ENVIRONMENTAL IMPACTS OF

PASSIVE HOUSES

A comparative analysis of life cycle estimated costs and environmental impacts of two different approaches to 'Passive House' construction

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7th semester, autumn 2007

Cover photos from: www.atelierwernerschmidt.ch

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1. Introduction

> **"My personal opinion is that we are at the peak of the oil age and at the same time the beginning of the hydrogen age. Anything else is an interim solution in my view. The transition will be very messy, and will take many and diverse competing technological paths...."**
>
> Herman Kuipers, Business Team Manager,
> Innovation & Research, Shell Global Solutions,

1.1 Context

The industrialized society has historically led the market to orient its choices around scarcity of work. When industrialization began to be the new standard, natural resources and energy were available in large quantities at very low prices. This reality has been transferred in the neoclassical model in the assumption of a world of unlimited resources. As a result, mechanization has been brought to astounding levels, where few workers are now necessary to accomplish the same tasks and produce the same products. This context gave the industry an opportunity to create more complex and specialized products, leading to significant increase in energy and resource inputs. As these inputs were cheap and available, mass consumption of energy intensive products became normality. In 1956, geoscientist Marion King Hubbert working for Shell Oil Company, (fairly correctly) predicted that the US production would reach its historical peak in 1969, then start to fall, never to rise again (Campbell and Laherrère 1998). This defined the concept of 'Hubbards Peak', According to which the production rate of oil will follow a roughly symmetrical bell-shaped curve based on the limits of exploitability and market pressures. This term later became interwoven in the term 'Peak Oil' (http://en.wikipedia.org/wiki/Peak_oil). Based on their experience and statistics, Campbell -ex-chief geologist for Amoco and petroleum engineer; Laherrère announced for 2008 the "cheap oil crisis", when the world will turn to a permanent fossil fuels scarcity, a context where it would become impossible for the industry to keep its actual level production, as the prices of energy will rise drastically (Campbell and Laherrère 1998.). This story can be told for the majority of the natural resources, and is reflected in the important rise of the gross materials. This movement is accelerated with the rise of new economies in the emerging countries, leading to an additional increase in overall demand.

In addition of this near economical crisis, the impacts caused by the externalities of these high levels of production and consumption are getting more and more important. In the last two decades, important environmental problems have risen to become major concerns. The ongoing debate about global warming and recent failure to reach specified targets at the UN climate change conference in Bali, shows the complexity and difficulties in solving these problems. Twenty years after the Brundtland report on sustainable development, we still have a big step to do toward sustainability:

"Humanity has the ability to make development sustainable - to ensure that it meets the needs of the present without compromising the ability of the future generations to meet their own needs"

(World Commission on Environment and Development 1987)

From this famous quote emerged the three interlaced dimensions of sustainable development: economic development, social development and environment protection, also known as the 3P: "Profit, People and Planet" (Kørnov et al. 2007, 196).

1.2 housing industry

The housing industry has slowly developed itself for a century or so in the cheap oil economy, and is now well-rooted and developed in the market and minds. As construction use stage spans over generally long time intervals, it is historically a conservative area of the economy, and the field shows a great reluctance to change, at each of its levels (producers, retailers, designers, consumers, etc.). This is especially true when changing means questioning the commonly accepted buildings practices, techniques and materials. In consequence, it is still oriented around cheap and easy to use products with little concern about the wider environmental impacts inherent to the size longevity of its products.

Residential housing is also an area that well exemplifies the three dimensions of sustainability: At an *economical* level, buying a house is, for most people - consumers - the most important (expensive) consumption act of their life, with mortgages of 40 years getting more and more common, even reaching the markets of Eastern Europe: During the past 3 years mortgages account for a 40% year-to-year growth in C.R, in a financial market which only is 12 years old (Sadil 2007, Kovacova 2005). In 2007, household expenditures related to housing accounted for 22,3% and 26,5 of the total family budget in countries such as Netherlands and France, for an average income (ILO Bureau of Statistics), clearly demonstrating the necessity for many home-buyers to prioritize economy when choosing their new home.

The *social* aspects are numerous. Maybe most significant is that houses, with their long lifetime, would last in average at least over two generations, perhaps up to three or four. In this perspective, the act of building is no longer personal. Indoor environment and health issues are also very important topics, and viewed wider, the urban planning and design largely influence community development and social interactions.

Looking at the *environmental* impact, the processing and transport of materials requires an increasingly amount of energy and natural resources, are responsible for large amounts of waste generation and typically includes many hazardous materials: In UK 90 million ton of construction and demolition waste is generated annually- the construction industry produces three times the waste produced by all UK households combined. Construction and demolition is responsible for creating 21% of the hazardous waste in the UK (UK Environmental Agency 2007). This figure represents all construction, these numbers would be smaller for residential construction, but the data could not be found. The use stage traditionally requires significant amount of energy, due to poorly insulated houses or energy demanding appliances etc. The statistics figures tell that the buildings would account for 40% of energy consumption in the EU (EU Sustainable Energy Week 2007). The residential sector accounts of 26 % of that amount (ibid.). In UK alone the figures are shocking: About 10% of national energy consumption is used in the production and transport of construction products and materials, and the energy consumed in building services accounts for about half of the UK's emissions of carbon dioxide (UK Environmental Agency 2007). George Monbiot details that UK's residential buildings account for 31% of national energy consumption, of which 82% is used for space and water heating. (Monbiot 2006, 65) .

1.3 Life Cycle

There is a consensus in life cycle thinking that states that for active products, such as houses, the use stage is bearing the most important environmental load, mainly through the energy consumption. LCA energy oriented studies, also called Life Cycle Energy (LCE) (LCE studies refer to life cycle inventory studies that have considered only the energy contents and consumption of the products) have been conducted over the last years on typical residential housing, and most of them arrive at the same conclusion: The use stage would contribute for most of the life-cycle energy, from 78% to 96% of the energy load (Suzuki and Oka 1998, 39; Aldarberth et al. 2001, 1; Blanchard & Reppe 1998, 18; Lin 2003, 411). However, parallel studies have been conducted on energy efficient houses. It has been stated that the use stage can account for up to 40-60% in energy efficient houses, significantly increasing the share of embodied energy. (Tormark 2001, 429; Yohanis 1999, 77).

1.4 Company perspective

The residential housing market demonstrates clear trends towards implementing more sustainable buildings. Increasingly terminology such as "green houses", "green architecture", "eco-houses" and none the least 'low energy houses' are used and thus tend to spread into consumers minds, hence to building companies. However, few standards have been clearly established, and the most common measure of sustainability considered in the residential housing labels is energy efficiency during the use stage.

Reducing the above mentioned 26% of energy/year for EU during use stage is important of course, but such approach neglects many other environmental issues, which may be viewed if the house is seen from a life cycle perspective. The reason is simple: energy savings can easily be translated into economic units, a language well understood by the consumer and market players. On the other hand, environmental impacts concerns may be either perceived as too theoretical via LCA or marginal, and most likely not felt as applicable to the business.

1.5. Problem definition and research question

The main purpose of the project is to determine how significant the choice of materials is when designing energy-efficient houses in relation to their life-cycle environmental impacts. Typical designs are oriented to reach low energy standards, but "building green" may and is also regarded in a wider perspective, in accordance with the three dimensions of sustainable development.

The impacts will be assessed with the LCA tool. We propose to substitute the normally adopted life-cycle energy approach to the life-cycle environmental load consideration. This switch from a precise aspect to the overall impacts is, to our conception more complete, and could contribute to give more room for the social and environmental issues in decision making, that are considerably shaded by the strong bind existing between financial aspects and energy, and the common belief that environment and social considerations generally implicates more costs to a project. For this reason, the life-cycle costs have also been selected as an important item to consider in the study. These elements are formulated in a research question:

> ***"Controlling for energy efficiency and design, what are the estimated costs and environmental impacts related to two energy-efficient houses, conceived in accordance with either a sustainable development or an energy-efficiency criteria?"***

This would be answered through a case study. The two construction techniques to be assessed are designed according to Passive House criteria: A straw bale house built with big bales (BBB), and a sand-lime brick masonry house insulated with expanded styrofoam. They will respect the 'PassivHaus' design of Peter Weber's model house built in Trier, Germany. The chosen site is Bouzov, Czech Republic.

1.6. Sub questions and report structure

In order to answer the research question, the following set of secondary questions have been established, that will organize the structure of the report.

- What is the energy consumption of the two houses in their use stage?
- What are the construction and use stage costs of the two houses?
- Can both houses be built for similar prices and affordable prices?
- What is the relative importance of the use stage, regarding environmental impacts?
- Do the study objects present significant differences in their life-cycle environmental impacts load?

A theoretical frame will first be presented, followed by a description of the methods used for the different analysis. The study objects will then be fully defined described. The estimated energy consumption obtained from a computer simulation of the two models will then be presented. Those results will be a part of chapter 6, where the costs estimates for the construction and use stages are shown. The environmental performance issues will be considered in chapter 7, through the LCA. The main research question will be answered in the final chapter, whit a recapitulation and a discussion of the most important features, including the limitations.

2. Theoretical frame

> **"Unfortunately, at most universities it is still possible to earn a master's degree in architecture without knowing how the sun moves through the sky, without being aware of energy or resource use in buildings. […] This tells us what counts for valid knowledge in the architectural profession and helps explain why 40% of the energy consumption in the US can be traced to building construction, materials and maintenance.**
>
> -Sim Van der Ryn/ Stuart Cowan 1996, 13

This chapter serves to provide the necessary background information initially around life cycle thinking, subsequently by relating the criteria of sustainable development to the certification schemes of the building industry. It presents a brief comparison of 3 of these schemes in order to illustrate the initial dilemma between the focus on energy savings or embodied energy in the passive house definition. It then provide a more in-depth introduction to the concept and definition of 'Passive House', which leads to an introduction to the concept of 'Big Bale Building', followed by a presentation of the materials for the reference passive house, before we present the issues around the HVAC system.

2.1 Life cycle thinking

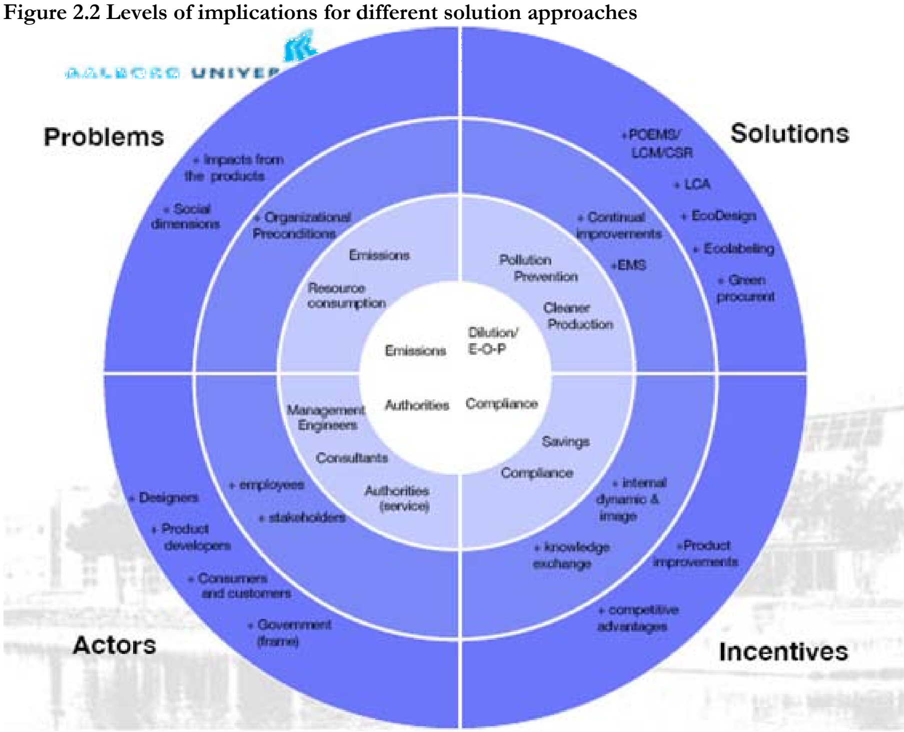
Figure 2.1. Evolution of the perception of environmental problems

	Perception of environmental problems	Causes mainly addressed	Solution approach	Actors involved
1960s 'Out of sight out of mind'	Smoke, noise, and waste	Point sources	Dilution	
1970/80s Environmental Protection	Emissions	Industry and households	End-of-pipe	Government
1990s Pollution Prevention	Resource use and emissions	Production processes	Cleaner Production	Industry, NGO's & government
2000s Life Cycle Thinking	Resource use, emissions and impacts from products	Consumption volume and patterns	Cleaner products	Industry, consumers, NGOs & government

From Tools for Sustainable Development (Kørnov et al. 2007)

Through the years, the perceptions of the environmental problems and the solution approaches have importantly progressed. The 'out of mind, out of sight' tendency of the 1960ies gave birth to what progressively became the Life Cycle Thinking (LCT) concept in the 2000s. As shown in figure 1. LCT refers to a Cradle-to-grave consideration of the production process, covering all the stages of the products, from the material extraction, to the disposal.

Figure 2.2 Levels of implications for different solution approaches



(EM lecture, AAU Autumn 2007)

The LCT translates in business strategy concept into Life Cycle Management (LCM), a whole cycle management system. "In order to achieve this, those systems, like the ISO 14 001 standard have to become more product oriented, including activities like product-chain management, [...] engaging all departments in the environmental activities" (Kørnov et al. 2007, 197). To apply these strategies, tools like Life Cycle assessment (LCA) and Ecodesign are being development and enhanced. The International Standard Organization, through the ISO 14 040 standard, has defined LCA guidelines. The ISO 14 062 proposes technical guidelines for EcoDesign. The proper use of these tools allows companies to develop green products and/or attach eco labels to their products.

2.2 Sustainable development and construction

The Sustainable development criteria (as outlined in the introduction) incorporate economic development, social development and environment protection as part of the design of 'human life systems'. Such whole systems thinking is apparent in the design science 'Permaculture', which in brief can be described as a toolbox based on the following ethics Earth-Care -People-Care - Fair Share, that are implemented in the following principles:

Observe and interact	Design from patterns to details
Catch and store energy	Integrate rather than segregate
Obtain a yield	Use small and slow solutions
Apply self-regulation and accept feedback	Use and value diversity
Use and value renewable resources and services	Use edges and value the marginal
Produce no waste	Creatively use and respond to change

(David Holmgren 2004)

The significance of these new 12 principles (and the book), is that it outlines how this design approach can be utilized in many different aspects including that of construction, especially after the oil-peak, in accordance with concept of Hubbards peak:

"In a world of constantly rising energy and resultant affluence, permaculture is always going to be restricted to a small number of people who are committed to those ideals which have some sort of ethical or moral pursuit. It's always going to be a fringe thing. Whereas in a world of ***decreasing*** *energy, permaculture provides, I believe, the best available framework for redesigning the whole way we think, the way we act, and the way we design new strategies. [......] the thinking behind permaculture is really based on this idea of reducing that energy availability and how you work with that in a creative way. That requires a complete overturning of a lot of our inherited culture.* (Holmgren, interview, 2005)

David Holmgren goes on to describe the build environment as a storage of energy and advocates the need to emulate natures characteristics for such storage: "Modest in scale - Well-designed for long life and/or made from easily renewable materials – Simple to maintain - Multi-purpose and Easy to adapt for other purposes" (Holmgren 2004, 6). This approach does fully cover the criteria of sustainable development, and is also applicable towards residential housing (and other fields). However, it does not constitute a set of officially recognized criteria applicable for the construction industry.

When establishing applicable criteria within the framework of construction, the criteria rapidly become much more fractionalized, as especially the social element gets excluded from defined parameters/criteria, and typically either the focus is either on the economic or the environmental parameters. Countries such as UK, Sweden and DK are presently in process of defining new criteria for this sector, however various approaches has already emerged simultaneously in different countries and continents, as the industry itself is aiming at establishing such parameters. In a short report, Lenormand & Rialhe compare three significant different approaches: the German 'PassivHaus', the Swiss 'Minergie', the American 'LEED' (Leader in Energy and Environmental Design) (Lenormand & Rialhe 2006). Table 1, shows well how the field of application and requirements differs between them.

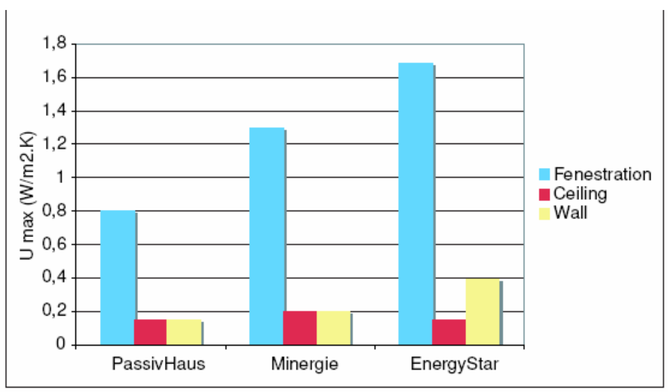
Table 2.1 Comparison of application fields for three labels

	Heating-Water Heating	Other Uses	Natural-Local Materials	Transport	Internal Air Quality	Water Mgt	Training
Passiv Haus	Yes	No	No	No	No	No	No
Minergie®	Yes	Minergie-P®	Minergie-Eco®	No	No	No	No
LEED	Yes	Yes	Yes	Yes	Yes	Yes	Yes

(Lenormand & Rialhe 2006,11)

We can observe that LEED is paying attention to many more issues than the energy in use phase. However at the same time, it is requiring less in the specific area of energy. Figure 1 shows the insulation requirements for the three labels. The figures display that the Passive House is the label which is most focused on the energy consumption in the use stage than LEED (a.k.a EnergyStar), but also that this specialization gives it a far more narrow view regarding other life stages and potential environmental impacts. When analyzing those differences, it remains unclear to determine which of these approaches would give the best environmental performance in the long term. LEED clearly covers issues that agree with the sustainable development concept and detailed with the Permaculture principles, by enlarging the environmental consideration and particularly by including social aspects in the projects. On the other hand, the improved energy gains obtained with the Passive House concept may cover a good part of its loss in the other fields. This is one of the dilemmas that perhaps a comparative LCA analysis could help clarify.

