maryland, 1998.

[Blanchard] Blanchard, Steven and Reppe, P.:
Life-Cycle Analysis of a Residential Home in Michigan. University of Michigan, October 1998.

[Block 1997] Block, Dave:
Untitled. *BioCycle*, Nov. 98, p.46.

[Boller 1998] Boller Markus:
Regenwasser auf neuen Wegen. EAWAG News 44D, Januar 1998. pp 6-11. (EAWAG, Duebendorf, Schweiz).

[BP 1998] BP Statistical Review of World Energy 1998.
http://www.bp.com/bpstats/ (May 1999)

[BREEAM 1998] Baldwin, Roger et al.:
BREEAM 98 for offices. Building Research Establishment, London, 1998.

[Brown 1998] Brown, Lester. R., Renner, M. and Flavin, Ch.:
Vital Signs 1998, The Environmental Trends that are Shaping our Future. Worldwatch Institute, Washington D.C, 1998.

[Brundtland 1987] World Commission on Environment and Development (The Brundtland Commission):
Our Common Future. Oxford University Press, New York, 1987.

[Buchanan 1993] Buchanan, Andrew H. and Honey, Brian G.:
Energy and carbon dioxide implications of building constructions. *Energy and Buildings, 20* (1994) 205-217.

[CML 1992] Heijungs et al.:

Environmental life cycle assessment of products, Guide and Backgrounds. CML, Leiden, 1992.

[Committee 1997] President'ts Committee of Advisors on Science and Technology, Panel on Energy Research and Development:
Federal Energy Research for the Challenges of the Twenty-First Century. November 1997.

[Conseil 1997] Conseil du Development Durable:
"Sustainable Development, Action plan for Switzerland." Federal Office of Environment, Forests and Landscape, Bern, 1997.

[CRB 1991] Anonymous:
CCE-Cost Classification by Elements. CRB Swiss Research Center for Rationalization in Building and Civil Engineering, Zurich, 1991.

[Cretton 1997] Cretton, Pascal:
Influence du plan de quartier sur les reseaux et les impacts environnementaux. Master en architecture et development durable. École Polytechnique Fédérale de Lausanne, Laboratoire d'énergie solaire et de physique du bâtiment, 1997.

[Da Graca 1999] Carrilho da Graca Guilherme:
Ventilative Cooling. MIT, Cambridge, 1999.

[Daly 1990] Daly, Herman:
Towards Some Operational Principles of Sustainable Development. Ecological Economics 2 (1990) 1-6.

[Debnath 1995] Debnath, Arabinda et al.:
Comparative assessment of energy requirements for different types of residential buildings in India. *Energy and Buildings,* 23 (1995) 141-146.

[EC 1995] European Commission, DG XII, Science Research and Development, Joule.:
Externalities of Fuel Cycles - ExternE Project. Report No.2-Methodolgy. EUR 16521 EN Brussels-Luxembourg, 1995.

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

[EIA 1995] Energy Information Administration:
Household Energy Consumption and Expenditures 1993. Department of Energy, Washington, October 1995.

[EIA 1997] Energy Information Administration, US Department of Energy:
1996 Annual review. US Government Printing Office Washington D.C., 1997.

[EIA 1998] Energy Information Administration:
A Look at Commercial Buildings in 1995: Characteristics, Energy Consumption, and Energy Expenditures. Department of Energy, Washington, October 1998.

[Enquete 1998] Enquete-Kommission "Schutz des Menschen und der Umwelt-Ziele und Rahmenbedingungen einer nachhaltig zukunftsverträglichen Entwicklung":
Abschlussbericht, Konzept Nachhaltigkeit, Vom Leitbild zur Umsetzung. Deutscher Bundestag, 13. Wahlperiode, Drucksache 13/11200, 1998.
http://www.parfors.dbtg.de/btd/13/112/1311200.pdf (May 1999)

[EPA 1994] Anonymous:
EPA's Guidebook to Comparing Risks and Setting Environmental Priorities (aka The Roadmap). US Environmental Protection Agency. Revised 17 November 1994.
http://www.epa.gov/docs/futures/risk/roadmap/ (May 1999)

[EPA 1994b] US Environmental Protection Agency:

Setting Priorities at EPA, Literature Review. By: National Academy of Public Administration 21 June 1994.

[EPA 1998] US Environmental Protection Agency:
Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1996. U.S. EPA, 1998.
http://www.epa.gov/globalwarming/inventory/1998-inv/pdf/1998-inventory.pdf (May 1999)

[EPA 1998b] US Environmental Protection Agency:
National Air Quality and Emissions Trends Report 1997. 454/R-98-016, U.S. EPA, 1998.
www.epa.gov/oar/aqtrnd97/ (May 1999)

[EPA 1998c] US Environmental Protection Agency:
Latest Findings on National Air Quality: 1997 Status and Trends. 454/F-98-009, U.S. EPA, 1998.
http://www.epa.gov/oar/aqtrnd97/brochure/ (May 1999)

[EPA 1999] US Environmental Protection Agency:
National Air Pollutant Emission Trends Update 1970-1997. U.S. EPA, 1999.
http://www.epa.gov/ttn/chief/trends97/browse.html (May 1999)

[EQUER 1997] Gaugain, Sebastian; Peuportier, B. and Polster, B.:
Development et Application d'un Outil pour l'Evaluation de la Qualite Environnementale des Batiments. Rapport final de la phase 2. Rapport final EQUER. Ecole des mines et Armines, Paris, 1997.

[ERG 1997] Demkin, Joseph A (ed.):
Environmental Resource Guide. American Institute of Architects. John Wiley & Sons, 1997.

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

[Freitas 1997] Freitas, Joana:
Etude de sensibilité aux données initiales de l'écobilan d'un batiment et analyse économique de ses installations techniques. Projet de maîtrise. École Polytechnique Fédérale de Lausanne, Laboratoire d'énergie solaire et de physique du bâtiment, 1997.

[Frischknecht 1996] Frischknecht, Rolf et al.:
Ökoinventare für Energiesysteme. Swiss Federal Institute of Technology, Zurich, 1996.

[Gardner 1998] Gardner, Gary and Sampat P.:
Mind over Matter: Recasting the Role of Materials in our lives. Worldwatch paper 144. Worldwatch Institute, 1998.

[Gay 1997] Gay, Jean-Bernard, Homem de Freitas, J.; Ospelt, Ch.; Rittmeyer, P. and Sindayigaya, O.:
Standardizing Sustainability: Creating a Sustainability Indicator for Buildings. *Journal of Urban Technology*, Volume 4, Number 2, pp.53-67.

[Gay 1998] Gay, Jean-Bernard:
Indicators for Sustainability Evaluation. Presented at the Conference on "Sustainable Building Design for the 21st Century", MIT, June 2, 1998. Swiss Federal Institute of Technolgy, Lausanne.

[GBC 1998] Cole, Raymond and Larsson, Nils:
GBC '98 Assessment Manual: Volume 4: Multi -Unit Residential Buildings. University of British Columbia and Natural Resources Canada, 1998.

[Geiger 1993] Geiger, B:
Energetische Lebenszyklusanalyse von Gebaeuden. In: Kumulierte Energie- und Stoffbilanzen und ihre Bedeutung für Ökobilanzen. VDI Berichte 1093.

[Glaumann 1997] Glaumann, Mauritz and Wolfram, T.:
External Environmental Impact of Buildings, the CBE Method. In: Second International Conference Buildings and the Environment, CSTB, Paris, 1997, pp.75-82.

[Goedkoop 1995] Goedkoop, Mark:
The Eco-indicator 95, Weighting methods for environmental effects that damage ecosystems or human health on a European scale. Pre Consultants, Amersfoort, NL, 1995.

[Goedkoop 1996] Goedkoop, Mark; Demmers, M. and Collignon, M.:
The Eco-indicator 95, Weighting methods for environmental effects that damage ecosystems or human health on a European scale, updated version November 1996. Pre Consultants, Amersfoort, NL.

[Goedkoop 1998] Goedkoop, Mark:
The Eco-indicator '98 concept. In: Oekobilanz-Bewertungsmethoden. 6. Diskussionsforum Oekobilanzen, Swiss Federal Institute of Technology, 1998.

[Hammond 1995] Hammond Allen et al.
Environmental Indicators: A systematic Approach to Measuring and Reporting on Environmental Policy Performance in the Context of Sustainable Development. World Resource Institute, 1995.

[Hardin 1968] Hardin, Garret:
"The Tragedy of the Commons." Science 162 (1968): 143-54 as excerpted in Stewart, Richard B. and James E. Krier: Environmental Law and Policy: Reading Materials & Notes. 2nd ed. New York: Bobbs-Merril Co., 1978: pp 68-70 (3pages).