Figure 2.3:
Comparison of requirements on insulations values



(Lenormand & Rialhe 2006,11)

2.3 Passive House

The concept of 'Passivehaus was co-developed by Professors Bo Adamson of Lund University, Sweden, and Wolfgang Feist of the Institut für Wohnen und Umwelt (Institute for Housing and the Environment) in 1988. The concept describes a way of designing a building enabling it to use between 77 and 84% less energy for space heating, when compared to similar size houses simply conforming to standard Northern European building code.

A set of technical standards defining the Passive House criteria:

1. The building must not use more than 15 kWh/m^2 per year (4746 btu/ft^2 per year) in heating energy.
2. With the building de-pressurized to 50 Pa (N/m^2) below atmospheric pressure by a blower door, the building must not leak more air than 0.6 times the house volume per hour ($n50 \leq 0.6$ / hour).
3. Total primary energy consumption (primary energy for heating, hot water and electricity) must not be more than 120 kWh/m^2 per year (3.79 × 104 btu/ft^2 per year)
4. Further, the specific heat load for the heating source at design temperature is recommended, but not required, to be less than 10 W/m^2 (8.789 × 10-4 btu/ft^2 per hour). (Wikipedia, 2007).

To achieve such performance the building designer has to use a series of low energy building approaches and technologies: The house has to be compact, employ passive solar gain, be extremely well insulated, tightly sealed, and typically incorporates automatic heat recuperation and ventilation systems. The buildings plan for the intrinsic heat produced by body heat of inhabitants, lighting, cooking and from electrical appliances. Furthermore they usually incorporate internal thermal mass to stabilize the temperature. It is quite possible to design a passive house in such a manner that it may not need any additional heating, if the heating load is kept under 10W/m2.

There exists several different approaches to constructing passive houses; however we can distinguish between 2 main avenues:

- A masonry core, typically of large panels of various compact mineral compositions, covered by an envelope of non-breathable insulation.
- Intricate wooden frames with different layers of insulation, ensuring lack of thermal bridges. Often such houses consist of sealed interior OSB sheets.

Several passive houses have also been built out of straw bales, however predominantly as very custom designed houses lacking ease of replication. (www.passivehaus.de, www.pasivnydomu.cz, 2007).

While it is intended that the lifestyle in a passive house should be equal to living in typical houses, it is worth mentioning that due to the high focus on 'reusing' hot air, the interior of the house must pay more attention to avoidance of unhealthy interior finishes and furnishes to eliminate indoor air pollution. Likewise inhabitants should pay more attention to how and when they air out, as the interior becomes a more regulated system. –This includes the fact that with the automated heat recuperation system, it becomes impossible to have different temperatures in different rooms; frequently an issue of controversy.
Computer simulation studies by Ing. Jakub Wihan, demonstrated how it is possible to design a passive house build of straw bales with earthen plaster, using a build in atrium/conservatory to gain the heat and regulate the heat flow, thereby eliminating the automated heat recovery units, using plants to filter the air, while ensuring a stabile yet varied temperature in the various rooms.

2.4 Passive and active systems (HVAC)

The above two different approaches to passive house constructions focus mainly on the aspect of insulation, while the chosen design allow for passive solar gain through the south oriented windows and accumulation in the thermal mass of the interior plaster or Lime-sand stone. However when focusing on reaching the performances of 'Passive House', it is necessary to also include other means of heating, ventilation and air conditioning (HVAC), none the least attention should be given to behavior of the occupants and their electrical equipment.

2.4.1. Heating

In accordance with theory of passive houses external heating should not be necessary, excepting in case of extended periods of long extreme winter conditions. In reality most architects incorporate some sort of back-up solution due to customer demand, also due to the fact that the element of visible flames brings up the interior comfort level. Due to such demands special low heat wood burning stoves has been especially developed for passive houses.

New type of biomass stove adapted to the requirements of passive solar houses. The stove stores the heat in a medium with high heat capacity.
The combustion air used for burning is taken from the outside of the building, because the controlled ventilation must not be disturbed by ovens.

(Wimmer et al. 2006)

The passive house concept relies to a high degree on simply utilizing the energy which typically is ignored in common households: The body energy and the heat generated by electrical appliances, light and various home activities such as cooking, showering etc.. By ensuring superior insulation and controlled ventilation, it is possible to 'trap' this waste heat and thereby supply part of the interior temperature. Table 2.4 demonstrates this issue:

Table 2.2 Examples of heat generation for typical home appliances

Example of equipment use	Heat generated in one day	Equivalent heated surface
TV on sleep mode (15 W) for 20 hours	0.30 kWh	2 m2
TV on (75 W) for 4 hours	0.30 kWh	2 m2
20 minutes ironing	0.30 kWh	2 m2
30 minutes oven baking	1.5 kWh	10 m2
Fridge (compressor + heat release on condenser)	3.0 kWh	20 m2
PC and cathode screen on for 24 hours (ADSL use - 250 W)	6.0 kWh	40 m2
PC and cathode screen on for 8 hours (office use - 250 W)	1.75 kWh	12 m2
PC and flat screen on for 8 hours (office use - 125 W)	1.0 kWh	7 m2
Laptop on for 8 hours (office use – 30 W)	0.24 kWh	2 m2

(Terre Vivante, in Lenormand & Rialhe 2006, 21)

2.4.2. Ventilation

Passive house designs incorporates both passive and active ventilation systems as unlike common perception, the main issue is not how to gain the solar heat: it is rather how to avoid it, at least through the summer months, as a serious (and raising) problem is energy spend for cooling our homes. A popular design is to secure air inflow through a 'Canadian Well', which secure cooling through summer time and a more stable incoming temperature during winter. Such systems are typically connected to a HVAC system, which heats the incoming air with the recuperated heat of the outgoing 'used' air. (Lenormand & Rialhe 2006, 18).

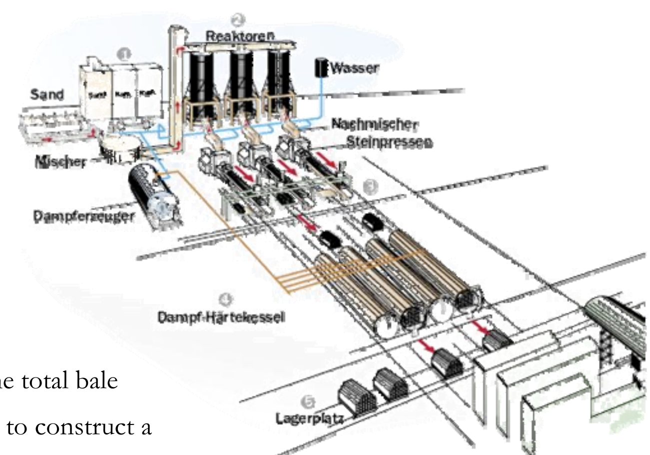
This is an area where our two models would likely differ to some extend. Even though the earthen plaster on the straw bales are able to fulfill the requirements of the 'blower door test' for air-tightness, the walls have a unique ability to breath and regulate interior moisture, as recently proven in the PhD research by Jakub Wihan "Humidity in straw bale walls and its effect on the decomposition of straw" or in 2003 by Straube and Schumacher; "Monitoring the Hygrothermal Performance of Strawbale Walls".

2.5 Big Bale Building

Whereas the technique of building with small straw bales was developed at the late 19th century, (with the appearance of the baling machines) and with significant developments happening at the end of the 20th century, Recent new development includes the approach of using the newer rectangular big bales [BB] (about 1 m x 1.3 m x 2.2m. (King 2003, 12).

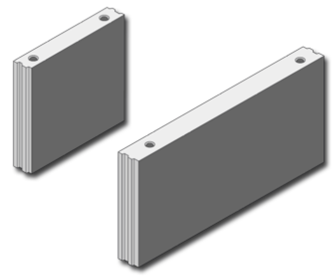
Once the technique of classical straw bale building had been developed, and the agriculture sector increasingly switches to only producing straw bales of large dimensions, the step towards BBB was predictable. The BB lend themselves towards the original 'Nebraska-style' building, also called "Load-bearing construction", where the unsupported bale walls are topped with a bond beam dimensioned to hold an additional story or simply the roof. The Big Bales allow for fast-mechanized construction of the exterior walls, and as the bales can be rendered directly, the wall system constitutes a complete wall with inner and outer skin, along with insulation. The large dimensions of the bales also have drawbacks: It imposes more limits in design, encourages mechanization to the weight, which again is a challenge to the logistics of the construction site. (Rijven 2007). Naturally it also requires that the homeowner can accept such thick walls, walls that in effect only had to be 35 cm thick to create the necessary insulation to fulfill Northern European building norms (Andersen & Møller-Anderson, 2004, 42).

As the wall raising becomes a matter of a few days, with a roof that may be crane lifted onto the building pre-constructed, and rendering done (predominantly) mechanized, the labor costs becomes reduced considerably as compared to conventional brick construction (Keller 2007). Add to this the common local availability, thus limiting long distance transport, or high energy demanding production, further savings and environmental impact is limited; in essence the straw-bales constitutes an inexpensive by-product from grain construction. They are typically utilized for large-scale husbandry, biomass heating or to be returned to the fields as a fertilizer. We estimate that for the next many years it is unlikely that the amount of bales used in construction industry constitute a measurable reduction of the total bale production. In effect it is fully possible to construct a BBB as a biodegradable house, all depending on the overall design and choice of additional material within the building. (Wimmer et al 2004). If the BB gets rendered with an earth plaster they are completely degradable, (apart from the plastic straps). This ensures a CO2 neutral material, which may be CO2 positive as it replaces other materials with a high-embodied CO2 consumption. (Rowan, 2007). The interior qualities of such house also adds



to the requirements of a passive house building, as computer simulation based on embedded moisture sensors, has found that a Straw bale wall rendered with 3 cm earthen plaster is able to regulate the atmospheric moisture content without degrading. A straw-bale wall rendered with an earthen plaster is neutral and improves the indoor environment through its ability to regulate interior moisture (Wihan 2007 /Minke 2006, 14)

2.6 LS/EPS Passive House



Production of Lime-sand bricks [LS]

LS is a quite 'clean' natural process and with a relatively low embodied energy when compared to burned bricks or concrete products. LS consists only of sand and lime, which through a steam process bonds and create a unified mass. The main energy input is through the extraction of the materials and generating the steam.
Due to a wide regional network of producers, there's typically only between 40-60 km between fabrication and building supply in Germany. (Bundesverband Kalksandsteinindustrie eV 2007)

Production of Expanded PolyStyren [EPS]

EPS is produced by dissolving pentane in a polystyrene base material, which then get steam-heated to form EPS beads. Expansion is achieved by virtue of small amounts of pentane gas dissolved into the polystyrene base material during production. The gas expands due to the hot steam, to form perfectly closed cells of EPS. The cells occupy approximately 40 times the volume of the original polystyrene bead. The EPS beads can then be molded into appropriate forms suited to their application such as insulation boards, blocks or customized shapes for the building and packaging industry (Manufacturers of Polystyrene & Foam Products, 2007)

Photos taken from: www.eps.com, www.kalksandstein.cz and www.strohhaus.de

3. Methods

"Our cultural bias toward focus on the complexity of details tends to ignore the complexity of relationships. We tend to opt for segregation of elements as a default design strategy for reducing relationship complexity. Any consideration of how they work as parts of an integrated system is based on their nature in isolation.
The purpose of a functional and self-regulating design is to place elements in such a way that each serves the needs and accepts the products of other elements."
David Holmgren 2007,17

This chapter is divided in three sections. The first section focuses on the methodology surrounding the establishment of the control variables, present in the research question. They are the design, the energy-efficiency and sustainable development criteria. This settled, the definition of the case study elements has been established according to these three variables. The last section explains the methods of analysis selected to assess the dependent variables of the research question in the case study. These elements are the energy consumption, the life cycle costs and environmental impacts.

Information has been obtained through personal conversations with people involved in construction of passive houses, along with studying printed and online information about the subject. Our personal background knowledge also includes various conferences attended in Czech Republic, Denmark and Germany during the past 5 years.

3.1 Control variables

3.1.1 Design

The main preoccupation for the design choice was to ensure a comparative ground for both houses. Due to time and resources limitations, it has been set that the study objects would be virtual, and that their design should be similar. The first choice was made mainly for timesaving in research and analysis, while the second aims to simplify the comparisons. We think that choice of using estimates satisfies the exploration purposes of the study. However, it implicates serious limitations on the interpretations that can be made from the results. In a further study, it is clear that built houses should be selected.

3.1.2 Energy-efficiency criteria

The criteria of high energy-efficiency had to be set. In order to answer what is an energy-efficient house, a research have been made in the literature, through reviews and scientific articles, Internet, also oriented by our personal knowledge and experience. Among the few labels described in a Leonardo-Energy review (Lenormand and Rialhe 2006,6), the German Passive House (PH) label have been identified to be the most severe standard for energy requirements, and also the most appropriate for the Czech Republic, with most of its popularity in Germany. Passive houses require certifications from passive House institute to be given the label. The use of PH terminology in the project thus means: "house designed according to PH standards", here mainly by respecting the isolation requirements. The criteria have been selected to ensure a certain level of energy consumption, for ends of comparisons. However, it does not give any numbers about energy consumptions, nor that he assures exact energy consumption for both houses. This aspect is identified as energy consumptions and is considered to be a dependent variable, to be estimated.

3.2 Case study

The study objects was identified and designed in order to fulfill the requirements of the research question. For the case study, it was important to select construction techniques that reflect the two different approaches for designing "green buildings": the sustainable criteria personified in the permaculture philosophy and predominantly in the LEED label; and the energy efficiency criteria, in the more European approach: the Passive House label.

3.2.1 Czech Republic as a study context

As we are working with somewhat virtual houses, any place could have been selected for the study context. Czech Republic has been selected due to our knowledge of prices, trends, climate and personal future plans. As the study is based on estimates, it was important to use a weather pattern with wide changes in winter and summer temperatures, where the energy design is important for both heating and cooling, and where the concept of energy-efficiency becomes relevant.

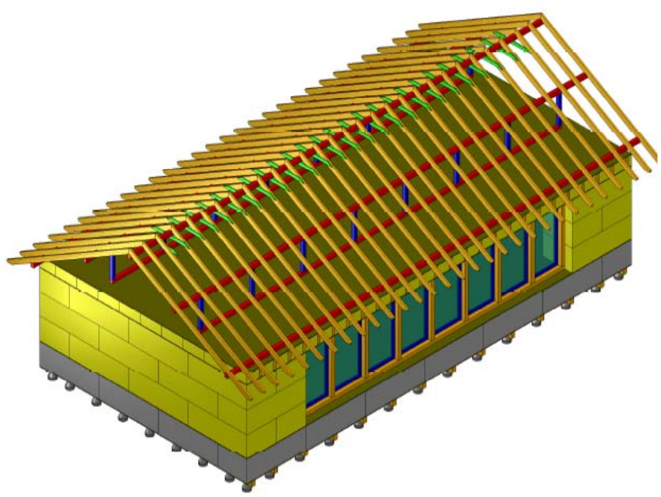
3.2.2 Straw bale as a point of departure

Straw bale houses have rapidly identified as an approach fulfilling many criteria of sustainable development. It has developed itself in parallel networks in many countries, however it is difficult for the housing market to accept and integrate its non-traditional approach. For most consumers and many builders, it is barely accepted as an official technique and considered as a curiosity. However, at the same time, authorities and experts also acknowledge straw bale building for its seriousness and good level of maturity as exemplified in the list of research in the attachment. Fact is that SB building will be included in the upcoming EU building law in 2009. (Scharmer 2007). In December 2007, the Danish technical advisory committee in its quarterly publication predicts that straw bale construction may be suitable for serial building of low-energy houses in Denmark (Teknologidebat, 4/2007, 1). This ambitious statement, and the debate around it, makes straw bale construction a very interesting subject that has served as a point of departure for defining the rest of the study.

3.2.3 BBB and Weber's model

The major difficulty in the choice of straw bale construction technique arises due to lack of uniformity of the straw bales. As straw bale construction is mainly excluded from the market, rarely standardized and often owner built, costs calculations constitute an obstacle. After contacts with different members of the European Straw Bale Network[1], the big bale building (BBB) technique was selected for the important degree of mechanization it proposes, allowing straw bale construction to be built fast and commercially. The model house from Peter Weber's project at Trier was selected. It meets both BBB and PH requirements, as proven through the construction of a prototype house, gaining a 1st prize in Germany for the low embodied energy, leading to a further 30 such houses to be build in 2008. An added incentive was that we had clear .pdf drawings, information and contact with the carpenter available.

Figure 3.1: Structural design of Peter Weber's model at Trier



From: Peter Weber of www.strohhaus.de (2007)

[1] Tom Rijven, (one of Europes leading straw bale builders) built a 400 seats conference center in Amsterdam of big bales, and is quite critical to the BBB approach.

3.2.4 Interview

We designed the attached questioner as a guide to learn about current market trends of low energy housing in Czech Republic. It formed the base for interview/talks with 5 experts within the field: 1) Very successful low-energy architect, 2) Consultant from national network to promote passive house standards 3) An architect/Engineer couple building straw bale low energy houses 4) well known architect/professor specializing in low energy and straw 5) International straw bale builder experienced with BBB. The information received from the questionnaire was not further compared or analyzed: It predominantly served to orientate us and helped us decide for the reference model.

3.2.5 LS/EPS

The goal of the interviews were among others to identify, according to their experience, the construction technique they would use to meet the PH requirements, and which would be accepted by the average Czech family. In brief it was pointed out that Czech are very conservative in regards to housing and have a preference for masonry construction: In terms of full-filling the passive house criteria, the research let us to the choice of a sand-lime brick construction isolated with expanded styrofoam (LS/EPS) as recommended by the Czech organization for passive house building.

3.2.6 Plans and materials

In order to keep the same energy consumption for both study objects, it was decided, when adjusting Weber's model to LS/EPS, to compensate the difference in walls' thickness on the outside. This had important consequences on the quantity of materials used, and made it an obligation to redesign most of the components. These changes were impossible to evaluate without plans, which had to be drawn. These drawings were realized with the assistance of AutoCad software.

3.3 Dependant variables

These are the variables to be analyzed, in order to answer the sub questions, and ultimately the research question. They are the energy consumption, the costs and the environmental impacts.

3.3.1 Energy consumption

The first approach used to determine the method to be used was to consult literature. The technique generally used is to consult the energy bills of the study objects, and to make a future projection with the averages. However, the virtual nature of our study objects made it impossible. The only solution was to get estimates with a simulation tool, which could provide accurate estimates.

3.3.2 Simulation software

An extensive research of the available tools was conducted, mainly by consulting Internet databases. The most important source of information was the Building Energy Software Tools Directory, provided by the US Department of Energy, available on the Internet (US Department of Energy 2007). The most interesting programs were selected, according to their availability and their ability to provide the results needed. They were then tested to evaluate their complexity and performance. Hot2000, from the Canadian Ministry of Natural Resources was finally chosen.

3.3.3 Input data

The insulation values of the foundations and different section of the envelope had to be determined in order to construct the two models in the software. The companies providing the materials generally provide the U-values for specific wall composition or thicknesses of materials. It appeared that this data was not usable, because it was not fitting our study objects characteristics. The strategy used was to find the specific thermal conductivity for each material, and convert them and sum them to global U-values for every section of the building. The Buildesk online software was rapidly found and selected to accomplish this operation. When available, its database was used. Missing information was found on different sources available on the Internet.

3.3.4 Costs

The cost analysis was based on a very detailed spreadsheet of majority of the materials for both houses; the list is likely 95% complete as we eliminated minor investments such as screws, nails, silicone, temporary tarps etc. Subsequently we solicited prices from building catalogues, online resources, personal experience and through phone interviews with representatives from both BBB and LS/EPS building companies. In addition to costs the distances from main source of extraction of components from the materials was measured and counted, as were the costs of transport and the labor of constructing the house. All costs are based on current market price in Czech Republic as well as current labor cost.

Following the overview of the construction phase, spreadsheet were comprised of running costs during the 50 year lifespan. Throughout this process we had to rely on our experience as builder/architect student in assessing the figures.

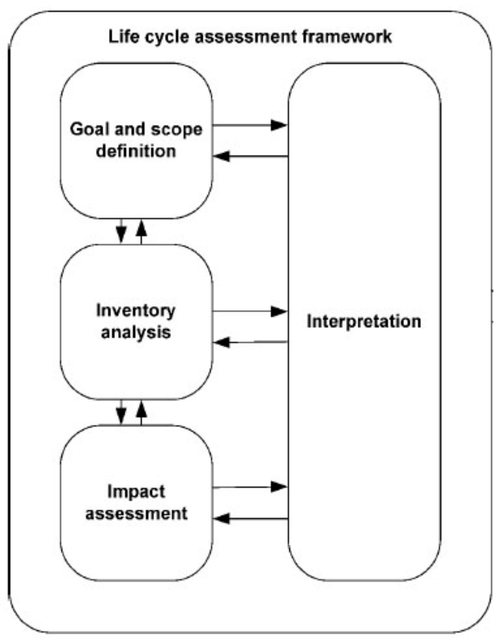
Our approach did not allow us to include a cheaper bid by the LS/EPS builder, however we compensated for this by not calculating the transport cost for these items.

3.3.3 Environmental impacts

The LCA tool has been selected for the assessment of the environmental impacts. It is to our knowledge the only assessment tool than allow to analyze the impacts of a product using the life-cycle thinking approach. The LCA has been conducted following the ISO 14 040 and 14 044 framework and guidelines. The terminology used thus refers to those guidelines. The four phases of an LCA are the goal and scope definition, the Life Cycle Inventory (LCI), the Life Cycle Impact Assessment (LCIA) and the life cycle interpretation. Their interrelation is shown in figure 3.1.

It was determined than a screening comparative process oriented LCA would be the best approach to provide the results needed and respect the nature of the study objects, while consideration the time limitation constraint. Three life stages were defined: the construction stage, the use stage and the end of life stage. Transport issues were integrated in those categories.

Figure 3.2 Phases of a LCA



The computer tool Simapro, by Pré Consultants, was chosen to conduct LCI and LCIA. The EDIP 97 assessment method was selected for its ability to provide results on the five impacts categories that were considered, and its good compatibility with the Ecoinvent database, the major source for the LCI data. These choices were recommended by an LCA expert. The Environmental impacts categories are the contribution to Global warming, Ozone layer depletion, Acidification, Nutriment enrichment and Low atmospheric ozone formation. They are considered show the most consistent results among the different methods, an aspect that was judged important for the great degree of uncertainty linked to screening LCA. The normalization factors included in the EDIP method were used to sum up the sources of impacts into equivalents, in order to compare their contribution for each impact categories. No weighing adjustment was done, as they include subjective considerations. More specific details will be discussed in chapter 7.

4. Study objects

“Most men appear never to have considered what a house is, and are actually though needlessly poor all their lives because they think that they must have such a one as their neighbors have. [….] It is possible to invent a house still more convenient and luxurious than we have, which yet all would admit that man could not afford to pay for.
Shall we always study to obtain more of these things, and not sometimes to be content with less? “

Henry D. Thoreau, 1854 Walden, (Economy)

This chapter provides the important information concerning the study objects.
The complete description of the study objects is mandatory to produce estimates of the energy consumption and the costs. This chapter will first define the functional unit for the houses. This item is part of the LCA terminology and will be used further in the analysis. The specific concept of house will be defined. Thereafter, construction details will be presented for the LS/EPS and BBB.

4.1 Definition of house as a shelter

Considering the low given amount of time to conduct the study, the list of materials to be considered had to be restrained to the most fundamental elements. Their selection was done according to our own judgment, with the intention of considering all three dependant variables: the costs, the energy consumption and the environmental impacts. It was determined that the only materials inputs that would be considered are those contributing to the shelter function of a house, resuming it to its foundation and envelope. Heating and indoor activities will be assessed only on the angle to energy consumption, based on estimates and average statistics. More specifically, the term “house” is defined by the followings components:

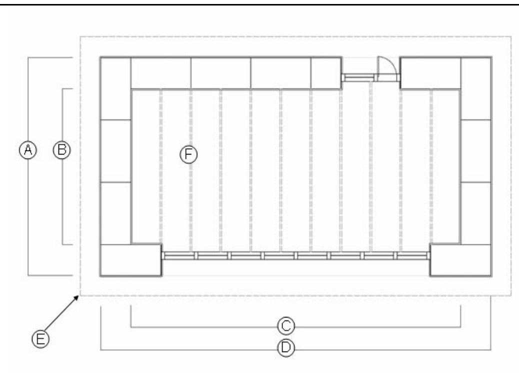
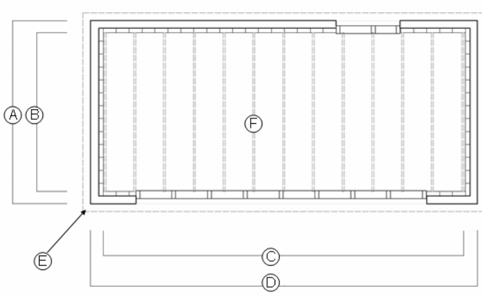
- Piers foundations
- Floors
- Finished outside walls
- Door and windows
- Ceiling/roof
- Energy consumption (use stage)

Therefore, indoor divisions, kitchen and bathrooms appliances, as well as electrical and HVAC systems are not part of the study. Many items, such as screws and nails, are also excluded. This important limitation of the boundaries will be considered when discussing the results.

4.2 Construction details

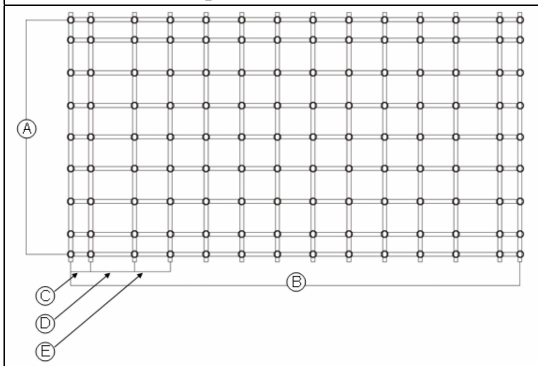
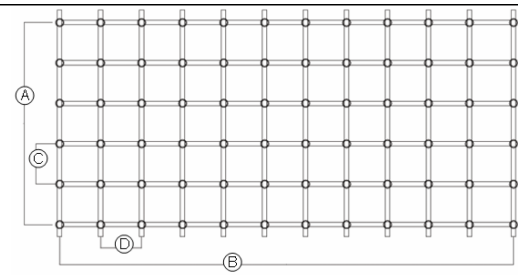
The difference is the wall thickness between the BBB and LS/EPS is having important effects in the global dimensions of the two houses. From 1,35 m for BBB, it was reduced to half a meter in LS/EPS. As the gap, was compensated on the outside, the area was reduced from 142 m^2 to 106 m^2, a diminution of 25%. At the same time, 0,8 m of overhang, designed to protect the earth plaster from the rain, was not required in LS/EPS. It was reduced to 0,3 m, a more conventional size. Those differences can be visualized in the plans, in table 4.1.

Table 4.1 Plans

BBB	LS/EPS
Wall thickness : 1350 mm	Wall thickness : 500 mm
Inside perimeter : 40 m	Inside perimeter : 40 m
Inside area : 86 m^2	Inside area : 86 m^2
Outside perimeter : 50 m	Outside perimeter : 44 m
Total area : 142 m^2	Total area : 106 m^2
	
A) 8750 mm	A) 7100 mm
B) 6250 mm	B) 6150 mm
C) 13 250 mm	C) 14 000 mm
D) 16 250 mm	D) 14 950 mm
E) roof overhang: 800 mm	E) roof overhang : 300 mm

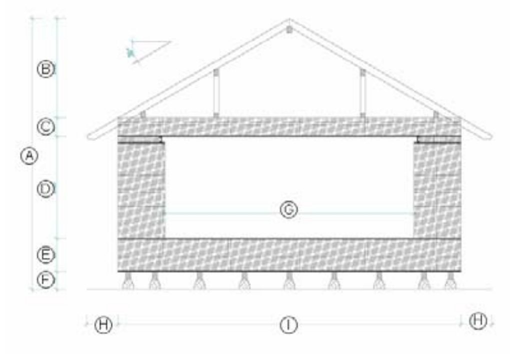
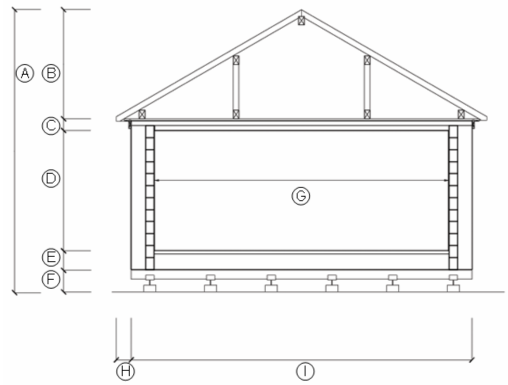
This de-sizing effect had also considerable impacts on the quantities of materials required for the foundations. The numbers of piers passed from 126 to 72. An important factor contributing to this drastic change is that only one row was necessary to support the LS/EPS structure, while it was doubled to insure that the large walls, mass is equally and entirely supported by the piers, and not the by the fiber cement boards. The grid structure is shown in table 4.2.

Table 4.2 Foundations detail

BBB	LS/EPS
Number of piers : 126	Number of piers: 72
	
A)8220 mm	A) 6320 mm
B)15720 mm	B) 14 170 mm
C) 700 mm	C)1260 mm
D)1530 mm	D) 1280 mm
E) 1250 mm	

The cross section (figure 4.3) gives allows in a single glance to observe the differences and similarities of the two houses. We can see that BBB is approximately one meter higher than its little brother. Another important difference occurs in the roof detail, which goes partially over the wall in BBB. The total area of the roof is 187 m^2 for BBB, compared to 127 m^2 in the case of LS/EPS. The roof is covered with Zinc-coated steel sheets.

Table 4.3 transversal cut

BBB	LS/EPS
 adapted from www.strohhaus.com	
A) 6880 mm	A) 5900 mm
B) 2520 mm	B) 2270 mm
C) 470 mm	C) 240 mm
D) 2580 mm	D) 2510 mm
E) 850 mm	E) 410 mm
F) 450 mm	F) 450 mm
G) 6250 mm	G) 6150 mm
H) 800 mm	H) 300 mm
I) 8750 mm	I) 7100 mm

The cold bridges in construction are well known to appear at the meeting points between two or more logical assemblies, for instance, between a wall and a window. They are responsible of the most important share of inefficiency, and without a good design of those meeting points, even an excellent insulation value of the materials will be useless.

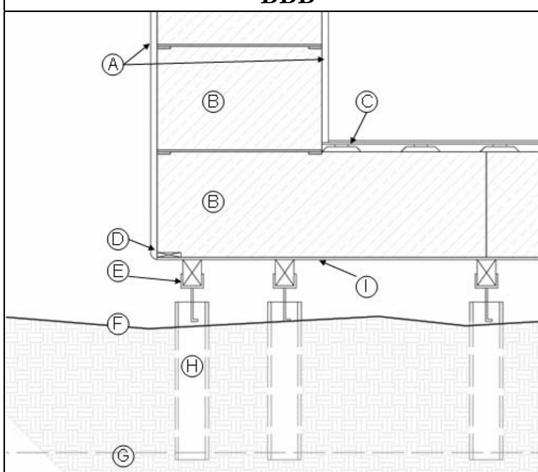
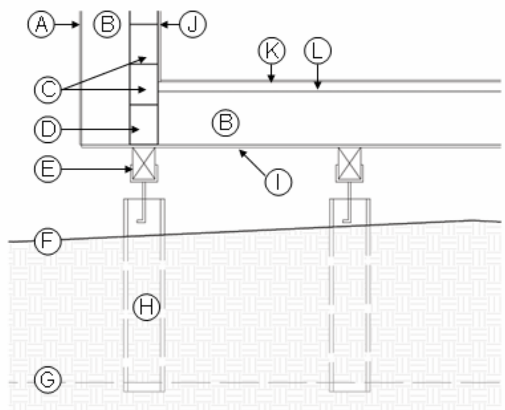
Their understanding is not essential to follow the study, but we consider them interesting enough to be presented closer. The zooms made on the junctions wall-foundations and wall-ceiling (tables 4.4 and 4.5) will show these details, and be used at the same time to describe the composition of the walls, layer by layer. The principal terminology used for materials in the figures is defined in the following list:

- Big bales: compressed straw. Dimension: 2500 mm x 1250 mm x 800 mm
- Small bales: compressed straw. Dimensions: 900 mm x 450 mm x 350 mm
- Earth plaster: Sand, clay, water.
- Earth mortar: Sand clay, water

- OSB boards: refers to 2440 mm x 1220 mm x 16 mm
- Gypsum board refers to 2440 mm x 1220 mm x 16 mm
- EPS: expanded Styrofoam
- LS: lime-sand composite blocks

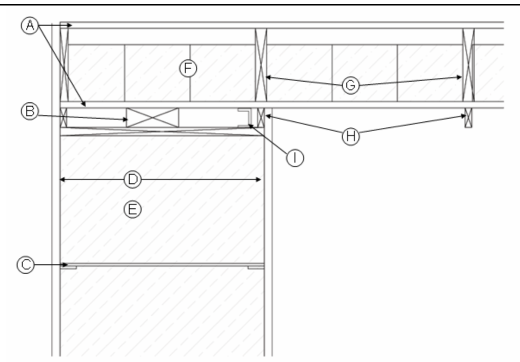
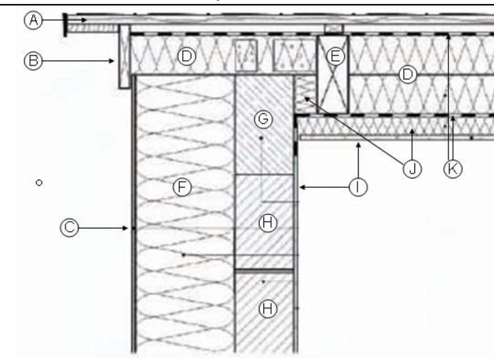
The wall composition for BBB is simple. The structure is the bales. On the top of each layer, wooden boards are placed in order to distribute the weight received from the above layers. The walls are covered with a earthen plaster body coat, finished by a finish coat, likewise of earthen plaster. The thickness is 50 mm outside and 30 mm inside.