[Hendrickson 1998] Hendrickson, Chris, Horvath, A.; Satish, J. and Lester, L.:
Economic Input-Output Models for Environmental Life-Cycle Assessment. *Policy Analysis*,
April 1, 1998 / Volume 32, Issue 7 / pp. 184 A-191 A

[HOK 1997] Mendler, Sandra and Leibowitz, Sandra:
In Search of Design Guidance: A Review of Design Guides and Guidelines for Sustainability. Hellmuth, Obatha and Kassabaum. In: Environmental and Economic Balance: The 21st Century Outlook. American Institute of Architects, US Green Building Council and US Department of Energy, Technical Papers. Miami, Florida, 1997.

[Holdren 1995] Holdren John P., Daily Gretchen C. and Ehrlich Paul R.:
"The Meaning of Sustainability: Bio-Geophysical Aspects." Defining and Measuring Sustainability: The Biogeophysical Foundations. Eds. Munasinghe and Shearer. World Banc (for United Nations University), Washington D.C., 1995.

[Huang 1989] Huang, Yu Joe:
Potentials for and Barriers to Building Energy Conservation in China. 1989. Berkley National Laboratories, LBL-27644.

[IISD 1996] International Institute for Sustainable Development:
Bellagio Principles. Rockefeller Foundation Conference Center, Bellagio, Italy, 1996.

[INFRAS 1996] Mauch, U. and Scheidegger, A.:
Nachhaltigkeit des Bauens in der Schweiz, Ein Diskussionsbeitrag. Infras, Zürich 1996.

[ISO 14040] International Organization for Standardization (ISO):

Environmental management - Life cycle assessment - Principles and framework. ISO 14040.

[IWÖ 1994] Braunschweig, Arthur; Förster, Ruth; Hofstetter Patrick and Mueller-Wenk Ruedi: Evaluation und Weiterentwicklung von Bewertungsmethoden für Ökobilanzen – Erste Ergebnisse. IWÖ Diskussionsbeitrag Nr. 19. Institut für Wirschaft und Ökologie, Hochsuchule St. Gallen, 1994.

[IWÖ 1996] Braunschweig, Arthur; Förster, Ruth; Hofstetter Patrick and Mueller-Wenk Ruedi: Developments in LCA Valuation. IWÖ Diskussionsbeitrag Nr. 32. Institut für Wirschaft und Ökologie, Hochsuchule St. Gallen, 1996.

[Jolliet 1997] Jolliet, Olivier and Crettaz, Pierre: Critical Surface-Time 95. A life cycle impact assessment methodology including fate and exposure. Swiss Federal Institute of Technology, Lausanne, 1997.

[Knoepfel 1995] Knoepfel, Ivo: Indikatorensystem für die ökologische Bewertung des Transports von Energie, Forschungsbericht LES Nr. 20, Diss. ETH Nr. 11146, ETH-Zürich, Juris Verlag, Dietikon, Sept. 1995.

[Kohler 1994] Kohler, Niklaus: Energie und Stoffflussbilanzen von Gebaeuden waehrend ihrer Lebensdauer. Abschlussbericht des BEW Projektes. ENET, Bern, 1994.

[Kytzia 1998] Kytzia, Susanne and Baccini, P: Ressourcenbewirtschaftung am Beispiel des Wohnens. *EAWAG News* 45D, Juni 1998.

[Lang 1992] Siwei, Lang; Huang, Y.J. and Levine, M: Energy Conservation Standard for Space Heating in Chinese Urban Residential Buildings. Lawrence Berkley National Laboratory, Berkley, 1992.

[Leed 1999] U.S. Green Building Council LEED "Leadership in Energy and Environmental Design". http://www.usgbc.org/programs/index.htm. as of 5/17/1997.

[Levin 1997] Levin, Hal: Ten Basic Concepts for Architects and other Building Designers. *Environmental Building News,* 1997. http://www.ebuild.com/Greenbuilding/Halpaper.html

[Lew 1996] Lew, Debra J. et al.: Industrial-Scale Wind Power in China. Center for Energy and Environmental Studies, Princeton University, Princeton and Ministry of Electric Power, 1996.

[Liu 1994] Liu, Feng and Wang, S: The Building Materials Industry in China: An Overview. LBL-37209. 1994

[Manual 1998] Osso, Annette et al. (project managers): Sustainable Building Technical Manual, Green Builidng Design, Construction, and Operations. Cosponsored by Public Technology Inc., US Green Building Council, Dep. Of Energy and Env. Protection Agency, 1998.

[Mc Donough 1998] Mc Donough, William and Braungart Michael: The Next Industrial Revolution. *The Atlantic Monthly*, 10 / 1998.

[Meadows 1972] The Limits to Growth.

[Meadows 1992] Meadows D. H., Meadows D.L. and Randers J.: "Beyond the Limits: Confronting Global Collapse, Envisioning a Sustainable Future". Chelsea Green Publishing Co., Vermont, 1992.

[Muller-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

[Murcott 1997] Murcott, Susan:
What is Sustainability: A Definitions, B Principles, C Criteria, D Indicators, E Conceptual Frameworks. Sustainable Living Network. www.sustainableliving.org.

[NEPA 1994] The National Environmental Potection Agency of China, The State Planning Commission of China, United Nations Development Programme, The World Bank:
China, Issues and Options on Greenhouse Gas Emissions Control, Summary Report. Supported by the Global Environmental Facility. 1994.

[Newman 1989] Newman, P.W.G. and Kenworthy, J.R.:
Cities and automobile dependence - An international sourcebook. Gower Technical, Aldershot, England, 1989.

[NIOSH 1998] National Institute of Occupational Safety and Health et al.:
Implementation of the National Occupational Research Agenda. 1998.

[Norris 1998] Norris, Greg:
Systematic/Holistic Application of Environmental Life Cycle Assessment to Building Material Selection. Phase 1 Research Report. Analysis performed under contract to Center for Maximum Potential Building Systems. Sylvatica, North Berwick, Maine, 1998.

[Norris 1998b] Norris, Greg:
Direct and Upstream Emissions of Carbon Dioxide from Fossil Fuel Combustion. Sylvatica, North Berwick, Maine, 1998.

[Notter 1995] Notter, Daniel:
Maisons à énergie zéro à Trin, GR. *Energie Solaire* 4-1995,pp.40-44.

[OECD 1990] OECD Group on Urban Affairs:
Environmental Policies for the Cities in the 1990s. OECD, Paris, 1990.

[OFS 1997] Office Federal de la Statistique (Ed.):
L'environnement en Suisse 1997 - chiffres, faits, perspectives. Swiss Federal Office of Statistics, Bern, 1997.

[Papamichael 1997] Papamichael, K.; La Porta, J. and Chauvet, H.:
Building Design Advisor: Automated integration of multiple simulation tools. Lawrence Berkley National Laboratory, Berkley, 1997. LBNL-40591

[PNL 1995] Anonymous:
Energy Efficiency in China, Industrial Equipment and Small Cogeneration. Pacific Northwest Laboratories, Richland, February 1995.

[Rio 1992] The Rio Declaration on Environment and Development (Agenda 21). Rio 1992.

[Rogers 1997] Rogers Peter P. et al.:
Measuring Environmental Quality in Asia. Division of Engineering and Applied Sciences, Harvard University and Asian Development Bank. Distributed by Harvard University Press, Cambridge, 1997.

[Romm 1994] Romm, Joseph J.:
Lean and Clean Management, How to Boost Profits and Productivity by Reducing Pollution. Kodansha, New York, 1994.

[Roodman 1995] Roodman, David Malin and Lenssen, Nicholas:
A Building Revolution: How Ecology and Health Concerns Are Transforming Construction. Worldwatch paper 124. Worlwatch Institute, Washington D.C, 1995.

[Ross 1991] Ross, Marc and Feng, L.:

The Energy Efficiency of the Steel Industry in China. *Energy* 16(5): 833-848.1991

[Schaltegger 1992] Schaltegger St. and Sturm A.:
Ökologie orientierte Entscheidungen in Unternehmen. Schriftenreihe des WWZ Basel, Bd. 27, Bern 1992.

[Schmidt-Bleek 1993] Schmidt-Bleek Friedrich:
Wirviel Umwelt braucht der Mensch? MIPS – Das Mass fuer oekologisches Wirtschaften. Birkhaeuser Publ., Berlin 1993.

[Schurke 1997] Schurke, Joel:
Defining Key Steps in Construction Waste Management Planning and Implementation. In: Environmental and Economic Balance: The 21st Century Outlook. American Institute of Architects, US Green Building Council and US Department of Energy, Miami, 1997.

[SCOPE 1997] Moldan, Bedřich and Billharz, Suzanne (ed.): Sustainable Indicators, Report of the project on Indicators of Sustainable Development. SCOPE 58, John Wiley and Sons, Chichester, 1997.