Table 4.4 Wall-foundations detail

BBB	LS/EPS
	
A) Earth plaster	A) cement plaster
B) Big bale	B) EPS, 300 mm
C) Floor: earth mortar, batten, wood planks and wood finish	C) LS blocks, 175 mm
D) Wood	D) LS ISO-Kimm, 175 mm
E)Wood beam and metal bracer	E) Wood beam and metal bracer
F) Ground line	F) Ground line
G) frost line 1000 mm	G) frost line 1000 mm
H)Foundation piers 1200 mm x 250 mm • Sonotube 25 mm • Concrete • Metal threated anchor, 254 mm	H)Foundation piers 1200 mm x 250 mm Sonotube 25 mm Concrete Metal threated anchor, 254 mm
I) Wood planks	I) OSB sheet
	J) Gypsum board
	K)Wood finish, 12 mm
	L)Concrete slab, 60 mm

The wall composition for the LS/EPS house is simply LS tongue and groove panels, glued together with a minimum of mortar which constitutes the load carrying wall. On the interior side the panels are cement plastered and painted, while the exterior side gets covered with 3 layers of 10 cm EPS to ensure the insulation. The EPS are subsequently plastered with a cement plaster.

Table 4.5 Wall-ceiling detail

BBB	LS/EPS
	 Modified from LS brochure (2007)
A) Wood planks	A) OSB sheet
B) Wood, 320 mm x 120 mm	B) Wood, 180 mm x 40 mm
C) battens, 16 mm x 100 mm	C) cement plaster, 10 mm
D) earth plaster, 50 mm	D) EPS, 100 mm
E) Big bale	E) Wood beam, 70 mm x 200 mm
F) small bales	F) ESP, 300 mm
G) Wood beam, 700 mm x 450 mm	G) LS ISO-Kimm 175, 175 mm
H) Wood beam, 400 mm x120 mm	H) LS blocks, 175 mm
I) C-beam, 120 mm	I) Gypsum board
	J) ESP, 50 mm

4.3 Conclusion

The chapter serves to explain the differences between the construction of the two models, and highlights the dilemma of adapting one building technique onto the other: It is very unlikely that a LS/EPS building firm ever would consider building on piers, however for the sake of comparison we had to adapt this approach to the model, though at same time the plan had to be objective and cut down on the amount of piers for the LS/EPS, as well as modify the roof overhang etc.

The illustrations also serve to illustrate that care has been taken to avoid any thermal bridges in both designs, and that both designs are fully able to be built in reality. The process of making the detail drawings of both models furthermore ensured that we had a precise list of building materials necessary for the cost analysis and subsequent for the LCA.

5. Energy in use stage

> **"Our energy future is choice, not fate. Oil dependence is a problem we need no longer have—and it's cheaper not to. […] oil dependence can be eliminated by proven and attractive technologies that create wealth, enhance choice, and strengthen common security"**
>
> Amory B. Lovins, 2005, xiii

Energy consumption data is a fundamental input for the costs and environmental impacts calculations. This consumption have been estimated through the Hot2000 simulation program, and controlled for the Passive House insulation requirements. It includes the HVAC energy load and household use, including lighting, hot water and appliances. The first step was to determine the thermal performance of the different sections of the envelope. This has been done by a U-value calculator, and collected data. The two houses were then modeled according to these values, and the simulation computed with Hot2000, a computer tool.

5.1 Thermal performance

The thermal performance of the building is tributary to each of its section's transmittance, known as U-value. It is named the R-value and the unit is $W.m^2/k$, and is obtained from the thermal resistance:

In the EU, thermal performance of buildings is measured through the transmittance, or U-value. "U value is the coefficient which characterizes the ability of the wall surface to heat transfer. U value is the inverse of R

"The thermal resistance will measure the capacity of a product to fight against heat loss. It will depend on thickness and thermal conductivity. […] Wall thermal resistance is the addition of thermal resistance of each component from interior coating to exterior rendering, and superficial resistances" (ibid.). It is equal to the ratio between the thickness of the material and its thermal conductivity:

"Thermal conductivity measures the capacity of a material to lead or to resist to heat transfer" (ibid.). It is identified by the Greek letter lambda (λ), in W/m.K

$R=\sum R + (R_{si} + R_{se})$, where are inside and exterior superficial resistances
$R = e/\lambda$, where e is the thickness of the material
$U = 1/R$

value and is expressed in W/m² K" (ibid.). "This means that, if a wall material had a U-Value of 1 W/m² K, for every degree of temperature difference between the inside and outside surface, 1 Watt of heat energy would flow through each meter squared of its surface" (CLEAR 2007).

5.2 Study objects U-values

In order to model the objects in Hot2000, it was necessary to obtain the R-values of the different sections of the envelope, which are the foundations, walls, windows and ceilings. Buildesk software was used for this purpose. When available, the data from the program's database was used, and completed with external data from literature and websites.

The results showed thermal performance that was fulfilling the PH requirements for every section of both buildings. The BBB offered a far better overall performance than the LS/EPS. The performances shown were too good compared to the 0,11 W/m² K as required by the Passive House standards. For instance, the U-value for the walls was 0,072 W/m² K. This difference between theoretical and measured values for straw bales has been observed by Andersen & Møller-Andersen. Their work on small bales shows 50% higher U-values in their measurements than what the theory predicts (Andersen & Møller-Andersen). The main reasons stated are the introduction of the plaster into the straw, but the reason cannot be totally explained. According to this information, this effect should be less important for big bales for two reasons. The important size of the bales in the BBB dilutes the influence of the plaster intrusion. With 1,25 m, BBB walls are more than 300% thicker than a normal 0,38 m wall with small bales. Moreover, as no direct contact exists between the bales in the foundations and the ceiling, this cannot happen. However, as the reasons are not well known, a 50% correction has been made.

After correction, the BBB offers a performance between 0,057 W/m² K for the walls and 0,122 W/m² K for the ceilings. The LS/EPS shows more similar performances with U-values of 0,126 W/m² K for walls and ceilings and 0,128 W/m² K for the foundations. The table 6.1 shows the summary of the calculations. Calculations and references for each detailed section and materials can be found in the Annexes. The U-values have been converted to R-values to match Hot2000 requirements.

Table 5.1 Calculated U-values and R-values of different sections of the envelope, and comparison with other sources

Envelope section	thickness	U-value	reference	R-value
KS/EPS, foundations	376	0,128	(Buildesk 2007)	7,81
KS/EPS, wall	501	0,126	see appendix	7,94
KS/EPS, ceiling	347	0,126	(Buildesk 2007)	7,94
BBB, foundations	882	0,108	see appendix	9,26
BBB, wall	1350	0,057	see appendix	17,54
BBB ceiling	532	0,122	see appendix	8,23
Window, Triple glazed, 13 mm Argon, Wood frame	n/a	~0,80	Hot2000	~1,20
BBB general		0,11	www.strohhaus.de	9,09
LS/EPS		0,13	interviews	7,69
PH requirements		0,15	(PH institute 2007)	6,67

5.3 Simulation

In order to simplify the simulation, some assumptions have been made. The climate data have been set to Vienna, Austria. It was the closest city to Bouzov available in the database of the program. Vienna's weather is known to be warmer. A more important heat load should be expected in reality, to an undetermined extent.

Ventilation and cooling requirements are assumed to be reached with passive strategies, through the openings. Only heating has been considered as an energy input for the HVAC systems. To our knowledge, neither of these systems is present in Trier's model. However, in order to fulfill the whole of PH requirements, they should be considered extensively in further studies. For this purpose, we suggest to use the tool Passive House Planning Package 2007 (PHPP), provided on the PH institute website. For financial reasons we chose Hot2000, which is well enough designed to provide accurate estimates.

Hard wood has been selected as the fuel for hot water and heating system. Again, the PH standard requires the use of renewable energy like solar heat collector or heat pumps for hot water supply. This factor has however been discarded of this study considerations. A wood pellet stove with 75% efficiency has been selected as the heating device, required to conduct the simulation.

Base loads defaults values of the software have been kept for the simulation. For internal gains, two adults and two children are considered to be inside 50% of the time. The total energy of interior loads was set at 20 kWh/day. 9 kWh/day are attributed to the electrical appliances, 3,4 kWh/day for lighting and 7 kWh/day for the other appliances and body heat?. The factor of internal gains is set to 15%. 4 kWh/day has been set for exterior load, and a consumption of 225 L/day of hot water is assumed. This consumption is based on the Canadian reality due to Hot2000 and is certainly more important than what the reality would show in the Czech context. It should therefore be adjusted, as it could lower the energy consumption in the use stage significantly. It is an important limit to the study.

Comment [T1]: Of water?

5.4 Results

The overall summary shows excellent energy-efficiency in space heating for both study objects. The BBB auxiliary energy is near neutral, with 458 MJ needed over the year. The LS/EPS will require 2232,2 MJ according to the simulation. The central reason for this difference is the main walls of the BBB, which shows a better performance than any other item, even the door and the north windows, which let go of respectively 1502,7 MJ and 1080,3 MJ. The most important leakage points for both houses are attributable to the south windows and the air replacement, with 7227,8 MJ and 5993,8 MJ. Table 6.2 shows the annual heat loss of the different components.

Table 5.2 Annual heat losses

Annual heat loss (MJ)	BBB	LS/EPS
Ceiling	2077,4	2258,8
Main Walls	993,5	2475,2
Doors	1502,7	1502,7
South Windows	7227,8	7227,8
North windows	1080,3	1080,3
Foundation	2703,9	3301,7
Ventilation	5993,8	5993,8

The loss through the windows is however composed by solar gains between 5554 MJ and 5190 MJ for BBB and LS/EPS. The difference cannot be fully explained since the overhang is more important in the BBB model. The solar gains compensate for an average of 65% of the windows losses. The sum of the solar and internal gains compensate for the great majority of both houses needs in heating, with a total of 97,2% for BBB and 90,7% with LS/EPS model. In this case, the amount of energy lost in air replacement is almost totally compensated. This model shows that it might not be relevant here to install mechanical ventilation and heat recuperation systems. The space heating summary is shown in Table 6.3.

Table 5.3 Annual space heating summary

Annual space heating summary	BBB	LS/EPS
Design Heat Loss (Watts)	2768	3043
Gross Space Heat Loss	21579,2	23840,2
Sensible Occupancy Gain (kWh/day)	2,4	2,4
Usable internal gains (MJ)	15566	16417,7
Usable Internal Gains Fraction (%)	72	68,9
Usable Solar Gains (MJ)	5554	5190
Usable Solar Gains Fraction (%)	25,7	21,8
Ventilation loss (MJ)	5993,8	5993,8
Auxiliary energy required (MJ)	**459,2**	**2232,3**

The same variables have been set for household consumption for both houses. They therefore show the same consumption levels. Electricity consumption is 8760 kWh per year and the heat load associated to the hot water use is 15 204,9 MJ, adjusted to 20 273,2 MJ with a 75% efficiency boiler. These numbers are subject to a high level of efficiency and should not be used. The hot water system should be identified and its efficiency validated, and the consumption adapted to the reality of Czech Republic. Table 6.4 shows the summary of the household consumption.

Table 5.4 Annual household consumption

Household consumption		
Daily Hot Water Use (L/day)	225	225
Domestic Water Heating Load (MJ)	15204,9	15204,9
Boiler efficiency (%)	75	75
DHW Consumption (MJ)	20273,2	20273,2
Lighting and Appliance Energy (kWh)	8760	8760

The total annual fuel load for heating have been estimated by Hot2000 to 1,2 and 1,4 tons of hard wood for BBB and LS/EPS. These loads represent a total of 20 732,4 MJ for BBB, and 22 505,5 for LS/EPS. The electrical consumption is equal to the household consumption for lighting and appliances, with 8760 kWh.

Table 5.5 Annual fuel consumption

Annual Fuel consumption		
Wood (1000 kg)	**1,2**	**1,4**
Electricity (kWh)	**8760**	**8760**

5.5 Conclusion

The thermal resistances of the different construction detailed have been calculated. The results are compatible to the data collected through queries and internet research, and respect the passive house requirement for insulation (less than 15 kWh/m^2a). This has been confirmed with the energy calculation simulation, which showed that the heating losses are mostly covered by internal and solar gains for both study objects.

There is however important limitations related to the assumptions made for the simulation. The model has been voluntary simplified, and some errors have not been solved. The difference between the internal and solar gains cannot be fully explained. This analysis should be conducted again and consider real consumption statistics of Czech Republic, and go through all HVAC issues. However, the results provided by the model are considered to be good estimates and will be used as input data in the costs calculation analysis and LCA.

6. Costs Analysis

"Ecology and economics are closely related, both words stem from the Greek word "oikos", which means house. Economics is derived from the Greek word oikonomos and is made of the words oikos (house) and nemein (to manage) which translates as "One who manages a household". Ecology, likewise, is also derived from the word oikos, along with the word "logie", which translates as "study of". Therefore, economics is the management of the house, and ecology is the study of the house."

-Steve King, 2007

This chapter is focused on analyzing and comparing the financial costs of the two models. In order to prove our goal and scope of the project, while having to limit a full LCA, the following life cycle costs were selected to illustrate the significant differences between the 2 models:

1. Fixed costs: In this case the construction of the study objects
2. Variable costs: Maintenance and energy costs/savings

We chose not to include a disposal cost of the 2 buildings, as it would become too hypothetical: It is beyond present knowledge to predict how the possibilities for reusing the materials will be in 50 years, none-the-less the costs associated with it. The easy assumption is that about 95% of the BBB house would be able to be turned into fuel or compost. With present technology a large part of the LS/EPS model would be recycled as landfill and used in new insulation. All in all the materials used in both models does not constitute a significant financial burden at the disposal stage.

6.1. Primary fixed costs

A detailed spreadsheet of materials was accumulated for each house model, based on the complete description of the study objects as defined by the functional unit for the houses, as described in chapter 5. The list was expanded to quantify the materials, and value was added based on current prices in the Czech Republic. The distance from main source of extraction of components from the materials was measured and counted, as were the costs of transport and the labor of constructing the house. These data constitutes the primary fixed costs, and were (informally) peer reviewed by 3 architects and passive house builders who deemed it plausible, but recommended a few national changes. Appendix 2 contains the detailed calculations and the results are outlined in table 6.1 and 6.2:

Table 6.1 Comparison of Primary Fixed Costs:

Total Costs	Costs (czk)	transport to the site (km) from raw source	Transport costs	labor (cost)	Total costs (czk)	Total costs (euro)
BBB	536,881	2,334	20,656	74,000	633,871	24,222
LS-EPS	881,423	7,860	12,900	118,000	1,020,183	38,983

The results illustrate that due to the size, low cost, and local availability of the BB, the initial cost and transport distance is significantly lower; this is again shown by the lower expense for labor, partly explained with the fact that the walls and foundation gets placed in 3 days.

The discrepancy in transport costs are due to the fact that the importer of the LS bricks offered us a package m2 price based on delivery of LS and EPS as well as construction. As such an offer would lower the individual prices we had gathered, we chose to not include the costs for transport of the LS-EPS, in order to illustrate such possible and realistic savings. We included the km distance to illustrate the real differences of this parameter.

Another significant detail is that on the BBB we chose to use local wooden boards rather than OSB for the large surfaces such as floors, ceilings and under-roof. The reason for this is the local availability of wood: Bouzov is surrounded by forest, and the OSB boards would constitute a huge amount of embodied energy and costs in comparison. In general boards are chosen through out C.R.: It requires more work (especially as in CR the width vary within every shipment), but the low labor prices makes up for it. However as need for speed in construction increases the OSB is gradually winning in. To illustrate this factor we deliberately chose to use the OSB on the reference model, the LS/EPS home

Within the total costs of the final building envelope, (delimited as our functional unit) it becomes clear that the LS/EPS model is 61% more expensive in fixed costs than the BBB model of same house. It should be noted that had the BBB used OSB rather than boards, the difference between the 2 would not have been so significant.

6.2. Variable costs

6.2.1. Annual fuel costs

As outlined in Chapter 5, the cost of energy necessary to heat up the models is quite low when compared to typical houses and fairly similar for both models - It may even be completely removed with solar collectors, or simply accounted for with more accurate data, however the data utilized in the following derives from chapter 5.

6.2.2. Energy costs

The energy costs used was also derived from chapter 5 but calculated from current Czech rates of 1670 czk/MWh, and due to the limitation of the Hot2000 it was based on the average of a Canadian household in a normal home. Inhabitants of passive houses are typically more aware consumers than average, the technology implemented is newer than average and none of the energy will derive from electrical heating; an issue which may be included in the average figures of Canada. Significantly it should be noted that whereas the LS/EPS model needs to use electricity for heat recuperation and ventilation, it is possible that the BBB would require less –if any- electricity for these functions.