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

[SIA 1993] SIA D093:
Canvas pour la declaration des charactéristiques écologiques des materiaux de construction. Schweizer Ingenieur- und Architekten-Verein, Zürich, 1993.

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

[Sinton 1996] Sinton, Jonathan E. et al.:
China Energy Databook. 1996 edition. Berkley National Laboratories, LBL-32822. Rev.

[Solow 1991] Solow R. M.:
"Sustainability: An Economist's Perspective". *Economics of the Environment: Selected Readings.* Eds. Robert Dorfmann and Nancy Dorfman. WW Norton Co., New York, 1991. Pp 179-187.

[SSB 1992] State Statistical Breau:
Statistical Yearbook of China 1992, China Statistics Press, Beijing.

[Starke 1995] Starke, Linda (Ed.):
State of the World 1995, A Worldwatch Institute Report on Progress Toward a Sustainable Society. W.W. Norton & Comapny, New York, 1995.

[Tagashira 1997] Tagashira, N. and Uchiyama, Y.:
Life Cycle Analysis of Urban Infrastructures, CRIEPI Report:Y96005, Japan, 1997.

[Takemasa 1998] Takemasa, Yuichi and Moser, Alfred:
A New Method for Evaluating Building Sustainability with Respect to Various Factors, Energy Consumption, Thermal Comfort and IAQ. AGS meeting at Swiss Federal Institute of Technology

[Tatsuo 1993] Tatsua, O. et al.:
The estimation of energy consumption and amount of pollutants due to the construction of buildings. *Energy and Buildings,* 19 (1993) 303-311.

[Therivel et al. 1994] Therivel, Riki et al.:
Strategic environmental assessment. Earth Scan Publications, London, 1994.

[Toman 1992] Toman, Michael A.:

The Difficulty in Defining Sustainability. *Resources*, No. 106, Winter 1992.

[Tu 1991] Tu, Fengxiang and Wang, Meijun:
Energy Conservation in Buildings. Beijing, State Planning Commission and Ministry of Construction.
As cited in: [Lang 1992]

[UNDPCSD 1996] United Nations Department for Policy Coordination and Sustainable Development:
Indicators of Sustainable Development, Framework and Methodologies. United Nations, New York, 1996.

[UNDPCSD 1997] United Nations Department for Policy Coordination and Sustainable Development:
Critical Trends: Global Change and Sustainable Development. United Nations, New York, 1997.

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

[Wernick 1996] Wernick, Iddo K.; Herman, R.; Govind, S. and Ausubel, J. H.:
Materialization and Dematerialization: Measures and Trends. *Deadalus* 125(3): 171-198 (Summer 1996)

[WorldBank 1997] World Bank:
Expanding the Measure of Wealth, Indicators of Environmentally Sustainable Development. The World Bank, Washington, 1997.

[WRI 1996] World World Resources Institute, United Nations Environment Programme, United Nations Development Programme, and The World Bank:
World Resources 1996-97, The Urban Environment. Oxford University Press, 1996.

[Xiaomin 1997] Xiaomin, Guo and Li, Gao:
Application of Indicators of Sustainable Development in China. In: Moldan, B. et al. (ed.): Sustainable Indicators. SCOPE 58, John Wiley and Sons, Chichester, 1997, pp.334-339.

[Yang 1996] Yang, Fuqiang; Xin, D.; Levine, M. D. and Naeb, J.:
Cogeneration Development and Market Potential in China. Berkley National Laboratories, LBL-38835. 1996

[Yost 1997] Yost, Peter:
Residential Construction Waste Management. In: Environmental and Economic Balance: The 21st Century Outlook. American Institute of Architects, US Green Building Council and US Department of Energy, Miami, 1997.

[Zentilli 1997] Zentilli, Bernardo:
Criteria and Indicators for Sustainable Management of Forests. In: Moldan, B. et al. (ed.): Sustainable Indicators. SCOPE 58, John Wiley and Sons, Chichester, 1997.

[Zhiping 1994] Zhiping, Liu; Sinton, J. E.; Yang F.; Levine M. D. and Ting, M.:
Industrial Sector Energy Conservation Programs in the People's Republic of China during the Seventh Five-Year Plan (1986-1990). Berkley National Laboratories, LBL-36395. 1994.

[Zimmermann 1996] Zimmermann P., Doka G., Huber F., Labhardt A., Ménard M.:
Ökoinventare von Entsorgungsprozessen - Grundlagen zur Integration der Entsorgung in Ökobilanzen. Swiss Federal Institute of Technology, Zürich, August 1996, ESU-Reihe Nr. 1/96.

Appendix

A. Indicators of the United Nations and their Relation to Buildings

See chapter 3 for further explanations

Requirement (Agenda 21, United Nations)	Relation to Buildings
Social	
Chap. 3: **Combating Poverty** -unemployment rate	Affordable Housing vs. Influence on employment? Should construction be industrialized?
Chap. 5: **Demographic dynamics** -population growth rate D -population density S	Scalability of project? (What if all people would live in houses built like this? Carrying capacity of the country for certain styles of buildings Max. density of population for certain building type?
Chap. 36: **Education**	Technology adequate to local knowledge? Skills and knowledge of designers and construction workers are essential for sustainable buildings.
Chap. 6: **Human Health** -Basic Sanitation (excrete disposal facilities) S -access to safe drinking water S	 -necessity for every building -necessity for every building -In addition: High Indoor Air Quality
Chap. 7: **human settlement** -growth of urban population D -Per capita consumption of fossil fuel by motor vehicle transport D -human loss due to natural disasters D -Percent of pop. In urban areas S -area and pop of urban formal and informal settlement S -floor area per person S	 -Urban societies as problem and chance for sustainable development. Can good, affordable housing and infrastructure be provided for everybody? What type of buildings allows for growth of urban population? Limit the size of urban areas? -mixed zoning, public transport -choice of site: check for probability of disaster, -Is there a balance between rural and urban population? -informal settlement often entails insufficient sanitation and water supply, often on lands predisposed to natural disaster; threat to local environment? -a very low value can indicate unsustainability due to

	overcrowding; very high values indicate an unsustainable way of living with over-consumption
-house price to income ratio S	-right for affordable housing for everybody
-infrastructure expenditure per capita	-provision, improvement and maintenance of infrastructure as prerequisite of good housing.
Economic	
Chap. 2: **International cooperation to accelerate sustainable development**	
-GDP per capita D	-building related industry is one of the biggest contributors to the GDP
-Net investment share in GDP D	-construction of new and maintenance of existing buildings are a major part of an economies investments.
-environmentally adjusted Net Domestic Product S	-A great part of expenditures on building repairs is due to environmental damage (acid rain, dirt...)
Chap. 4: **Changing consumption patterns**	
-annual energy consumption D -Proven fossil fuel energy reserves Lifetime of proven energy reserves S -Share of consumption of renewable energy resources S -Share of natural-resource intensive industries D -Proven mineral reserves D -Intensity of material use S	-about 40% of the total annual energy consumption is directly building related: -> improve energy efficiency -roofs and other structures should be used to integrate surface intensive solar energy plants -building industry is one of the most natural-resource intensive industries: -> build more resource efficient, recycle
Chap. 33: **Financial resources and mechanisms**	-access to financial resources is a prerequisite for affordable good housing and extra investments for energy efficiency and to protect the environment
Chap. 34: **Transfer of environmentally sound technology, cooperation and capacity building** -share of environmentally sound capital goods S	-transfer of know-how of sustainable building -import environmental friendly technologies if not locally available vs. keep transport distances short
Environmental:	
Chap. 18: **Freshwater resources**	