6.2.3. Maintenance costs

The calculation has included the most significant maintenance points related to the 2 models within a 50 year life span, such as maintenance of exterior and interior walls, exchange of windows: The average lifespan of the roof is 50 years, and has thus not been included in the maintenance cost projections. These processes are based on variable intervals, in accordance to products (lime-wash, paint or plaster), and the typical recommended lifespan of windows (25 years).

The figures represent a 2007 value, as accumulated interest has not been accounted for. We chose to limit this process as it is clear that the figures are so identical that the costs of maintenance will not influence the choice of

Table 6.2.
Variable costs per years: Energy, heating and maintenance

BBB:

	Years					
	1	5	10	20	25	45
Total in Euro	667	3,334	7,050	14,100	20,299	34,590

LS/EPS:

	Years					
	1	5	10	20	25	45
Total in Euro	618	3,376	7,325	14,650	20,892	34,986

which technique to opt for. In addition it would constitute a very hypothetical analysis due to a large number of uncertain factors: The current price of the windows are high, as it is a specialty item used for passive energy houses. It must be presumed that this parameter will change in 25 years, likely being replaced by new technology. In addition all prices will be influenced by the costs of energy, a factor that is very likely to rise at unpredictable rates.

6.3. Conclusion

The results of the fixed costs calculation of the construction process illustrate that the LS/EPS model is significantly (61 %) more expensive than the BBB model. It further illustrates that the variable costs during the use phase of the two different models pose no significant difference based on the available data.

The most serious limitation of the cost calculation lies in the lack of precise data for the energy consumption of an average Czech 4 person family in each of the 2 house models, based on the difference of the HVAC systems. We predict that would show a show an additional financial difference in favor of the BBB model.

It is absurd, but such positive financial gain might be negatively balanced out, if the cost of property taxes had been included, as these are based on the external area of the house, a factor which is many countries work against a wider implementation of passive houses; especially houses with such extreme wall thickness as presented by the BBB.

Austrian residential house based on the same concept as the BBB in this study.
(Photo from www.baubiologie.at)

7. Life cycle assessment

"Because energies and monies for research, development, and thinking are abundant only during growth and not during energy leveling or decline, there is a great danger that means for developing the steady state will not be ready when they are needed, which may be no more than 5 years away but probably more like 20 years".

Howard T. Odum, 1973

A comparative screening LCA has been conducted under the ISO 14 040 framework and ISO 14044 guidelines. Screening LCA should not be open to public. The reader should have in mind that several limits and assumptions have been set in order to conduct the analysis in time, and that it should be considered for academic purposes only. Some fundamental steps of the ISO 14 040 standard have been skipped, especially regarding validation checks for data and results.

The results obtained were different than what was expected. Before presenting results, the goal and the functional unit will be briefly recapitulated, the system and boundary will be defined and delimited, after which the assumptions and the principal characteristics of the data will be commented. The goal and scope will first be presented, after which the data used will be described in the LCI, followed by the Life Cycle Impact assessment (LCIA). The chapters will end with a general discussion on results and limitations of the analysis.

7.1 Goal

The present analysis aims to provide basic estimates of the environmental impacts of the BBB and LS/EPS over their life cycle. At this exploration level, the goal is to answer the two following questions:

- What is the relative importance of environmental load attributed to the use stage of the study objects, and is it coherent with data from literature?
- With similar use stage regarding energy consumption, how significant is the difference showed by the study objects in their overall environmental performance?

The intended audience is the academic researchers involved in the field crossing over environmental studies and architecture spheres, which could use the outcomes of this research as a point of departure for deeper analysis of the issues treated.

7.2.1 Functional unit

As the two houses are similar, it was determined that the functional unit would be the house itself. It is defined as a building providing 86 m^2 of living space for a family of 4 people in Czech Republic, during a lifespan of 50 years. At a qualitative level, it should be accessible to an average income household, thus affordable at normal house price. For further studies, the functional unit could also be 1 m^2 of usable floor area, allowing comparison with any model of house, and results from other studies.

7.2.3 System boundary

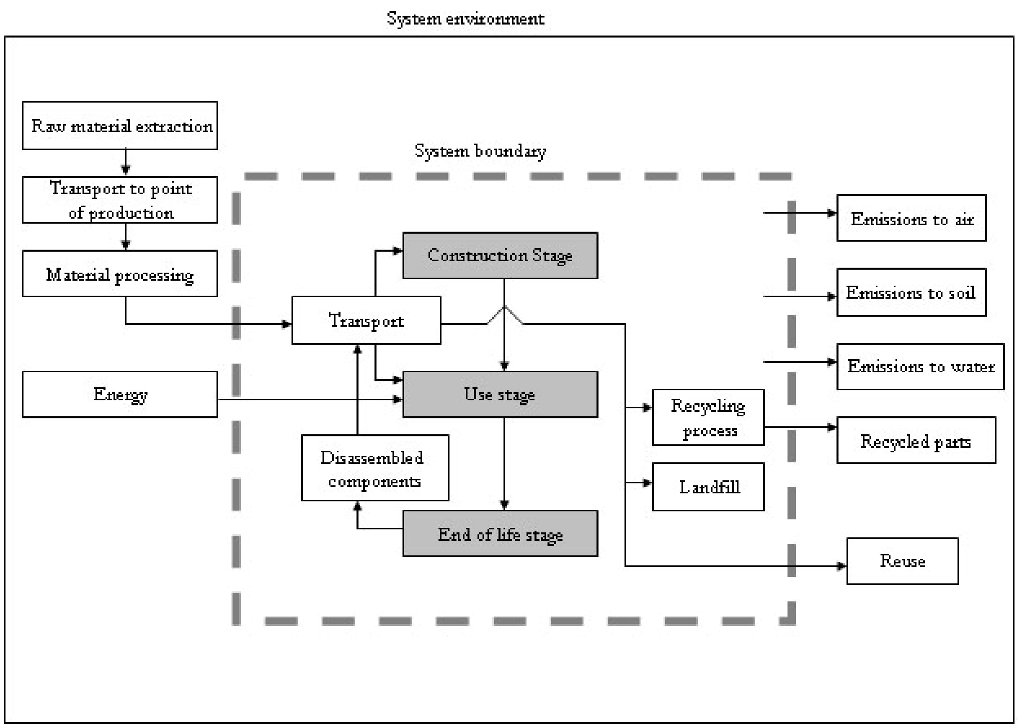
The system has been restrained to three life stages: the construction stage, the use stage and the end of life stage, or deconstruction. In order to attain the fixed goal, the required level detail to be reached is low. Only the major inputs of the envelope, described in the previous chapters, are included. This upstream pre-selection of the materials and processes to be assessed makes the use for cut-off criteria not relevant. This step has been disregarded.

The construction stage strictly accounts the materials used and the extra processes that were necessary to obtain the construction material, when available. For instance baling the straw has been considered, but no data was available for the window production. The transport from the point of production to the construction site is included in the analysis. Equipment and energy consumption for the construction has not been considered in the analysis, as the quantification of these elements is subject to a great level of uncertainty and unknowns, and the processes were not available in the software database. It is assumed that the overall contribution of these elements on the environmental load of the construction stage is marginal and therefore that disregarding them will not influence the global outcome. The same logic is also applied for the other stages.

The use stage accounts the energy consumption and the material for maintenance. Transport to the site is included, but the disposal in relation to maintenance is considered being part of the household waste, and outside the boundary.

The end of life considers the reuse, recycling processes and the chemical transformations occurring in the landfill. The transport of the materials to their final destination is part of the inputs. The system and its boundary are shown in figure 7.1.

Fig 7.1 System boundary



7.2.4 Allocation and system expansion

Houses are not common products that are massively produced. There is no co-product associated with our study objects. However, it was questioned how to consider the straw bales. In some countries, like Denmark, straw is used as biomass to produce heat and/or electricity in plants. This case does not apply in Czech Republic, as the electricity predominantly is produced from non-renewable resources, along with some district heating from waste wood.

It is believable that the straw could end its course with the wood for district heating, which would end by a CO_2 neutral balance. In the worst case, we could say that the use of straw implies the burning of coal for electricity; that would be compensated at the end of life of the product, when straw is burnt again. In all cases, the balance is zero. In a positive scenario, it would be considered as waste reused both for construction material and energy production, which would give considerable good posture in the analysis.

The other important aspect about straw is that it's a by-product of grain production and is considered as unwanted waste in the Czech context. It is not obvious if its production should be accounted as a whole in the LCI. In every case, straw would decompose and liberate its trapped CO_2.

With these considerations, and the lack of precise data, the solution that has been retained is to account the production, but reuse 95% of the product at the end of the life cycle, to which will be added the burning of wood in a heating biomass plant, for the same amount of energy that straw would have produced. It gives straw a small load of environmental impacts linked too its process, but considers the emissions at the end of life. This allocation represents the average of the scenarios above, and is to our point of view a realistic and simple approach that is suitable for the context of the study.

7.2.5 Impact categories and methodology

The EDIP 97 method was selected to conduct the assessment, and the five first categories of impacts will be considered: Global warming; Ozone depletion; Acidification; Eutrophication (nutrient enrichment); and Photochemical smog. These categories are considered giving consistent results between different assessment methods, thus showing the least level of uncertainty. It was necessary to minimize uncertainty at this stage, as the frame of the study already includes a fair amount of uncertain parameters.

7.2.6 Limitations

There are three important levels of limitation in this LCA. The study objects as they were detailed are very limited representations of the reality. Many components, assemblies and/or materials which can be responsible for important impacts are likely to have been removed from the considerations in the definition of the study objects. The electrical system and plumbing work are good examples

The second level is the definition of the system boundary. To shorten and facilitate the data collection and analysis, many important inputs and outputs are not accounted, especially the energy and ancillary inputs/outputs linked to the assembly and disassembly of the houses. Many simplifications have also been made. As an example, the windows have been defined as three layers of glass and a wooden frame. It is probable that the materials only account for a small portion of the embodied impacts in the window, as it is also comprised of 2 layers of argon, insulation and an important mechanic process is required for their manufacturing.

The data quality is also a considerable source of potential inaccuracy. To reduce uncertainty in the method and avoid important effort in data validation, the provenance of the data has been mostly limited to a single database, and the characteristics, year and technological mixes were not always fitting the Czech context. This will be discussed more extensively in the next chapter.

7.3 Life Cycle Inventory

The inputs for the LCI are principally based on the data provided by the previous chapters. The Ecoinvent database is the major source for LCI data collection. The source, year of application and geography of LCI data can be found in Appendix 4. The field of application for the data was more adequate than expected. Most of the data is directly destined to be used for Central Europe or Europe in general. The other provenances are Germany, Switzerland, Austria and Netherlands. The origin is sometimes plural: many processes are geographically interlinked. For instance, the wood LCI data relies on Finish wood industry, calculated by Germans, and adapted to be used for calculations of a Central European context. In a case like that, it is hard to state that the use for central Europe is really adapted; the local saw mills by Bouzov are non-automated and quite old: It would be important in a complete analysis to validate the information.

The technology mixes that are considered in the different LCI also refer to different time periods, and it is possible that some of them are outdated. The example of the wood can again be stated. The LCI considers the technology that was in use in 1986. It is an eventuality that the forest industry profile in Finland is similar to what it was 20 years ago, but this should be verified. Most of this data checking process has been discarded in the present study, due to lack of available time. When it was verified, the data was ranked from fair to good data by the authors of the report. The rest of the information would be accessible in the complete Ecoinvent report no 7 (Ecoinvent 2003).

It was assumed that more uncertainty was linked to the upstream decisions and system boundary definition. As the data was not going to be checked and corrected, the most important for the studies was to use the least sources as possible. The only exceptions are the choice of the steel from ETH-ESU 96 and the zinc coating process for roof sheeting, from the ISEMAT 2001. They have been selected because no equivalent material/process was available from the Ecoinvent database.

7.3.2 Construction stage

The construction stage accounts the material production and the transport. Some materials needed a pre assembly before being accounted. The accounting for the bales include the straw production, the baling and loading processes, quantified according to table 7.1.

Table 7.1 Included processes for straw bales

process	yield (kg/ha)	mass (kg)	area (ha)
Baling	7050 (1)	1000	0,142
Loading bales	7050 (1)	1000	0,142

(1) www.ias.enu.edu

The zinc coating process has been added to the steel accounted for roof sheeting, per square meters of area. The aggregated quantity of materials for both study objects is shown in table 7.2 and 7.3. The conversion units and references can be found in the appendix 5.

Table 7.2 quantities of materials and distances for BBB, construction stage

Materials/components	volume (m3)	mass (kg)	distance (km)	mass x distance (tkm)
Concrete, for foundation	4,99	9980	10	99,8
Sonotube	3,12	229,008	200	45,8
metal, for foundations and structure	0,2125	1657,5	150	248,6
fibre cement, foundation	2,43	3402	40	136,1
Soft wood, structure	30,55	16191,5	5	81,0
Hard wood, window frames, door and floor	3,68	2318,4	5	11,6
Straw bales		33226	1	*33,2*
Clay, only for transport	0,58	929,16	100	*92,9*
Lime, for limewash	0,22	264,22	500	*132,1*
windows		632,6	300	189,8
zinc coated steel, roof sheeting	0,185	1443	200	288,6

Table 7.3 quantities of materials and distances for LS/EPS, construction stage

material	vol (m3)	mass	distance (km)	mass x distance (tkm)
Concrete, for foundation	2,85	5700	10	57,0
Sonotube	1,43	104,9	200	21,0
metal, for foundations	0,0749	584	150	87,6
fibre cement, foundation	1,7	2380	40	95,2
OSB, structure	3,92	2352	2000	4704,0
Soft wood, structure	7,1	3763	5	18,8
Hard wood, window frames, door and floor	3,68	2318,4	5	11,6
sand-lime brick	17,45	33155	500	16577,5
Expanded polystyrene	53,63	1608,9	500	804,5
Stucco	1,13	2443,06	150	366,5
Cement mortar	1,5	3243	150	486,5
gypsum board	1,24	3455,88	100	345,6
Base plaster	0,77	2145,99	50	107,3
Paint	0,0566	59,9	25	1,5
Window		632,6	300	189,8
zinc coated steel, roof sheeting	0,132	1029,6	200	205,9

Different transport vehicles have been chosen according to the distance and the nature of the material transported. Transfers of merchandise have been neglected. We assume that the materials go directly for the point of production to the construction site. This approximation is not realistic, but has been done to simplify the model. It should represent the major mean of transportation for the material. These assumptions are based on our own decision and do not root themselves on any data. It should be checked in a deeper analysis, but is considered as a good enough proxy for the purposes of the study. The grid for transport allocation is presented in table 9.4. This grid is also used for the other stages.

Table 7.4 Means of transport related to distance and use

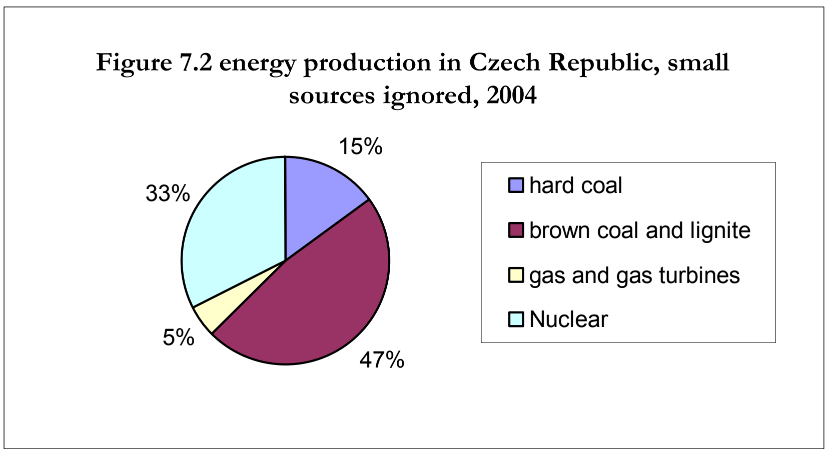
type	distance
Transport, tractor and trailer	bales, farm
Transport, lorry 16t	<=100 km
Transport, lorry 28t	>100 km
Transport, muncipal waste collection,lorry 21 t	waste
Transport, van<3,5t	reuse wood

The first observation that can be made is that total masses for both houses are similar. With a total of about 70 tons, the total mass of BBB's materials is 10% higher than LS/EPS, with 6,5 metric tons. This similarity is mainly due to the low density of the straw, with 100-130 kg/m^3 (Andersen & Møller-Andersen 2000), compared to 1900 for sand-lime bricks (Physics Factbook 2003). This low density compensates for the important difference of the volumes of the houses. A major difference can be observed at the transport level. LS/EPS mass multiplied by distance is 24 000 tkm, compared to 1360 tkm for BBB. This difference of 95% reflects the impact of local availability of the materials composing BBB.

7.3.3 Use stage

7.3.3.1 Energy consumption

The major constituent of the use stage is the energy consumption. It is quite similar between the two houses, mainly because the study objects have been designed according to the same insulation requirements, and that the electricity consumption is based on the same, substitutes and us. The data used is imported from the results of the energy simulation. The distribution of electricity production has been done according to the data for the year 2004, as shown in figure 7.1.



Modified from: International Energy Agency (2007)

The annual energy consumption was summed up for 50 years. Energy for heating space and water was entered to the model, considering a 75% efficiency. That is the only point where there is a slight difference between the two study objects. It is important to remember that PH normally does not require energy for space heating. Table 7.5 and 7.6 summarize the total energy consumption. We can notice that space heating accounts for a maximum of 10% in the case of LS/EPS, so that uncertainty about heating will not be significant in the final outcome.

As it is a great source of uncertainty, it is important to remember that the electricity consumption has been calculated by Hot2000 according to its default settings, from Canada. The consumption of electricity is probably overrated at an unknown level and it will probably have an important influence in the final environmental performance of the objects.

7.3.3.2 Maintenance

The maintenance only accounts for a small share of the use stage. Windows are assumed to be changed once in the life time. For BBB, a lime wash every year is considered, and the part of the interior finish plaster is redone every ten years. The same frequency is considered for redoing the painting and some plastering for LS/EPS. Transport to the site is included, but waste disposal is assumed to be non significant.

Table 7.5 Energy consumption in the use stage, for BBB and LS/EPS

	Annual consumption	Consumption over 50 years
LS/EPS & BBB	(kWh)	(kWh)
electrcity	8760	438 000
LS/EPS	(Mj)	(Mj)
wood, hot water	20 273	1 013 650
wood, heating	2 232	111 600
total	22 505	1 125 250
BBB		
wood, hot water	20 273	1 013 650
wood, heating	459	22 950
total	20 732	1 036 600

7.3.4 End of life stage

For simplification, a municipal landfill scenario has been selected for the study. Most of the countries separate construction waste from municipal waste in dry deposit points. The short amount of time available for the assessment and the absence of pre made scenario in this orientation in the LCA database made us take this shortcut. The impacts of this choice are unknown, as the landfill scenario has not been examined. However, the disposal has to be considered and we assumed that the municipal landfill was the more accurate way to treat the waste.

In the scenario selected, metal is assumed to be recycled in the proportion of 50% for the metal parts in structure and foundation, and 80% for the roof sheeting. 25% of reuse was assumed for the wood components, which could have been higher. The bales are reused at a proportion of 95%. The following distances were considered for the transport:

Table 7.6 Distances to final destination

final destination	distance (km)
biomass plant	10
recycling center	100
recycling center	100
neighborhood	2
neighborhood	2
landfill	20

In general, the transport for the end of life stage is not significant when compared to the construction stage, and is quite similar for both study objects, with 1797 tkm for BBB and 1361 for LS/EPS.

The combustion of the straw has been assumed to be equivalent to the same amount of energy produced from wood in a 300 kW heating plant at 82% efficiency. The straw possesses 13 Mj of potential energy per kg (Newman 2003). Total energy produced from 33,2 tons is 326 353 Mj.

7.4 Life Cycle Impacts Assessment

Within the selected categories, the comparison of the two houses does not show an important difference for the environmental impacts. On the global level, the BBB seems to perform slightly better than the LS/EPS house. The more important difference is in the Eutrophication category, where BBB's environmental load is 29,3 % less important than its reference model. In the relative scale, the Global warming and Photochemical smog categories occupy the second position, with a scores lower by 15,0 % and 12,7 %, for BBB, while less than 5% gap between the two objects in the other categories. The observation of the figures showing the contribution of the different life stages enlightens more interesting facts.

Figure 7.3 comparison the LCIA characterization results for 5 impact categories For BBB and LS/EPS, in percentage

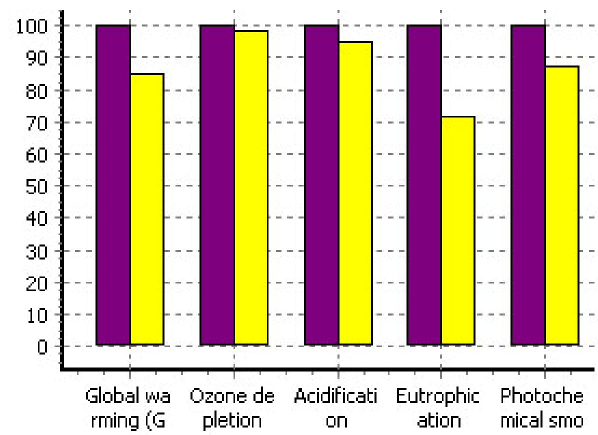
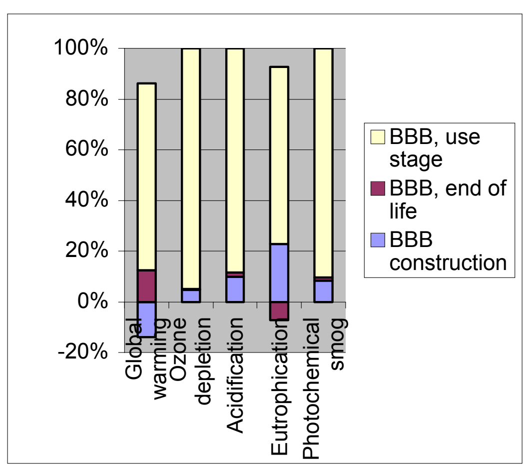


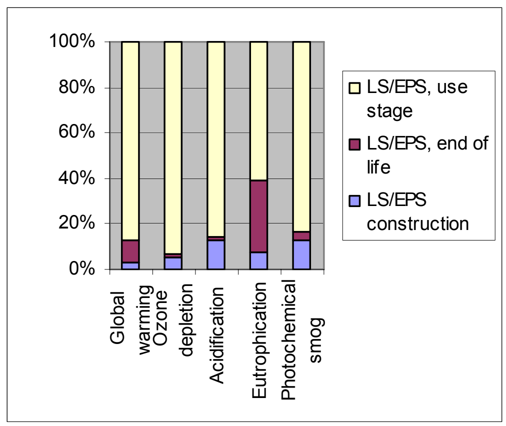
Figure 7.4 Share of the life stages of the BBB for each impact categories



We can see that the use stage is by far the most important in both houses life cycles. For the BBB, it accounts for more than 81,7 % of the total in all categories. Its burden for global warming is 101,2% of the total contribution, consequence of a negative contribution of the construction stage. It is caused by the trapping of 5,8 tons of CO_2 in the construction materials. The contribution of the construction stage for BBB is -19,2% for global warming, 26,8 % for Eutrophication, while it represent less than 10% for the two others groups of impacts. The end of life stage contributes mainly to global warming, with 17,3 % of the total load. The major contribution is the reemission of the CO_2 trapped in the materials to the atmosphere. The other interesting point to notice is the negative contribution (-8,5 %) to nutrient enrichment –i.e. enhancement of environmental performance, caused by the reuse of the bales, modestly counterweighing for the overalls impacts linked to the construction stage.

In general, the results for the LS/EPS house show the same trends. Here again, the use stage is by far predominant. Apart for the eutrophication, with 61,1 %, the share of its total impacts is situated in the interval between 83,4 % to 93,6 %. This low relative score in the use stage for Eutrophication is due to the important of contribution of the end of life stage. This was not present in BBB because of its small flux of materials to the landfill where the nutrient enrichment is happening. It is caused by contamination of underground water, through the migration of decomposed matter in the soil. This is not observed is the case of the BBB for two reasons. The smaller flux of disassembled materials finishing its life in the landfill plays an important role. However, the major factor is the decision we took to reuse the bales. It prevents in the model an important amount of NO_3 equivalents to be emitted when growing the wheat at the farm. These results should however be completely disregarded, for the percolation would probably be less important in a dry depot than in the landfill, where the construction waste is likely to end.

Figure 7.5 Share of the life stages of the LS/EPS for each impact categories

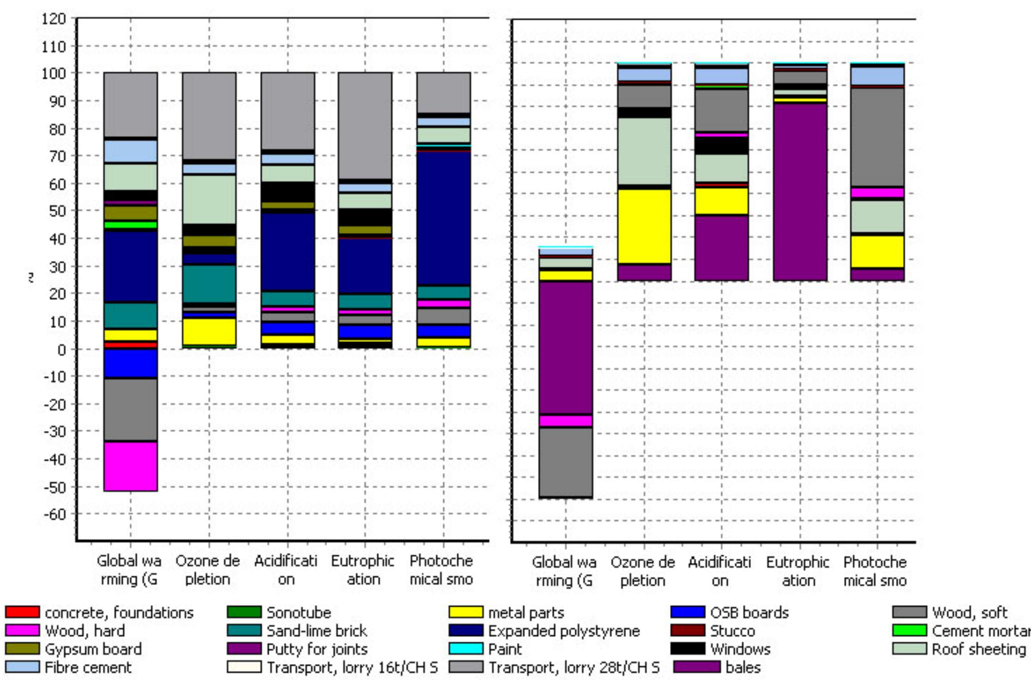


7.4.2 Identification of the hotspots

As previously mentioned, the use stage is responsible for the great majority of the environmental impacts. Electricity consumption is clearly the major source of pollution, with nearly 100% of the share in the global warming and Ozone layer depletion categories. The combustion of the wood for heating water (mainly) is however significant for local impacts. 27 % of the acidification burden, 52 % of eutrophication and 67 % of photochemical smog is attributed to the high emissions of particles and dust resulting by the incomplete combustion in the furnace. As the energy consumption is about the same for both study objects, there is nothing important that can pulled from a comparison of the objects.

The construction stage presents more interesting facts. Figure 7.5 presents the relative importance of the impacts induced by each of the construction materials and processes. The negative figures represent the CO_2 trapped in the wood and bales, and should be considered as neutral, as it is eventually going to be reemitted.

Figure 7.6 Contribution of the materials/processes of LS/EPS and BBB to each impact categories, construction stage

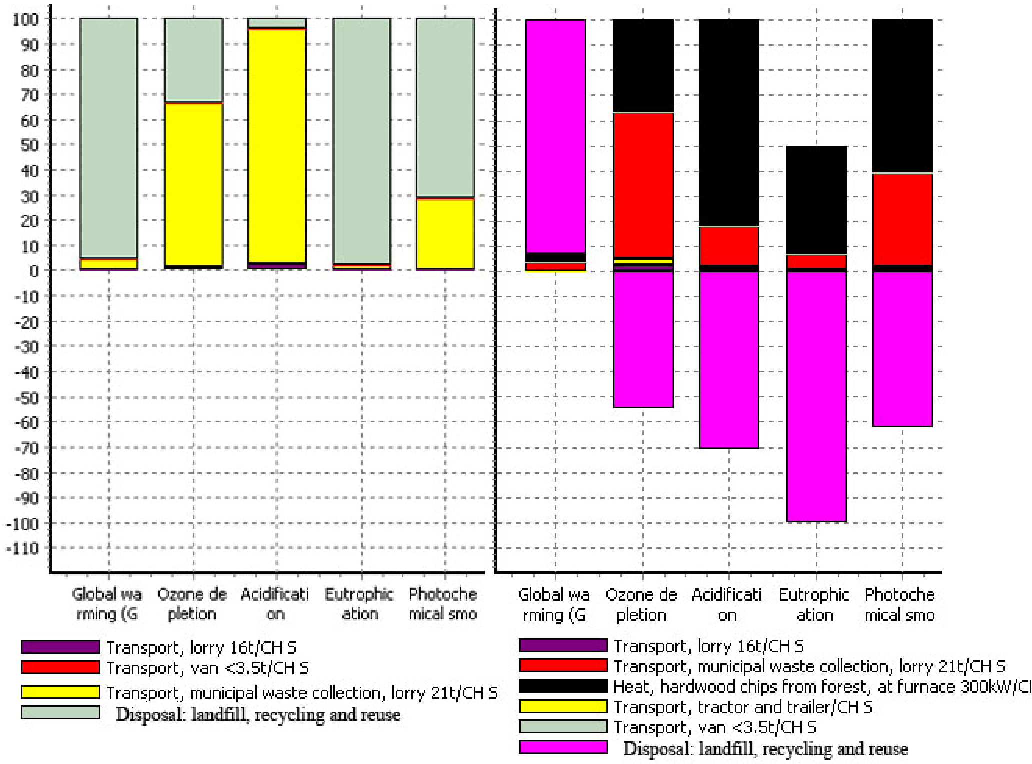


What we can observe from the diagram is that for the LS/EPS house, the transport and the expanded polystyrene are the most important features, with the metals in second rank. Since the first items are mostly absent in the BBB, we can see that in its profile, the metal takes a more important share, mainly in the Ozone depletion field. It is however important to remember that there is more metal in the BBB, due to bigger sized foundations and the use of the C-beam at the top of the wall.

Apart for the Ozone depletion contribution, we can see that the organic materials, mainly bales and soft wood, take the most important share of BBB's impact profile. We can already tell from this figure that the use of local and organic materials in BBB construction gives it a clear advantage on LS/EPS, especially in the Global warming field. By comparing the same materials in the two figures, we can already conclude that the overall impacts are definitely lower for BBB.

The end of life profile is closely linked to the construction stage, as it is tributary to design choices and materials. The figures differ significantly for the two houses. In figure 7.5, we can see for LS/EPS that the negative impact contribution of recycling and reuse of the materials do not compensate for the emissions occurring at the landfill. Even with this contribution, the disposal of the different assemblies is more than 95 % responsible for the contribution to Global warming and eutrophication, and around 70 % for the smog effect. Transport is playing an important role in the Ozone depletion and acidification categories.

Figure 7.6 Contribution of the processes of LS/EPS and BBB to each impact categories, end of life stage



For BBB, the reuse of the bales gives the disposal scenario a negative column profile in all the impact categories, with the exception of Global warming. This shows the effect of the combustion of the bales at the biomass plant. The disposal impacts on this field are in consequence similar to the LS/EPS, with around 95 % of the impacts attributed to the disposal. The combustion processes and transport share the scores or effective impact. They account respectively for around 35 % and 60 % in the Ozone depletion impacts, 80% and 15% in the acidification process, and 60% and 35% in the photochemical smog field. The negative contribution of the disposal scenario, mainly caused by the reuse of the bales, compensates for more than 50% of these sectors, and completely covers the impacts on eutrophication.

7.4.3 Quantification and normalization

The previous results by themselves do not have significance without normalization. All the substances have been converted in equivalents of a single molecule for each category of impact, according to the EDIP method. Those units represents the mass of CO_2 for global warming (considering 100 years), CFC-11 for ozone depletion, SO_2 for acidification, NO_3 for nutrient enrichment and ethene for the photochemical smog.

We already know that the construction and the end of life of the houses are closely linked. By isolating their normalized impacts from those of the use stage, we can see that there is only a significant difference for the contribution to global warming and the eutrophication, and at a lesser degree to the photochemical smog. It is shown in figure 7.6. The criteria for significance was set at 100% difference at minimum between two categories

Table 7.7 Normalized impacts, construction and end of life stages summed up

BBB	summation (tons)	percentage of total
Global warming (GWP 100)	-5,81	-1,9
Ozone depletion	0,0000024	5,1
Acidification	0,11	11,6
Eutrophication	0,26	18,3
Photochemical smog	0,02	9,5
LS/EPS		
Global warming (GWP 100)	46,71	13,1
Ozone depletion	0,0000030	6,4
Acidification	0,14	14,1
Eutrophication	0,78	38,9
Photochemical smog	0,04	16,7

This combination of both stages gives for BBB a negative value of -5,81 tons of CO_2 equivalents, compared to 46,7 tons with LS/EPS. This is clearly the most important result coming out from this study. The negative value is however an irregularity that causes problem. The emissions should have been superior to zero, since the bales are supposed to emit back their inner CO_2. The only way it can be explained is that a mistake was done when converting the straw to wood, or that the wood possesses more energy than straw for the same amount of CO_2 released in the atmosphere. We however know that there is 32 tons of straw used in BBB, and that the mass of the embodied CO2 can only be a fraction of it, after the energy and ashes are separated. We are also sure that at least good quantity of emitted CO_2 is accounted in the burning of the wood. With that in consideration, it seems that if we add an unrealistic 15 tons of CO2 to the figure, there would still be around 450% difference between the two houses, which is enough to affirm that it is significant, at this screening level.