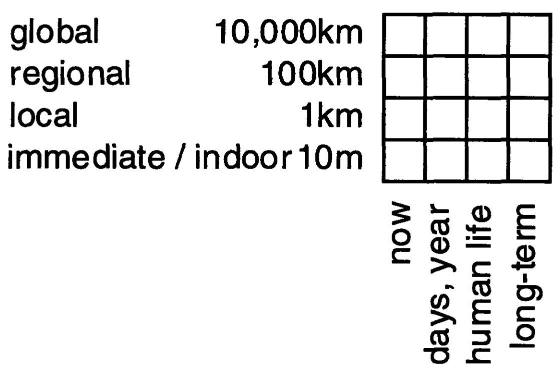
-Annual withdrawal of ground and surface water D -Domestic consumption of water per capita D -Groundwater reserves S -Faecal coliform in freshwater S -Biochemical oxygen demand on water bodies S -Wastewater treatment I	-use water-saving sanitary equipment and domestic appliances; use of gray water for non potable use. -necessity for water saving can vary locally -monitor water quality, ensure access to clean water -connect buildings to public system or provide an adequate local treatment
Chap. 17: **Oceans, seas and costal areas**	
Chap. 10: **Planning and management of land reosources** -land use change D -Changes in land condition S -local-level natural resource managem. R	-settlement is in competition with other forms of land use; building construction and operation can have a big impact on land use (mining, timber for construction and fuel,...); long term planning, to preserve quality of land, is needed.
Chap. 12: **Desertification** Chap. 13: **Mountain development**	
Chap. 14: **Agriculture**	
Chap. 11: **Deforestation** -Wood harvesting intensity D -Forest area change S -Managed Forest Area Ration R	-use of timber from sustainable forestry for construction and fuel reduces greenhouse gas emissions and the use of non renewable resources
Chap. 15: **Biological Diversity** -Threatened species S -Protected area S	-Prevent building in environmentally sensitive areas; prevent use of materials which threaten the biodiversity indirectly
Chap 16: **Management of biotechnology**	
Chap. 9: **Protection of the atmosphere** -emission of greenhouse gases D -emission of sulphur oxides D -emission of nitrogen oxides D -consumption of ozone depleting substances D -Ambient concentration of pollutants in urban areas S -pollution abatement R	-reduce airborne emissions due to operation of buildings reduce airborne emissions due to the production of building materials and on the construction site

Chap. 21: **Management of solid waste**	
-Industrial and municipal solid waste D	-choose material providers with waste management plan
-Household waste D	-Provide facilities allowing the separation and storage of household waste for recycling
-Waste management R	-management of construction and demolition waste
-Waste recycling and reuse R	-Use recycled materials, separate materials for recycling
-Municipal waste disposal R	-access to municipal waste disposal is a prerequisite for proper treatment of waste
Chap. 19: **Management of toxic chemicals**	-Build in a way that there is no need for toxic chemicals during construction and operation. Look for less toxic alternatives
Chap. 20: **Management of hazardous waste** -Generation of hazardous waste D	-Build in a way that the direct and indirect generation of hazardous wastes is prevented.
Chap. 21: **Radioactive wastes** -Generation of radioactive wastes	-Can be reduced by reducing the electricity consumption in buildings
Institutional	
Chap. 8: **Integrating environment and development in decision making**	
-Sustainable development strategies R	-Define indicators to measure building related sustainability
-Mandated environmental impact assessment	-Sustainability building assessment
Chap. 35: **Science for sustainable Development**	-research in how to make sustainable buildings
Chap. 37, 38 & 39: **national and international mechanisms and institutions**	
Chap. 40: **Information for decision making**	-like education, access to information is a prerequisite for sustainable design
Chap. 23-32: **Strengthening the role of major groups**	
D=Driving Force indicator S=State indicator R=Response Indicator	

B. Impacts

The following lists gives an overview of the most urgent problems identified by a number of sources that impact the environment and human health. The impacts shown below are not all at the same level in the chain from emission/extraction to damage. Some, like heavy metals, are on the level of emission, others, like Toxicity, are the last step before specifying damage on our safeguard subjects. Some of them are also overlapping or follow each other in the damage chain. Not all impacts are explained in detail.

Explanation



The icon with the dimensions of time and space has been introduced in chapter 2.

effect: Beside the icon is an explanation of the mechanisms of the impact.

damage: Specifies the type of damage caused by the impact.

space: Gives the typical spatial range of the impact as depicted by the icon.

time: Includes the time lag until the damage will occur and aspects of reversibility of the damage

originator: Lists the major sources for a pollutant or waste and the major consumers for resources.

threshold: Critical value that shows a lower threshold for no damage or an acceptable damage. The closer an impact is to this threshold, or the more it has passed it, the more severe will be the impact.

momentum: Includes the driving forces behind the originator and the rate of change for an impact. An impact that has become more severe in the past is considered as more problematic.

control: Impacts can be controlled by shifting to other technologies, end of pipe solutions, or a reduction of consumption. For some problems this shift is easier than for others.

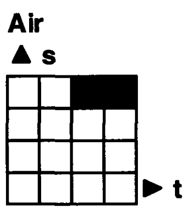
indicator: The focus is on available indicators that can measure the incremental pressure of our activities on an impact.

science: The mechanisms behind some of the impacts are better understood than for others. High uncertainty about the mechanisms means a high risk.

overall: Summarizes the sections above.

Pollution and Waste

Climate Change / Global Warming / Greenhouse Effect



Solar radiation is absorbed at the earth's surface and in the atmosphere and is re-emitted as infrared radiation. Certain molecules absorb this infrared radiation and therefore prevent it from being directly re-emitted into outer space. This trapping of heat is the so-called Greenhouse effect. Natural concentrations of these molecules keep the temperature at ambient temperatures. An increase of the concentration of absorbing molecules leads to an increase in the average temperature in the atmosphere, which in turn can lead to fatal climatic changes.

damage: Change in global climate, increase of temperature in general, but also lowering of temperatures in some other regions, increase of extreme weather conditions with storms, drought, flooding etc.

The probable changes in seasonal timing, rainfall patterns, ocean currents and other parts of Earth's life-support systems will have an impact on fauna and flora. Depending on the rate and absolute value of temperature increase, habitats could be altered and species can become extinct.

Sea levels will rise due to melting ice caps on the poles. Low level islands and waterfront land will be flooded.

The possible positive feed-back and non linear behavior could lead the whole system to a collapse or a new equilibrium with different environmental conditions. The damage in this case, would be infinite.

space: global

time: Very slow response to reduced emissions. The time for removal of CO2 of the atmosphere into a geological stable form is infinitely long in terms of human lives. It can be considered as irreversible.

originator: USA, measured in carbon equivalents for 100 years: 82.3% CO2 (of which: fossil fuels 99%, cement production 0.67%), 10% CH4 (landfills, animal farming, leakage in natural gas pipelines, coal mining, rice cultivation), 5.8% N2O (agriculture, soil management) and 1.9% HFCs, PFCs and SF6 (Substitution of Ozone depleting substances, HCFC-22 production, electrical transmission and distribution). A small indirect contribution also comes from precursors to O_3, which effects terrestrial absorption of radiation: CO, NO_x, NMVOCs.

About 14% of the CO_2 emissions from fossil fuel combustion were offset by increased mass of forest trees, litter, soils, and carbon stored in the U.S. wood product pools and landfills [EPA 1998].

China: 85% CO2 (of which: fossil fuels 95.7%, cement production 4.3%), 13% CH4, 2% N2O (agriculture, soil management). CFCs not included in data [NEPA 1994].

threshold: Proposals for a threshold for a non-effect concentration of Greenhouse gases vary. They all take pre-industrial concentrations as a reference point. At the moment discussions focus on thresholds for emissions, which means that the CO_2 concentration of the atmosphere will keep rising.

momentum: The concentration of CO_2 has risen from about 280 parts per million in 1800 to 364 parts per million in 1998. In spite of a large drop of carbon emissions in the former Eastern Bloc in the late 1980s, the world carbon emissions are still increasing. It is in particular the developing countries that show a high rate of increase in carbon emissions.

The U.S. greenhouse gas emissions rose in 1996 to 1,788 MMTCE, which is 9.6% above 1990 baseline levels [EPA 1998].

Greenhouse gases are emitted by a very large number of processes that are part of everybody's daily life. The momentum is very high.

science: A large majority of scientists agree on the existence of the Greenhouse effect. Less agreement exits on the rate of temperature change that can be expected and the potential damage.

Statistics support the theory of a general warming of the earth atmosphere: With the record temperature of 1997, the 14 warmest years since record keeping began in

1866 have all occurred since 1979 and the 5 warmest have occurred in the 1990s [Brown 1998].

control: International efforts, in particular the Kyoto protocol, are under way to limit the emission of Greenhouse gases. The major hurdle for an international agreement, is the decision on the contribution of developed versus developing countries.

The technical means to limit greenhouse gas emissions would be available. To what extent this means will be applied depends on the political process.

indicator: Pressure: release of Greenhouse gases: [CML 1992]: Global Warming Potential (GWP) measured in CO_2 equivalents. This means that each emission is expressed by its potential contribution to Global Warming relative to CO_2. As the weights differ with the considered time scale, three different GWPs can be calculated (20,100 and 500years).

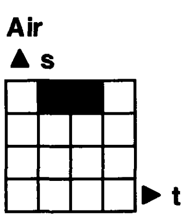
In Kyoto it has been agreed to consider the potential for Global Warming over a time span of 100 years (GWP100).

GWP is a mechanism oriented indicator and does not give any information on the damage. Quality: (+)

State: Greenhouse gas concentration in the atmosphere, world or oceans average temperature.

overall: Global Warming has an infinite damage potential, it affects the whole world and is irreversible. The momentum that drives Greenhouse gas emissions is very high. The uncertainty about the absolute temperature increase and the resulting damage is high. Means to get Greenhouse gas emissions under control would be available. The impact has **high importance**.

Ozone Depletion



Halogens emitted by human processes, mainly in the from of chlorofluorocarbons (CFCs), reach the stratosphere, where they destroy ozone molecules by a photochemical process. Stratospheric Ozone is essential for filtering UV-radiation out of the sunlight. Mainly in the southern hemisphere the Ozone concentration periodically becomes very low in an area of the size of Europe. This is the so called Ozone hole.

damage: UV radiation is a health risk for human beings (skin cancer), animals and also inhibits plant growth.

space: global

time: The removal time for Halogens from the Stratosphere is in the order of decades. Although CFC production has already plummeted, these compounds take years to reach the stratosphere, and some last for decades or centuries once there. Thus the maximum ozone loss is expected right now, as the concentration of CFCs in the stratosphere peaks between 1997 and 1999, although the emissions are already declining for some years [Brown 1998].

originator: The primary source are CFCs, which were / are used in HVAC equipment, as foaming agents, and aerosol propellant. Other halogens from chemicals like methyl bromide (pesticide) are also a source.

threshold: There is no lower threshold. Any emission of ozone depleting substances will result in an incremental damage.

momentum: Production of CFCs has dropped from a peak 1260 tons in 1988 to 141 tons in 1996 [Brown 1998]. The stratospheric halogen concentrations are at their peak value, and are expected to decrease in the future.

science: The mechanism of Ozone Depletion is scientifically understood.

control: In 1987 the first Montreal Protocol on substances that deplete the ozone layer was signed. The Protocol has been tightened several times since. Developing countries are allowed a delay in phasing out CFCs.

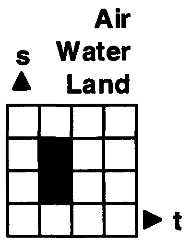
indicator: pressure: emissions of gases with Ozone Depletion Potential (ODP) measured in CFC-11 equivalents[CML 1992].

ODP is a mechanism oriented indicator and does not give any information on the damage. Quality: (+)

State: Concentration of stratospheric O_3

overall: The damage would be very high to infinite for a further depletion of the ozone layer. It affects primarily Polar Regions but would have extended to other regions too. The effect is reversible within decades. The emissions of the major sources have been reduced significantly. The physical and chemical mechanisms of Ozone Depletion are understood. This impact had highest priority a few years ago, but is now 'under control' -> low importance.

Acidification / Acid Rain



Acidic deposition, or acid rain as it is commonly known, occurs when emissions of sulfur dioxide (SO_2) and oxides of nitrogen (NO_x) react in the atmosphere with water, oxygen, and oxidants to form various acidic compounds. This mixture forms sulfuric acid and nitric acid.

The Acidification of soils is primarily due to wet and dry deposition of acids and acid forming molecules from the atmosphere. Sulfur- and Nitrogen compounds are dominant. But also inputs of ammonium compounds or chemicals with organically fixed nitrogen increase the formation of acids by means of oxidation by bacteria.

damage: damage and killing of aquatic organisms
damage of habitat
erosion of buildings and monuments

In soils the increase of H^+-ions, results in loss of nutrients (Calcium, magnesia, Sodium) and release of toxic ions (aluminum) and heavy metals, plants get damaged.

The effect on soils and water bodies depends on the local buffering capacity.

The toxic effects of sulfur dioxide (SO_2) and oxides of nitrogen (NO_x) are included in the section on toxicity.

space: Regional. The severity of the problem of Acidification can vary locally and regionally.

time: The acidity in rain etc. shows a fast response (days to weeks) to reduced emissions, but existing Acidification of soils needs a longer time to be cured.

originator: United States: Electric utility plants account for about 64% percent of annual SO_2 emissions and a minimum of another 30% is also fuel related. 95% of the NO_x emissions are fuel related, of which 30 percent are emissions from power stations. Mobile sources (transportation) are the other major contributor of NO_x emissions [EPA 1999].

In China coal is the base fuel for electricity production, industrial processes, and building heating.

momentum:

U.S.: SO_2 1978-1997:		air	quality	concentration	-55%
SO_2 1988-1997:	emissions -12%	air	quality	concentration	-39%
NO_2 1978-1997:		air	quality	concentration	-25%
NO_2 1988-1997:	emissions -1%	air	quality	concentration	-14%

[EPA 1998b].

The acid rain program together with the Regional Transport Rule of the EPA will achieve significant regional reductions in SO_2 and NO_x emissions [EPA 1998b]

In Switzerland the SO2 emissions dropped by 66% between 1980 and 1990 after stricter standards were enforced on industrial processes, building heating systems, and transportation [OFS 1997,p.69].

threshold: A moderate level of SO2 and NO_x emissions is buffered by the environment and will result in no or only a small damage.

science: The effect is understood

control: The problem of Acidification has been recognized, and countermeasures have been taken in most countries. It is possible to lower Acidification to an acceptable level with an economically reasonable effort by means of a shift to cleaner technologies and end of pipe solutions. It is the political willingness to act that defines the level of Acidification.

In China only very little of the coal-fired boilers have desulfurization equipment and only little of the coal is washed. This is supposed to change in the future.

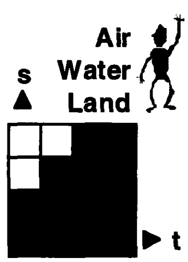
indicator: pressure: [CML 1992]: The different emissions are weighted according to their stoichiometric increase of H+. Buffering and place of deposition (land or water) is not taken into account. This is a relatively simple model.

The effect-score is expressed in SO_2 equivalents.

overall: Acidification has a medium damage potential, that will occur on a regional level, the damage is mostly reversible. Technical means to control acidification are available and in many countries the emissions causing Acidification have been reduced significantly. The importance of the impact will depend on the local background conditions and varies between **low to medium**.

Human Toxicity

see also general urban air pollution, Photosmog, heavy metals, carcinogenic substances



Pollutants are released into air, water or soil. Through different processes, which depend on the local physical environment and weather conditions, the chemicals are transferred to different environmental compartments, meaning soil, plants, surface waters, air etc. Through different exposure routes, e.g. intake by food, inhalation, dermal contact, the chemicals get into the human body, where they exert a negative effect on health. Human toxicity is a summary expression that can include different effects like cancer, cardiovascular or blood toxicity, developmental toxicity, endocrine toxicity, gastrointestinal or liver toxicity, immunotoxicity, kidney toxicity, musculoskeletal toxicity, neurotoxicity, reproductive toxicity, respiratory toxicity, skin and sense organ toxicity.

damage: Depending on the toxicity effect listed above, an impairment or deformation up to malfunctioning of certain organs of the human body will occur. The result is a reduced quality of life and a reduction of lifetime.

space: Some chemicals have a short lifetime once they are released and will only exert local damage. Other highly toxic chemicals are very persistent and can be found in any region of the world.

time: see above 'space'.

originator: There are thousands of different chemicals which are toxic for human beings. Accordingly there is a large number or sources that includes industrial production, transportation and energy production and waste disposal (see also chapter on Indoor Air Quality for indoor sources of toxic chemicals).

See also the other effects with relate to Human Toxicity.

momentum: As there is a large number of sources, the momentum is large. For most major known toxins, emissions have been reduced in developed countries.

threshold: For some chemicals 'no-effect concentrations' have been defined by human or animal studies. For many chemicals, in particular carcinogens, there is no lower threshold and any small quantity has an adverse health effect.

science: For thousands of chemicals the toxicity or a risk of toxicity is known. But there are still many chemicals for which the toxicity is not quantified.

control: The control strategy is primarily based on emission standards which in turn imply technical solutions. Technically most emissions could be lowered. It depends on the political process on what level of immission and accordingly emissions will be accepted. More problematic are the many chemicals for which the toxicity is not known yet and emission standards do not exist.

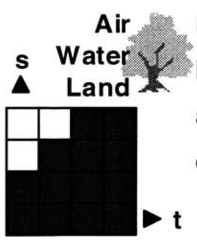
indicator: [CML 1992]: Emissions into air (HCA), water (HCW) and soil (HCS) are differentiated. The emissions are multiplied with an exposure factor and an effect factor. The exposure factor expresses, which part of the emitted substances will be breathed by humanity. The effect factor expresses how many kg of body weight will be burdened up to a critical value by breathing the substance in question. The model assumes in an extremely simplified manner that the emissions are dispersed in the world air volume and that they are not removed over time. This model is not very satisfying. Quality: (-)

A new proposal of Jolliet takes into account fate and exposure [Jolliet 1997]. The human Toxic Equivalency Potentials (TEP) developed in the USA is based on a sophisticated fate and exposure model. The TEP is expressed as benzene equivalents for carcinogens and toluene equivalents for chemicals with non-carcinogenic effects. The TEPs from different chemicals can be added within the two categories for carcinogens non- carcinogens [EDF 1999].

overall: The damage from disperse intake of toxics by the whole population is expected to be quite high. On the level of the individual it can be fatal. The spatial range and persistence varies strongly from chemical to chemical. Existing and new control strategies have to address many sources and will have to take a long-term perspective. The problem is considered of **medium** importance in general, but can have a **high** importance in locations with a high exposure to toxics.