In the eutrophication category, BBB shows 0,26 tons of NO_2 equivalents and LS/EPS construction and end of life stages would be responsible for 0,78 tons, a 300% difference. Finally, the contribution to photochemical smog is exactly 100%, with 0,018 tons of ethene for BBB and 0,036 tons for LS/EPS. As it was already known from the previous figures, the environmental load of the two houses for the acidification and ozone layer depletion categories is similar.

The summary for the whole life cycle of the houses has been compared with the average annual contribution per person to each category, for the year 1994. The EDIP method proposes an adjustment for the year 2004 by weighing the categories. This option has however been rejected as weighing also includes other considerations that will add more uncertainty than fixes: the year 1994 was kept. This does not represent a problem for interpretation of the results. The normalization is here used only as a scaling tool to identify the important impacts categories. The outcome can be seen in table 7.7.

Table 7.8 Comparison of the results to average impacts per person per year, 1994 data.

Global	unit	average / person/year	BBB /year	BBB, person/ year	% of average, BBB/person	year of reference	Geography
Global warming	kg CO_2-eq	8700	6082,0	1520,5	17,5	1994	World
Ozone depletion	kg CFC-11-eq	0,103	0,000929	0,00023	0,2	1994	World
Regional and local							
Photochemical ozone Formation	kg C_2H_4-eq	25	3,8	0,9	3,8	1994	EU-15
Acidification	kg SO_2-eq	74	18,3	4,6	6,2	1994	EU-15
Nutrient enrichment	kg NO_3^--eq	119	28,7	7,2	6,0	1994	EU-15
Global	unit	average / person/year	LSEPS /year	LSEPS, person/year	% of average, LSEPS/per	year of reference	Geography
Global warming	kg CO_2-eq	8700	7156,1	1789,0	20,6	1994	World
Ozone depletion	kg CFC-11-eq	0,103	0,00094	0,00024	0,2	1994	World
Regional and local							
Photochemical ozone Formation	kg C_2H_4-eq	25	4,3	1,1	4,3	1994	EU-15
Acidification	kg SO_2-eq	74	19,3	4,8	6,5	1994	EU-15
Nutrient enrichment	kg NO_3^--eq	119	40,0	10,0	8,4	1994	EU-15

Viewed on this angle, the whole results that have been presented before get a new meaning. The numbers obtained for the Global warming category are certainly the most important results of this LCA. Shared by its occupants, the impacts of the house (as it is defined in this study) accounts for 17,5% and 20,6% of the average annual contribution per person, for BBB and LS/EPS respectively. This means that the choice of one house or another will only make a 3% change yearly, if it is inhabited by 4 people. The nutrient enrichment category is less important in the global figure, with 6,0% and 8,4% for BBB and LS/EPS, but show a similar difference, with 2,4%

The role of others impacts become really modest. With 0,2 % of the annual contribution, ozone layer depletion should be completely disregarded as an important impact category in housing, as least with the definition of the house that has been used in this study. The two other groups of impacts account for less than 6,5% of the average yearly emissions, and won't be discussed about more, as they have been identified as similar for both houses.

As they are compared with data from 1994, it is probable that these impacts would look even less important with the updated figures. It is also important that these relative numbers are closely linked with the number of people in the household.

7.5 Conclusion

Based on the LCI data used, and the short time available, we can extract the following outcome of the screening LCA:

The use stage is by far the most important stage in the life cycles of the study objects. It accounts for 81,7 % and more for all categories of impacts, with one exception in the eutrophication category, where its share is 61,1% for LS/EPS. The other important fact is that for BBB the use stage contributes around 100% of the global warming load. This number is however subject to some error in the model, but should stay high. The results disagree with the studies proposing 40% to 60% of the energy attributed to the construction stage. However, energy is only an approximation of environmental impacts, so the data cannot exactly be compared.

A reason for this importance of the use stage is the choices of the materials for the study objects. Lime-sand brick and expanded polystyrene are materials that more or less show a good environmental profile. It is probable that a house made from concrete, OSB boards and mineral wool would show different results. The most important factor is the definition of the house. It is probable that when everything is included, the share of the use stage would be more similar to the 40-60% stated in Tormark and Yohanis reports (Tormark 2001, 429; Yohanis 1999, 77).

With this great importance of the use stage, the differences made by the other stages are modest. Only the Global warming and Eutrophication categories show important differences when the construction and end of life stages are isolated from the use stage, with a more important load for LS/EPS of at least 450% for Global warming and 300% in the nutrient enrichment consideration. These factor gives respectively a 15,0% and 29,3% lower scores for the same categories in the life cycle of the two houses, but this would consist only two a change of 3,0% and 2,4%, when compared to average annual emissions per person.

We therefore cannot say that the choice in these different construction approaches would make an important difference in the environmental performance of the house, for the categories considered. However, other important issues will be brought in perspective in the general discussion of the report.

8. Conclusion

> **Because energies and monies for research, development, and thinking are abundant only during growth and not during energy leveling or decline, there is a great danger that means for developing the steady state will not be ready when they are needed, which may be no more than 5 years away but probably more like 20 years.**
>
> Howard T. Odum, 1973

The construction costs were clearly the most persuasive element of the partial results. The BBB is significantly less expensive to construct; the envelope and foundations can be built at 62,1% of the LS/EPS price, for a total around 24 000 euros, compared to 39 000 euros. The major reason of the low cost for BBB is the very low price of the bales, which at same time constitutes insulation and structural walls. The real prices could have been significantly higher had the BBB included OSB sheets (rather than wooden boards) as it is planned in the new BBB subdivision in Germany. If a customer were to judge from cost alone, we can assume the BBB to be chosen. This is likely a more important issue than the results provided by the LCA.

The use stage showed an important financial dominance over the two other stages, illustrating that the use costs constitute 87,1 % and higher of total cost in all categories for both houses with only one exception. The global warming category revealed itself to be the most important feature to consider among the environmental categories selected in this study, and at a lesser degree nutrient enrichment. This should be verified with a more detailed end of life scenario. An overall 15% better performance for BBB was observed for global warming. The comparison of the construction and end of life scenario demonstrated that the difference is sufficient significant to be confirmed at the screening level. Conducting the screening LCA made it clear that it would be advantageous to the study to include parameters of a similar sized average house, as a point of comparison, in order to scale the performances of the study objects.

The choice in the materials is of great importance for the other stages especially in relation to the embodied energy due to transport which formed an important feature in LS/EPS impact profile. Some materials have also a great amount of embodied impacts in their fabrication: The fiber cement showed significant impacts despite the small quantity used in both houses. The expanded polystyrene is also far beyond the energy of the straw, with EPS responsible for a significant part of the impacts on global warming, and the straw neutral in the whole life cycle. In the environmental view point, the straw makes a clear difference for the construction stage, and for a fraction of the price.

It also appeared that the toxicity in water and human toxicity impact categories – which were chosen not to be considered due to their important known degree of uncertainty – are likely to entail important relevance in LCA studies of buildings. The changes observed in the result between both houses were more significant than all other 5 issues: However, in the context of a screening LCA, these results should not be presented. It is important to emphasize that the definition of the study objects, the delimitation of the boundary and the LCI data entailed a fair amount of uncertainty. In the context of a comprehensive LCA, it would be relevant to widen the field of impact categories.

Despite the various uncertainties and limitations, we believe the various analysis included in the project served to provide a detailed answer based on the initial research question:

"Controlling for energy efficiency and design, what are the estimated costs and environmental impacts related to two energy-efficient houses, conceived in accordance with either a sustainable development or an energy-efficiency criteria?"

Summarizing, we found results to our query, and in this comparison the BBB showed a superior performance for both aspects of the question. This poses a central dilemma, to be solved in future studies: What if the inexpensive model would have been the model most harmful for the environment as often is the case? Due to this issue we recommend the LEED labeling over the Passive House.

9. Evaluation

> **"Accounting is not an answer, but it gives some guidance, because we can look at other systems that do work and use these accounting methods as a crosscheck on our common sense. […] A study was done in Britain some years ago on recycled paper. They concluded it was easier to just put paper in an energy-efficient furnace and use it for fuel rather than recycle it. Ironically, using the permaculture strategy of using the paper as a sheet mulch technique to establish a food garden is probably light years ahead of either of those options. So the things that look very, very simple, rudimentary, even amateur, often when you use these more complete accounting methods, come up as the most energetically efficient."**
>
> David Holmgren, 2006

The following chapter serves as a final 'disclaimer' to the fractionalized technical approach of the project, discussing some non-rational hindrances for the results to be implemented, before addressing the initial issue of environmental sustainability within residential construction

The Western Scientific approach

This project represents a model of classical fractionalized research. All issues to be researched were broken down in components and evaluated individually, only to be treated as a whole during the final conclusion. The results thereby achieved are typically weighted as more serious, than the 'common sense' mentioned by David Holmgren. Unfortunately such scientific approach often limits more that it includes.

In our case we did not view the effect of the main investment of materials circulating longer in the local economy, rather than being paid to importers of foreign products. -Or on a personal level; some home owners may be able to stay mortgage free by growing the main building materials themselves, and supplying the plaster from the site, rather than supplying the cash for the materials? Neither does the project consider the considerable difference between living in a house made from 'raw' natural materials, within walls which 'breathes' and regulate moisture, compared to the sealed interior, forced air circulation and toxicity of materials represented by the reference model.

These are very important elements to include when considering which house to build, elements which may be as serious as costs, future energy savings or contribution to global warming. One has to ask; what use is it for the homeowner to know about eutrophication, if his children develop serious allergies from living in the house?

The LCA approach:

Another overall question with such scientific research is the reliability of the approach; an international LCA expert, Arnold Tukker, concluded that the underlying weaknesses of the LCA method are too great to withstand skeptical scrutiny:

"Personally, I believe it will never be possible to solve controversial discussions about products with an LCIA [life cycle inventory assessment] method that is based solely on mathematical relations between interventions and protection areas. There are simply too many uncertainties, there is too much ignorance, and they can only be overcome by all kinds of subjective, subtle, and basically value-laden choices. …

(Arnold Tukker 1999),

We noticed some of the issues while doing the screening LCA; lack of real data for the windows, miss guiding data of the wood (based on effective Finnish saw mills), and lack of possibility to ensure that all of the impacts of securing the resources for producing LS or EPS were in fact included in the databases.

In 2002 the U.S. Department of Housing and Urban Development arranged for a forum about LCA in the home building industry. The event presented five different LCA tools and it became apparent that each tool had its own unique application. Some of the key issues concluded by the participants included:

• The information produced by the LCA tools is not valuable as stand-alone data. The data would need to be coupled with other information since the LCA data is not an absolute measure of product value;

• The data output is too complex for home builders to use in a timely manner;

• Input data is sparse and includes many assumptions that are hidden from the LCA tool user; while uncertainty in the results is not addressed.

Most academics, officials and business associates involved in with LCA are aware of several cases where LCA has been conducted in a biased manner or have been misused for political or marketing purposes. Summarizing the view surrounding the LCA approach, it can be concluded that it provides a very fractionalized result and should not be considered as the holistic study that is implied in the title 'LCA'.

The "Straw/Earth factor"

Even though the project concludes that the BBB model is significantly cheaper to construct and have a better environmental performance than the LS/EPS reference model, it may not change anything for the market acceptance. In same way that the poor people in S. America or Africa's shanty towns view a tin shed as more prestigious and modern than the cooling mud hut with a more sound proof thatch roof, so does the European/American home owner suffer from the 'straw/earth effect'. Modern generations have been alienated to these traditional building materials, and assume them to be inferior. A significant factor in this process is the fact that these products become the losers in the ever-growing marketing wars, as it is hard to secure a solid profit from selling straw bales and earthen plaster in building supply ware houses. Environmental management students at University of California, Santa Barbara, performed a comprehensive 'Willingness To Pay' analyses for an innovative building block made from rice straw. Their research found that the once consumers became aware the block was made from straw, the estimated house value dropped by 14%. (Abbott et al 2006, 8)

Currently in Denmark the 'straw/earth effect' has taken a twist: the general public has learned that it is an acceptable building material, but as it has been 'medialized' as a mean for creative owner builders to reach financial independence, it also became publicly perceived as a 'hippie', approach and fails to attract the kind of consumers as we see in countries such as Belgium and Austria, where prestigious architect designed straw bale houses are the norm within natural building.

Passive House and Sustainable development:

Disregarding the BBB, the project demonstrated how a house which lives up to the Passive house criteria, may have a significant environmental impact through out it's whole life cycle; and the LS/EPS is one of the better environmental options compared to what is being used for passive house construction.

It becomes clear that while the European focus on passive houses may serve to save the energy budget for the individual home owner, and Kyoto –Co2 points for the society, the criteria is much to narrowly focused on energy. It becomes increasingly clear that to obtain the three interlaced dimensions of sustainable development: economic development, social development and environment protection, a more holistic permaculture approach is necessary, such as the one outlined in the American LEED criteria which also incorporate such issues as natural or local materials, transport, air quality, water management and training.

A fractionalized approach will never secure the aim of sustainable development.

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Appendix 1

Questioner sent to the architects

Dear Passive House designer

We are in process of doing a University research comparing passive houses from 'conventional materials' with passive houses built from load bearing big straw bales. We look at elements such as Embodied Energy, Life Cycle Analysis and Financial pay-back rate.

We believe the outcome of the project will be beneficial for all involved in low energy housing; designers, builders as well as potential homeowners.
The comparison and recommendation of combined computer based tools to execute it will be available in February '08.
"We" describes:
-Francois Gonthier-Gignac from Quebec (Bc. Architecture), Master student of Sustainable Energy Management at Aalborg University of Denmark.
-Max Vittrup Jensen, (Bc. Human Ecology), professional Natural Builder and Master student of Environmental Management also at Aalborg University, but resident in C.R.

We hope you will be able to help our research by answering the following questions: We plan to interview you and tape the answers, the reason for e-mailing them to you is simply to allow you to prepare and make most effective use of your time.

General information:

1. **How did you get involved in passive house building?**

2. **How many passive houses have you been involved in making?**

3. **Over how long time?**

Years	

4. **Please describe your customers?**

5. **What are the interest/motivation of the majority of customers?**

6. **Have you noticed a change in type (social background) of customers over the years?**

7. **Do you find the motivation of customers regarding passive house has been changing over time?**

Design specific questions:

1. **What is your strategy/focus for passive house standards?**

2. **Do you use any computer-based tools to optimize material, energy and/or financial efficiency of the passive house?**

3. **How do you use estimate the building costs?**

4. **Is it necessary to build airtight and to use heat recovery in order to achieve the energy efficiency of passive-energy building standard?**

5. **How long time do you think it will take for the energy savings to compensate for the added energy input during constructing?**

6. **Do you consider the energy involved in the production of the materials when designing a passive house?**

7. **Does the geographical origin influence your choice of materials?**

8. **Have you considered using plastered straw-bales for the house? Please motivate your answer.**

9. **How much do you estimate the added cost is for a passive house, as compared to a house build in accordance with minimum energy requirements? (in percent)**

For the development of our comparison model we would appreciate help with the following parameters

<u>Technical information:</u>

1. **Please describe your preferred**

(Please outline composition from outside to inside (include brand names of materials)

  Foundation…………………………………………….
  Wall………………………………………………………
  Roof………………………………………………………

2. **What is the insulation value per m2?**
  Foundation…………………………………………….
  Wall………………………………………………………
  Roof………………………………………………………

3. **What is the cost m2 Materials/labor?**
  Foundation…………………………………………….
  Wall………………………………………………………
  Roof………………………………………………………

4. **Expected energy consumption kwh/year**
  Heating of space
  Heat re-cuberation unit
  House hold consumption (bath, kitchen, lights etc.)