Ecotoxicity

see also Toxic and micro-biological pollution of Water:



Ecotoxicity includes all toxic impacts on the biosphere. Many chemicals that show a high Human Toxicity will also show a high Ecotoxicity. But some of the exposure roots are different and some chemicals that are not toxic for humans, can have toxic effects on other species.

indicator: [CML 1992]: Aquatic (ECA) and terrestrial (ECT) ecotoxicity are differentiated. Emissions into air are neglected. m^3 of water or kg of soil loaded up to a critical value are calculated. As the toxic impact on millions of species has to be considered, the lowest critical value for the most sensitive species is taken. The summation of critical volumes/masses that have been derived from critical values for species as different as a salmon and a coral, is a problematic point of the method.

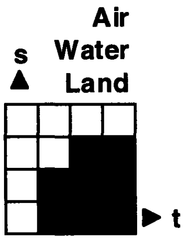
As in human toxicity, the model does not take into account the fate of emissions. This model is not very satisfying yet. Quality: (-)

Carcinogenic Substances:

See Toxicity

effect: PAH (polyaromatic hydrocarbons) benzo[a]pyren in particular, Benzene, some heavy metals, Dioxin, Asbestos and many other chemicals can cause cancer.

Heavy Metals:



Heavy metals are released into air and water. They accumulate primarily in soil and also in water. They reach the human body through the food chain. Direct intake of airborne heavy metals also occurs.

In Switzerland all soils were found to be charged with heavy metals above natural concentrations. 9.1% of the land surface were found to be polluted with heavy metals up to a medium level, 0.3% up to a high level.

damage: Airborne heavy metals have different effects on human beings, Cadmium for example will primarily affect the kidneys; lead impedes blood biosynthesis, the nervous system and raises blood pressure; manganese effects the lungs and nervous system; and mercury primarily will affect the brain.

Waterborne heavy metals will have similar effects and in addition can cause cancer, reduced fertility and mutagenic effects.

space: The persistence is very high. Airborne heavy metals can spread over regions. Local high concentrations near major sources.

time: Heavy metals are very persistent

originator: Primarily Lead (Pb) leaded fuel used to be a major source. Paint containing lead is still a big problem for contamination of building occupants. Copper (Cu) inputs are mainly from agricultural sources. Copper and Zinc used in construction can be released in significant amounts, in particular if exposed to Acid Rain.

Cadmium (Cd), and all the other heavy metals have many sources in industrial processes. Coal power stations are also a major source for airborne heavy metals.

threshold:

momentum: The emissions of lead in the United states dropped from a peak of more than 240.000 short tons in 1972 to about 400 short tons in 1991. The reduction was mainly due to the introduction of unleaded fuel. Since 1991 lead emissions have remained about stable and will be more difficult to reduce further, as the sources are mostly diffuse in many industrial processes.

science: The effect is understood.

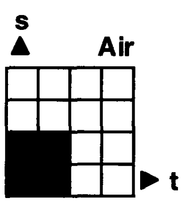
control: Technically the control of heavy metals is possible.

indicator: releases and concentrations of certain heavy metals. Aggregation with toxicity potentials.

overall: The damage from heavy metals at current ambient concentrations is not very high in countries where leaded fuel is banned. Individual buildings, which contain lead paint, can cause a severe damage to individuals. Heavy metals in the soil are very persistent. Long term accumulation in soil could present a severe, nearly irreversible problem. Technically a control would be possible. Overall the problem is of **medium** priority.

Photosmog / Tropospheric Ozone / Summersmog

see also general urban air pollution



VOCs together with NO_x react in a photochemical process forming O_3. In rural areas besides human activities, VOCs are released from plants, and NOx is mostly the limiting component. In urban areas VOCs are rather the limiting molecules.

damage: O_3 irritates mucous membranes and increases respiratory diseases. It inhibits plant growth.

space: The effect shows up locally or on a regional level on summer days.

time: The effect appears seasonally and has a daily pattern within the season. The time for cure is very short once the sources for VOCs and NO_x are removed.

originator: VOC's from traffic, industrial combustion processes, evaporation of solvents (paints) and natural VOCs from plants in rural areas.

NO_x from combustion processes.

threshold: It is the ratio of NO_x and VOCs that is relevant. At certain ratios, an increase in NO_x can result in a decrease of O_3.

momentum: U.S.: 1988-1997:
emissions (VOCs) -20%
air quality concentration of O_3 -19% (annual second daily 1-hr max.) [EPA 1998b].

Together with NO_x, O_3 is a continuous problem in many cities.

science: The effect is quite well understood.

control: The problem of Photosmog has been recognized for a long time. Nevertheless it is still a notorious problem in many cities. Technical solutions like catalytic converters for cars have helped to some degree. NO_x from transportation is still a problem and therefore so is ozone.

Different restrictions and technical solutions limit VOC emissions.

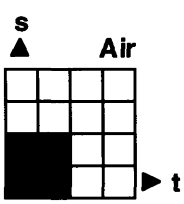
California is releasing new standards restricting VOC based solvent for paints, but the share of paints on the total of VOC emissions is minor.

indicator: [CML 1992]: Emissions are transferred into an effect score of Ethylene equivalents. The formation of O_3 from VOCs and NO_x is a non-linear effect. For the determination of the weighting factors, it is linearized. Quality: (0)

overall: There is a medium damage potential, that will be confined to local or regional levels and is reversible within hours. The impact strongly depends on local conditions, and can have a **low to medium** importance.

Winter Smog

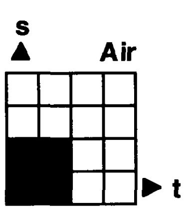
see also general urban air pollution



During the winter, the concentrations of SPM (suspended particulate matter) and SO2 can cause respiratory problems. NO_x, organic substances and CO are also involved, but to a lesser extent. This type of smog claimed 4000 victims in London in the winter of 1952. Nowadays this type of smog occurs mainly in Eastern European cities.

General Urban Air Pollution

see also photsmog and wintersmog



In the US, between 40million and 75 million people live in areas that fail to meet air quality standards for ozone (O_3), carbon monoxide (CO) and particulates. In OECD countries, trends in emissions of sulfur-dioxide (SO_2), suspended particulate matter and lead have been downward since the mid-1970s. However, national air quality standards as well as recommended concentration limits set by the World Health Organization (WHO) are still exceeded in certain densely populated or industrial areas, especially for CO, nitrous oxides (NO_x) [OECD 1990, p.22].

Worldwide, more than 1.1 billion people live in urban areas with unhealthy air. Air pollution is particularly severe in megacities such as Beijing, Seoul, Mexico City, and Cairo, Egypt.

damage: The World Bank estimates that if particulate levels alone were reduced to WHO guidelines, between 300,000 and 700,000 premature deaths per year could be avoided. In Mexico-City it is estimated that every year 4000-5000 people die due to the high air pollution. CO binds to hemoglobin and disturbs blood circulation and central nervous systems. Suspended particulate matter is adsorbed in the lungs where the active surface is reduced and cancer can be caused. NO_x have toxic effects on the human lung and on plants.

space: regional

time: CO has a residence time in the atmosphere in the order of months. But most pollutants are diluted to a non-acute toxic level once they are out of urban or industrial areas.

originator: Industrial, energy, and vehicular sources. NO_x (traffic, furnaces) O_3 (as result of chemical reaction of NO_x and VOC), SO_2, CO (incomplete combustion of traffic vehicles, heating systems and any other combustion), particulate matter (industrial processes, combustion processes)

threshold: There are WHO guidelines which give maximum concentrations for the major pollutants.

momentum: many sources

science: effect is understood

control: Technical means to solve the problem would exist. An integrated approach that addresses many sources is needed to solve the problem.

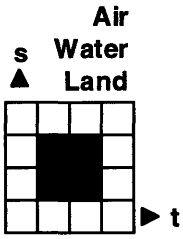
indicator: Concentrations or emissions of the major pollutants contributing to Urban Air Pollution.

overall: The damage on human health can be very high locally, but conditions are reversible once emissions are under control. The impact strongly depends on local conditions, and can have a **low to high** importance.

Occupational Health / Industrial Health

Progress has been made over the last years to improve worker protection. However employers still reported 6.3 million work injuries and 515,000 cases of occupational illnesses in 1994. In 1995, occupational injuries alone cost $119 billion in lost wages and lost productivity, administrative expenses, health care, and other costs. Not included in this figure are the costs of occupational diseases [NIOSH 1998].

Eutrophication / Nutrification:



An increased amount of nutrients, primarily nitrogen and phosphorous, from human activities leads to an overgrowth of algae in rivers, lakes, and bays. As the algae die they use up large amounts of the waters oxygen, depriving other species of the oxygen they need. In the case of the US Golf, this hypoxic area is equal to the size of New Jersey each summer at the peak of fertilizer runoff from the Corn Belt [Brown 1998].

Eutrophication also takes place on land through atmospheric deposition. This can be problematic for ecosystems with an originally small input of nutrients like heaths and bogs.

damage: Water ecosystems are destroyed. Toxic blue algae in lakes.
Certain terrestrial ecosystems can also suffer from input of nutrients.

space: regional / large regional

time: The typical response time for cure of fresh water systems to a reduced input of nutrients is in the order of some years.

originator: Fertilizer, waste water (washing powders etc.), manure and sewage sludge (used in agriculture) wash off, emissions of N and P into atmosphere from burning of fossil fuel and industrial processes.

threshold: up to a certain threshold Eutrophication is not a problem.

momentum: medium

science: The effect is understood.

control: Measures at the source: reduce nutrients in washing powders etc. The concentration of phosphor in the "Glatt", a Swiss river, has been reduced from nearly 0.6 grams/liter to less then 0.2 grams/liter within two years after a new law was passed that prohibited phosphate in washing powders. The European Union pays farmers for a reduced and controlled use of fertilizers in sensitive areas.

Waste water treatment is a major measure for reducing aquatic Eutrophication. Plants releasing the treated water into fresh water should be provided with a PO_4 elimination step, no waste water should be released untreated into oceans.

More difficult to control is the Nutrification from atmospheric deposition. Its source are different processes releasing P and N into the atmosphere.

Technically Nutrification can be reduced to an acceptable level with an affordable economical effort.

indicator: [CML 1992]: Nutrification is measured in PO_4 equivalents, which are calculated on the basis of potential production of biomass. Only P and N are considered. To include another important problem for aquatic systems, chemical oxygen demand is multiplied by a factor to equal the mass that can be decomposed with the COD.

Any form of deposition of nutrients, also the one on agricultural surfaces, is considered as bad. The local background loading, which can be important, can not be taken into account. Qualtiy: - / 0

overall: medium damage potential, mostly reversible, regional, scientifically understood. Overall low to locally medium problem.

Pesticides / Herbicides

Some pesticides are very persistent. They can be found anywhere in the world and accumulate over the food chain.

Toxic and micro-biological pollution of Water:

See also Ecotoxicity

damage: Health risk to public if the water is accessed by people. Damage to water ecosystem.

space: local to large regional. Local in the vicinity of the polluted water. Rivers can transport the pollution over large distances.

time: Polluted waters recover in the range of days to decades, depending on type and grade of pollution.

originator: Heavy metals, organic compounds, nitrates
fecal bacteria

Inadequate or no treatment of wastewater from industry and households, agriculture

control: The problem has been recognized, and many rivers and lakes that have been heavily polluted are much cleaner compared to their peak pollution time. This is especially the case in industrialized countries. Some countries undergoing industrialization face serious water pollution.

Oceans and coastal zones

See Toxic and microbiological pollution of water, Eutrophication

Radiation

effect: Under certain geological conditions, natural radon can occur in very high concentrations and special measures are necessary to prevent it from entering buildings or to flush it out if it does enter.

Nuclear power stations are not a major emitter of radiation under normal working conditions. However the nuclear fuel cycle as well as accidental releases of radiation are a major concern.

Noise:

effect: Surveys and opinion polls in many OECD countries have found that the disturbances most frequently cited by respondents is noise in home. 15% of the OECD population are exposed to potentially harmful urban noise levels. [OECD 1990, p. 24]

Another form of impact are very high level of noise at work. They can lead to hearing disabilities.

damage: Many health problems have been linked to noise problems from constant background noise. The immediate effects are concentration and sleeping problems. The overall result is a loss in social and economical welfare.

space: local to source, but diffusely spread sources

time: Immediate response to countermeasures

originator: The prime offending source of noise in terms of the number of people disturbed is road traffic, followed by neighborhood and aircraft noise. [OECD 1990, p.24]

threshold: Thresholds for noise in residential areas as well as for workplaces exist.

momentum: High noise levels are a permanent problem. In Switzerland, major technical measures to reduce the noise impact from highways and trains are underway.

science: The generation of noise is understood, however an exact correlation with different diseases is difficult to quantify.

control: Due to the strong linkage to traffic, control could be at the source by reducing traffic or making traffic less noisy.

indicator: [CML 1992]: Emitted acoustical energy is summed over all sources. This model does not take into account the properties of the receptor and should not be applied. Quality: -

overall: can have a high local importance, often underestimated, will probably get increasing attention, increasing exposure to noise in urban areas is predicted. -> importance **low to medium**

Odor:

time: Odours from industrial processes are an immediate impact, odors from waste disposal can be a longer lasting problem. It is fully reversible with the removal of the source.

indicator: [CML 1992]: The threshold of human reception of an odor is taken as critical value to calculate the m^3 of air polluted. The assumption that two odors with the same threshold of reception have the same importance is not based on scientific findings. Quality: - / 0

overall: odor is a local, reversible effect, general low importance, has to be addressed locally, **low importance**

Waste

effect: There is a wide range of waste qualities ranging from stone-like and inert waste from building demolition to highly reactive hazardous waste. Whereas the first tends to be problematic in terms of volume, the problem with the latter is its toxicity.

damage: visual impact
land use
ground water pollution
air pollution (smell, CH_4)
health problems

In Switzerland it is estimated that 40,000 to 50,000 old uncontrolled waste disposal sites exist, of which 25,000 will have to be remedied over the next 25 years for costs of $3 billions.

space: regional

time: Landfill of waste can represent a long term problem.

originator: municipal, industrial waste and hazardous waste, mainly from industry.

threshold: Gradual increase of impacts with amount of waste.

control: Many cities and countries have improved their waste management. Proper waste management including polluter-pays principle, separation, recycling, waste to energy facilities and proper disposal of waste can contribute a lot to reduce the impact to an acceptable level, as it has been shown for example in Germany and Switzerland.

	Proper waste management is capital intensive and more expensive in the short term than landfill.
indicator:	kg of industrial, municipal, non-toxic and toxic waste etc. Recent advancements in LCA allow to transfer waste into emission data by assuming a treatment form (landfill, incineration...) and calculating the resulting emissions.
overall:	importance depending on regional conditions,

Waste heat

effect:	Particularly problematic is the thermal pollution of rivers, usually caused by the cooling water of power stations Release of heat into air: heat island effect of cities is an issue of research.
space:	The damage is locally restricted.
indicator:	[CML 1992]: In the CML model only waste heat released into surface waters is considered as harmful. No threshold or local importance is taken into account. The accuracy of the indictor in terms of MJ is high, but the usefulness low. Quality: 0 Waste heat is a local problem and should to be addressed by an indicator that can take into account local background data. Besides the release of heat into water, the release into the atmosphere can also be problematic (heat island).
overall:	into water: localized controllable sources, reversible, generally low importance, can be a locally important issue

Resources

Non Renewable Energy:

effect: ..	Depletion of oil, natural gas, coal and nuclear energy. After a slight drop of primary energy consumption in the early 1980s, there followed a steady increase until the beginning of the 1990s. After staying constant until 1993, the world's energy consumption has continued rising again. Between 1987 and 1997 the consumption of non renewable energy increased by 15.7% [BP 1998].
originator:	see chapter 4
time:	By definition, non renewable energy can not be recovered.

The proved reserves for oil have increased from 653 to 1037 billion barrels since 1977. The ratio of proved reserves to yearly production stands at 40.9 years.

The proved reserves for natural gas have increased from 71 to 141 trillion cubic meters. The ratio of proved reserves to yearly production stands at 64.1 years.

The ratio of proved reserves to yearly production for coal is 219 years [BP 1998].

The emissions of CO_2 and other molecules seems to be more limiting for the total of fossil fuels rather than their limited stocks.

indicator: [CML 1992]: effect score = Extractions * (1/reserves)
Another multiplier (world yearly extractions/reserves) should be included, but the available data was insufficient to do so. Different scarcities are added (fossil fuels, ores etc.). Quality: (-)

Overall : Energy is a basic input of our economy as fuel energy and also as feedstock energy. It is irreversibly lost. **High importance**.

Abiotic resources (minerals, ores):

effect: This includes the depletion of all minerals and ores.

For most and ores no shortage is anticipated in the near future. However for some specialty metals the ratio of production to proven reserves is in the order of decades.

See also chapter 2, 3 and 4 for a further discussion on the depletion of resources, the according impacts, and indicators.

indicator: [CML 1992]: effect score = Extractions * (1/reserves)
Another multiplier (world yearly extractions/reserves) should be included, but the available data was insufficient to do so. Different scarcities are added (fossil fuels, ores etc.). Quality: (-)

Overall : There are different viewpoints on the importance of resource depletion, for which the importance varies between low and high.

Land use:

Land for urban settlement, Arable land and Food production:

effect: The loss of arable land and of soil fertility has particularly far reaching consequences for feeding an increasing world population. Erosion and desertification are the consequences of overexploitation and improper use of land and irrigation. [Conseil 1997]. Other reasons for reduced fertility are micronutrient depletion, compaction or the excessive use of pesticides.

Land used for growing urban areas and interconnecting infrastructure is in direct competition with the land necessary for food production. The area occupied by urban settlements will continue to increase. This is due to an increase in the population but also due to an increased area occupied per person in low density suburban expansions.

Very different opinions exist on the importance. Whereas some predict huge shortages in food supply [Brown 1998] others see a decrease in land used for farming due to increased productivity [Ausubel 1998]. So far the total and the per capita food production have been steadily increased according to the United Nations [UNDPCSD 1997, p.35, fig.3]. According to Brown et al. the per capita food production is decreasing [Brown 1998, p.16].

damage: Every year 50.000km^2 of arable land are lost, and for 200.000km^2 a marked reduction in production is observed. [Conseil 1997] In Germany, 10,8 per cent of land surface was covered by buildings, industrial plants and traffic and transport facilities in 1981, representing a 36 per cent increase in coverage from 1963 [OECD 1990].

space: local/regional. A food shortage could have global consequences

originator: Land occupation: land used for urban settlement, transport infrastructure, mineral mining and waste deposition.

Soil degradation: Over exploitation and improper use of land and irrigation

time: Land recovery is a very slow process, arable to urban land is almost an irreversible effect.

threshold: not defined

momentum: Loss of arable land is an ongoing process in many countries.

science: the phenomena is known for a long time already.

control: Intensification of land use. Zoning of land. Prevent sprawl. Recovery of brownfields. Depends on political willingness to recognize and solve the problem.

indicator: see also habitat loss

overall: ... Land is one of our very essential resources. The recovery rate is very slow. The momentum of land loss is high in many countries. Overall importance: **medium to high**

Soil erosion

See Land for urban settlement, Arable land and Food production:

Landscape degradation / Aesthetics / Visibility

Landscape degradation and aesthetics are a problem. However, they do not have an influence on Sustainability in a narrow definition, which considers the physical well being of nature and human beings. The quantification is difficult.

The impacts of reduced Visibility due to air pollution is similar to landscape degradation and aesthetics. However visibility can be measured and quantified.

Habitat loss:

see also biodiversity

effect: Land provides the support for natural habitats. If land is claimed for agriculture, settlement, exploitation of resources, waste disposal, or infrastructure, the natural habitat is destroyed.

Freshwater systems and wetlands have been heavily altered by drainage, channelization, dams, and industrial and agricultural pollution.

damage: Loss of habitat and therefore biodiversity. Loss of recreational space. If a large habitat is destroyed, secondary effects like landslides, floods etc. can occur.

space: The extent of the impact is limited to the area of used land.

originator: land use for agriculture, settlement, exploitation of resources, waste disposal, or infrastructure.

time: Land recovery is a slow, partially irreversible effect.

threshold:

indicator: [CML 1992] The indicator "damage to ecosystem" comes closest to addressing this problem. It also considers other forms of land use (see also land use). The indicator is a provisory model that distinguishes five classes of land use between natural land and a fully sealed surface. The unit is surface times time. Time is the time of existence of the precedent state. This concept is somehow unclear and the transitions from one state to another have equal weights. Quality: 0 / -

Frischknecht et al. use the time which it takes to bring land from one state to the next state closer to the natural state. [Frischknecht ...] Example...

momentum:

science:

control: Locally very different. Depends on political willingness to recognize and solve the problem.

overall: local/regional high damage potential, partially irreversible, also affects biodiversity which is irreversible. **high priority**.

Biotic Resource Depletion

See also Deforestation, Biodiversity

effect: Exploitation of biotic resources. Of particular concern are forests (see deforestation) and fish.

indicator: [CML 1992]:
effect score = Extractions * (world yearly extractions/reserves) * (1/reserves). Different scarcities are added (plants, animals). Very quantitative approach to a delicate problem full of non-linearity. Quality: (-)

overall: see Habitat Loss

Deforestation:

effect: Forests fulfill several functions such as supplying wood, providing a habitat for animals and plants, regulating the local climate, and protecting against natural dangers. Reducing the area or quality of a forest results in reduced functions of the forest.

The total amount of forests is stabilizing in Europe and the United States. But the quality is decreased in some of them. Virgin forest are replaced by monocultures for timber harvesting. 70% of this plantation take place in China. In the last 15 years, the area of tree plantation doubled and is expected to double again in the next 15 years [Brown 1998,p.124]. On a worldwide level the forests are shrinking, in particular the virgin tropical forests. The per capita consumption of wood is about steady, but with the population increase, the absolute consumption is increasing as well.

Between 1980 and 1995, the world lost at least 200 million hectares of forest - an area three times as large as Texas [Brown 1998].

With 16 million hectares of deforestation and three million hectares of new plantations we have an annual forest cover reduction close to 13 million hectares worldwide [Zentilli 1997].

On a global scale plantation forests only supply about 10% of the industrial wood demand [Buchanan 1993].

Harvesting wood in a sustainable way and conserving it in the building stock in the form of building material, results in a net CO_2 deposition.

damage: -Loss of Biodiversity
-Contribution to Global Warming
-Destabilization of soils and watersheds
-influence on climate (humidity)
-Decrease of Renewable Resource Capacity

momentum: see effect

science: see habitat loss

Biodiversity / Extinction of Species

See Habitat Loss and Land for urban settlement, Arable land and Food production

effect: Over 1.7 million species of animals and plants are known today throughout the world. The total number is presumed to be between 4 and 40million species. Of the about 50.000 known invertebrate species 19% are considered vulnerable to or in immediate danger of extinction. It is estimated that between 70 and 300 species are now becoming extinct every day.

The single largest problem is habitat loss (conversion, pollution and fragmentation of forests, thornscrubs, coral reefs, rivers and many other habitats), that accounts for about 70% of the species extinction. The second largest problem is over exploitation, in particular of fish and some large reptiles and mammals. The third major problem is competition and predation from invasive animal and plants, which usually spread with human help. A longer-term problem could be the fast habitat alterations due to climate change. [Conseil 1997] [Brown 1998, p.128]

damage: Loss of resources, especially genetic resources, and harm to biological stability and biodiversity.

space: regional / large regional

time: Irreversible

originator: see effect

indicator: pressure: land conversion, land fragmentation,
state: Wildlife species at risk

overall: see habitat loss, which is the major reason for Extinction of species.

Water

Fresh Water Reserves:

effect: The availability of fresh water is very unevenly distributed. In general the lack of sufficient supply of fresh water is increasing. Nearly in any area the consumption of large amounts of water has some negative impacts in the form of energy used for pumping and waste water treatment. Rivers are left with insufficient water for their original ecosystem.

The lack of water can be a natural condition but very often is a manmade problem. A local shortage can appear in high density urban areas. In many cities large amounts of water are lost due to an insufficient infrastructure.

The number of people living in countries with a shortage of water is estimated to increase from today's 130 millions to one billion in 2025.

In China's north central plain, which supplies nearly 40% of the countries grain harvest, the water table is falling by a reported 1.5m per year [Brown 1998].

damage: Insufficient provision of clean water results in sanitary problems. In some areas farming is impossible without fresh water.

space: regional

time: If the reasons for the shortage are identified and tackled, the problem is reversible. In the special case where fossil fresh water is used, as it is done in parts of Libya, no recovery is possible.

originator: The major uses of fresh water withdrawal are for Electrical cooling (of which most is released again), public water supply, irrigation and industry. In the USA, public water supply, irrigation and industry are of the same order of magnitude.

threshold: Countries are considered likely to experience chronic scarcity problems when water availability falls below about 1000m^3 per person per year.

In terms of water stress, as defined below, a range of 10 to 20 per cent indicates that water availability is becoming a limiting factor. Water withdrawals exceeding 20 per cent of available water indicate a high potential for water related problems.

control: Management of water supply and demand.

indicator: Consumption of fresh water measured in m^3. Weighting by water stress, which is the ratio of water withdrawal to water availability on an annual basis [UNDPCSD 1997, p.47].

overall: Very location specific. Importance ranges from no problem to locally very high importance, increasing importance in the future for some regions.