Appendix 2

Costs calculations

BBB: Variable costs per years: Energy, heating and maintenance

Items	Unit price	Cost, incl labour all at '07 prices	Years					
			1	5	10	20	25	45
Firewood	1100/ton	1 320	1 320	6 600	13 200	26 400	33 000	59 400
Electricity	1670/mwh	14 629	14 629	73 145	146 290	292 580	365 725	658 305
Limewash	500/25 kg	1 500	1 500	7 500	15 000	30 000	37 500	67 500
Interior plaster or paint	5000 kc	10 000			10 000	20 000	20 000	45 000
Exchange of window panes	71,400 kc	75 000					75 000	75 000
Exchange of roof	56,000 kc	70 000						
Total in czk			17 449	87 245	184 490	368 980	531 225	905 205
Total in Euro			667	3 334	7 050	14 100	20 299	34 590

LS/EPS: Variable costs per years: Energy, heating and maintenance

Items	Unit price	Cost, incl labour all at '07 prices	Years					
			1	5	10	20	25	45
Firewood	1100/ton	1 540	1 540	7 700	15 400	30 800	38 500	69 300
Electricity	1670/mwh	14 629	14 629	73 145	146 290	292 580	365 725	658 305
Exterior plaster/paint repair	500/25 kg	15 000		7 500	15 000	30 000	37 500	52 500
Interior plaster or paint	5000 kc	15 000			15 000	30 000	30 000	60 000
Exchange of window panes	71,400 kc	75 000					75 000	75 000
Exchange of roof	56,000 kc	70 000						
Total			16 169	88 345	191 690	383 380	546 725	915 105
Total in Euro			618	3 376	7 325	14 650	20 892	34 968

Construction costs BBB (1/3)

BBB	Description	unit dimensions (m)	quantity	adjusted quantity	total length (m)	total area (m2)	total volume (m3)	cost/unit (czk)	costs (czk)	transport to the site (km) from raw source	Transport costs	labor (cost)	Total costs (Czk)	Total costs (euro)
Foundations	**piers**													
	sonotubes	1,20 m x 250 mm x 20 mm	126	132,3	151,20		2,49	500	63 000	200				
	concrete	1,20 m x 200 mm	126	132,3			4,99	2500	12 469	10	700			
metal)	anchors	16 mm x 300 mm	126	130			0,00784	25	3 250	150				
	bracers, U-shaped	170 mm x 100 mm	126	130			0,12022	25	3 250	150				
	Lumberstructure													
(transversal)	*wooden beam*	*100 mm x 140 mm x 8,750 m*	*14*	14,7	*128,63*		*1,80*							
(longitudinal)	*wooden beam*	*100 mm x 140 mm x 550 mm*	*18*	18,9	*10,40*		*0,15*							
(longitudinal)	*wooden beam*	*100 mm x 140 mm x 1400 mm*	*18*	18,9	*26,46*		*0,37*							
(longitudinal)	*wooden beam*	*100 mm x 140 mm x 1100 mm*	*81*	85,05	*93,56*		*1,31*							
total	wooden beam	100 mm x 140 mm			259,04		3,63	6000	21 759	5	700			
	Eternit Turi	2440 mm x 1220 mm x 16 mm	51,00			142,19	2,43	364	51 756	60				
	Insulation													
	bales	2500 mm x 1250 mm x 800 mm	46	54			115,00	300	16 200	1	1 000			
Floor	earth mortar	40 mm x 300 mm x 6250 mm	23 rows				1,84	0	0	0				
	lattes	16 mm x 100 mm x 6250 mm	23	24,15	150,94		0,24	6000	1 449	5				
	Boards	4000 mm x 200 x20 mm	31			85,94	1,48	4000	5 906					
	Lumberfinish	19 mm x 120 mm x 4000 mm?				90,23	1,08	500	45 117	20	800			
												30 500		

Constructions costs, BBB (2/3)

Walls	**structure**											
(perimeter, plank)	wood	180 mm x 38 mm			359,63		2,46	6000	14 759	5		
	bales	2500 mm x 1250 mm x 800 mm	36	41	n/a		90,00	300	10 800	1	1 000	
(between bales)	*batten*	*100 mm x 16mm x 13750 mm x 2 rows*	*4*	*4,2*	*57,75*		*0,09*					
	batten	*100 mm x 16mm x 8750 mm x 2 rows*	*8*	*8,4*	*115,50*		*0,18*					
	batten	*100 mm x 16 mm x 1250 mm x 2 rows*	*36*	*37,8*	*519,75*		*0,83*				700	
total	batten				693,00		1,11	6000	6 653	5		
(outside)	earth plaster	50 mm thickness			36,25	141,38	7,42	0		0		
(inside)	earth plaster	50 mm thickness			28,75	73,89	1,72	4000	6 888	150	1 000	
limewash	Hydraulic lime	1mm						500				1 000
	openings											
frames	Boards	4000 mm x 200 x20 mm	4	4			0,19	4000	762	5		
s-window frame, hz	wood	*300 mm x 150 mm x 11 250 mm*	*2*	*2,1*	*23,63*		*1,06*					
s-window frame, vert	wood	*300 mm x 150 mm x 2150 mm*	*9*	*9,45*	*19,35*		*0,87*					
n-frame, horiz	wood	*300 mm x 150 mm x 2500 mm*	*2*	*2,1*	*5,25*		*0,24*					
n-frame, horiz (door)	wood	*300 mm x 150 mm x 800 mm*	*1*	*1,05*	*0,84*		*0,04*					
n-frame, vert	wood	*300 mm x 150 mm x 2150 mm*	*3*	*3,15*	*6,77*		*0,30*					
	wood	300 mm x 150 mm		17,85			2,51	6000	15 076	5	700	
n-window	glass, 3L, arg	1219 mm x 2150 mm	1			2,62		3000	7 863	300		
s-windows, south	glass, 3L, arg	1234 mm x 2150 mm	8			21,22		3000	63 649	300	3 000	
n-door	wood	800 mm x 2000 mm x 50 mm	1				0,08	15000	15 000	10		**30 000**

Constructions costs, BBB (3/3)

Ceiling/roof	**Ceiling**													
	inside beams	120 mm x 40 mm x 6500 mm	14	14,7	95,55		0,46	6000	2 752	5				
	Earth plaster	20 mm thickness				86,10	1,72	4000	6 880	150				
	Boards	4000 mm x 200 x20 mm				142,19	0,00	4000	0	5				
	junction wall/roof													
on the bales	Lumberplank	2440 mm x 1220 mm x 50 mm	12	13			1,93	6000	11 610	5				
on the bales	c-beam	120 mm 80 mm x 12 mm			27,05		0,08		5 000	150				
	Lumberbeam	120 mm x 320 mm			50,00		1,92	6000	11 520	5				
	insulation													
	beams	450 mm x 70 mm x 8750 mm	14	14,7	128,63		4,05	6000	24 310	5				
	small bales	450 mm x 300 mm x 900 mm	390	410			49,82	10	4 100	2	250			
	Boards	4000 mm x 200 x20 mm				142,19	0,00	4000	0	5				
	sealing tape	rolls of ??? M			167,95			10	2 000	200				
(membrane)	Jutafol	dunno				149,30		45	6 718	200				
	roof													
Roof joists	wood	120 mm x 38 mm x 5200 mm	60	64	332,80		1,52	6000	9 105	5				
linker fo joists, need cut	wood	100 mm x 16 mm x 1850 mm	30	32	59,20		0,09	6000	568	5				
trusses	wood	*180 mm x 120 mm x 17 850 mm*	*5*	*5,25*	*93,71*		*2,02*							
	wood	*180 mm x 120 mm x 16 250 mm*	*2*	*2,1*	*34,13*		*0,74*							
	wood	*180 mm x 120 mm x 950 mm*	*16*	*16,8*	*15,96*		*0,34*							
	wood	180 mm 120 mm			143,80		3,11	6000	18 636	5	700			
	Boards	4000 mm x 200 x20 mm	65			185,64	3,10	4000	12 383	5				
Metal roofing	steel, zink coated					185,64		300	55 692	200	2 000	**12 500**		
Machinery rental	Sprayer, compressor		4					4000	16 000	50				
	Crane		5					3000	15 000	50				
Total									536 881	2334	20 656	74 000	633 871	24 222

Construction costs, LS/EPS (1/3)

LS-EPS	Description	unit dimensions (m)	quantity	adjusted quantity	total lenght (m)	total area (m2)	total volume (m3)	cost/unit (czk)	costs (Czk)	transport to the site (km)	transport costs	labor (cost)	Total costs (Czk)	Total costs (euro)
Foundations	**piers**													
	Sonotubes	1,20 m x 250 mm x 25 m	72	75,6	90,72		1,43	500	36 000	200				
	Concrete	1,20 m x 200 mm	72	75,6			2,85	2500	7 125	10	700			
threated metal)	Anchors	16 mm x 300 mm	72	76			0,00458	25	1 900	150				
	Bracers	170 mm x 100 mm	72	76			0,07028	25	1 900	150				
	Lumberstructure													
(transversal)	*wooden beam*	*100 mm x 140 mm x 71*	*12*	12,6	*89,46*		*1,25*							
(longitudinal)	*wooden beam*	*100 mm x 140 mm x 11*	*66*	69,3	*79,00*		*1,11*							
total	wooden beam	100 mm x 140 mm			168,46		2,36	6000	14 151	5	700			
	Eternit Turi	2440 mm x 1220 mm x 1	39,00			106,15	1,70	364	38 639	60				
Floor														
	Styrofoam, expanded	300 mm				94,71	28,41	5000	142 065	500	1 000			
	concrete	60 mm				94,71	5,68	2500	14 207	10				
	Lumberfinish	12 mm x 100 mm x 4000 mm?				90,41	1,08	500	45 203	10	700			
												30500		
Walls	**Walls**													
Bottom and top	KS ISO-Kimm 175	250 mm x 500 mm x 175	246	258,3			5,65	1030	5 820	500				
	KS blocks, 175 mm	250 mm x 500 mm x 175	491	539,55			11,80	1030	12 157	500				
	mortar	15 L/m2				99,73	1,50	2500	3 740	150				
	Styrofoam, expanded	300 mm				75,08	22,52	5000	112 613	500				
	Glue	???				75,08		500	37 538	150				
	cement plaster, outside	10 mm				113,34	1,13	100	11 334	150				
	gypsum board	2440 mm x 1220 mm x 1	26,0			77,28	1,24	100	7727,54	275				
	cement for joins					77,28	0,77	50	3 864	150				
	paint		140			77,28		50	7 000	50				

Construction costs, LS/EPS (2/3)

	Openings											
s-window frame, hz	Lumber	300 mm x 150 mm x 11	2	2,1	23,63		1,06					
s-window frame, vert	Lumber	300 mm x 150 mm x 21	9	9,45	19,35		0,87					
N-frame, horiz	Lumber	300 mm x 150 mm x 25	2	2,1	5,25		0,24					
N-frame, horiz (door)	Lumber	300 mm x 150 mm x 80	1	1,05	0,84		0,04					
N-frame, vert	Lumber	300 mm x 150 mm x 21	3	3,15	6,77		0,30					
	Lumber	300 mm x 150 mm		17,85			2,51	6000	15 076	5	700	
N-window	Glass, 3L, arg	1219 mm x 2150 mm	1			2,62		3000	7 863	300		
S-windows, south	Glass, 3L, arg	1234 mm x 2150 mm	8			21,22		3000	63 649	300	3000	
N-door	Lumber	800 mm x 2000 mm x 50	1				0,08	15000	15 000	5		
												80000
Ceiling/roof	**Ceiling**	**Lumberstructure**										
	Inside beams	200 mm x 70 mm x 650	13	13,65	88,73		1,24	6000	7 453	5		
	Batten	40 mm x 16 mm x 7100	13	13,65	96,92		0,06	6000	372	5		
	OSB sheet	2440 mm x 1220 mm 16	38			111,94	1,81	166	18 581	2000		
To close wall-ceiling jct	Lumber	200 mm x 40 mm			46,41		0,37	6000	2 228	5		
	Membrane	??				123,13		30	3 694	200		
		insulation										
2 layers	Styrofoam, expanded	100 mm x 6150 mm x 10	12,00	13,20		87,67	8,77					
	Styrofoam, expanded	100 mm x 7100 mm x 10	12,00	13,20		101,22	10,12					
	Styrofoam, expanded	101 mm x 7100 mm x 52	2,00	2,20		16,87	1,69					
	Styrofoam, expanded	100 mm				94,71	9,47					
	Styrofoam, expanded	50 mm x 100 mm x 615	2,00		12,30	1,23	0,06					
	Total					301,70	30,11	5000	150 543	500	2000	
	Gypsum board	2440 mm x 1220 mm x 1	31,82			94,71		100	9471	175	700	
	Putty for joints					25,00		750	750	175		
	Paint					94,71		25	2367,75	50		

Construction costs, LS/EPS (3/3)

	Roof													
Roof joist	Lumber	120 mm x 38 mm x 3080	52	55	286,00		1,30	6000	7 825	5				
Braces for joists, need cut	Lumber	100 mm x 16 mm x 1850	26	29	53,65		0,09	6000	515	5				
Trusses	Lumber	*180 mm x 120 mm x 17*	*5*	*5,25*	*93,71*		*2,02*							
	Lumber	*180 mm x 120 mm x 16*	*2*	*2,1*	*34,13*		*0,74*							
	Lumber	*180 mm x 120 mm x 950*	*14*	*14,7*	*13,97*		*0,30*					**7500**		
	Lumber	180 mm 120 mm			141,80		3,06	6000	11 520	5	700			
	OSB sheet	2440 mm x 1220 mm x 1	44,4			132,05	2,11	166	21 920	400	700			
Metal roofing	steel, zink coated					132,05		300	39 615	200	2000			
Machinery rental	Crane							3000	30 000					
	Brick lifter							1000	5 000					
Total									881 423	7 860	12 900	118000	1 020 183	38 983

Appendix 3

Thermal conductivity and U-values of the materials

LS/EPS, foundations				
material	thickness (mm)	lambda (λ)	reference	U-value
Concrete, 2000 kg/m3	60	1,35	(Buildesk 2007)	4,663
Expanded polystyrene	300	0,04	(Buildesk 2007)	0,130
OSB	16	0,13	(Buildesk 2007)	3,412
TOTAL	**376**			**0,128**

LS/EPS, wall				
material	thickness	lambda (λ)	reference	U-value
Gypsum plasterboard	16	0,25	(Buildesk 2007)	4,274
Lime-sand brick, 1900 kg/m3	175	0,9	(CLEAR 2007)	2,744
Expanded polystyrene	300	0,04	(Buildesk 2007)	0,130
cement-sand plaster	10	1	(Buildesk 2007)	5,556
TOTAL	**501**			**0,126**

LS/EPS, ceiling				
material	thickness	lambda (λ)	reference	U-value
Gypsum plasterboard	16	0,25	(Buildesk 2007)	4,274
Expanded polystyrene	300	0,04	(Buildesk 2007)	0,130
air layer, sligthly ventilated, heat upward	15	0,188	(Buildesk 2007)	2,175
OSB	16	0,13	(Buildesk 2007)	3,412
TOTAL	**347**			**0,126**

BBB, foundation				
material	thickness	lambda (λ)	reference	U-value
OSB	16	0,25	(Buildesk 2007)	4,274
Unventilated air layer, heat flow downwards	50	0,238	(Buildesk 2007)	2,631
straw parallel to heat flow, 150 kg/m3*	800	0,06	(MCabe 1993, in Munch Andersen & Moller-Anderson, ?)	0,074*
OSB	16	0,13	(Buildesk 2007)	3,412
TOTAL	**882**			**0,072***
total, adjusted				**0,108**

*: according to Munch Andersen & Moller-Anderson, observed results are 50% than calculated

BBB, wall				
material	thickness	lambda (λ)	reference	U-value
earth/clay plaster	50	0,8	(Munch Andersen & Moller-Anderson, ?)	4,301
straw perpendicular to heat flow, 150 kg/m3*	1250	0,048	(MCabe 1993, in Munch Andersen & Moller-Anderson, ?)	0,038*
earth/clay plaster	50	0,8	(Munch Andersen & Moller-Anderson, ?)	4,301
TOTAL	**1350**			**0,038***
total, adjusted				**0,057**

*: according to Munch Andersen & Moller-Anderson, observed results are 50% than calculated

BBB, ceiling				
material	thickness	lambda (λ)	reference	U-value
earth/clay plaster	50	0,8	(Munch Andersen & Moller-Anderson, ?)	4,301
OSB	16	0,25	(Buildesk 2007)	4,274
straw perpendicular to heat flow, 100 kg/m3	450	0,038	(Haus der Zukunft 2000, Munch Andersen & Moller-Anderson, ?)	0,083*
OSB	16	0,25	(Buildesk 2007)	4,274
TOTAL	**532**			**0,081***
total, adjusted				**0,122**

*: according to Munch Andersen & Moller-Anderson, observed results are 50% than calculated

APPENDIX 4

List of materials and distances for the construction stage

BBB

part	material	vol (m3)	density (kg/m3)	mass	distance (km)	mass x distance (tkm)
Concrete, sole plate and foundation	foundation	4,99	2000 (1)	9980	10	99,8
Solid Unbleached Board	foundation	3,12	73,4 (2)	229,008	200	45,8
Steel ETH S	foundation / structure	0,2125	7800 (3)	1657,5	150	248,6
fiber cement, facing tile at plant	foundation	2,43	1400 (4)	3402	40	136,1
Sawn timber, soft wood, air dried	structure / boards	30,55	530 (5)	16191,5	5	81,0
Sawn timber, hardwood, planed, air / kiln dried. U=10%	Structure / door/frames /finish	3,68	630 (6)	2318,4	5	11,6
Straw IP, at farm	bales		100, 130 (7)	33226	1	*33,2*
Clay, only for transport (account for 10% of indoor plaster volume 5,78m3)	walls	0,58	1602 (3)	929,16	100	*92,9*
lime, milled and packed, at plant	lime wash	0,22	1201 (3)	264,22	500	*132,1*
windows	windows			632,6	300	189,8
Steel ETH, zinc coated	sheeting	0,185	7800 (3)	1443	200	288,6
				70273,39		**1359,5**

(1) Buildesk (2007)
(2) www.sonotube.com
(3) The Physics factbook (2007)
(4) Marley Eternit 2007 www.marleyeternit.co.uk
(5) for Douglas fir, www.simetric.co.uk
(6) for high quality , www.simetric.co.uk
(7) Munch-Anderson & Moller Anderson (2000)

LS/EPS

material	section	vol (m3)	density (kg/m3)	mass	distance (km)	mass x distance (tkm)
Concrete, sole plate and foundation	foundation	2,85	2000 (1)	5700	10	57,0
Solid Unbleached Board	foundation	1,43	73,4 (2)	104,9	200	21,0
Steel, ETH	foundation	0,0749	7800 (3)	584	150	87,6
fiber cement, facing tile at plant	foundation	1,7	1400 (4)	2380	40	95,2
Oriented Strand Board	structure	3,92	600	2352	2000	4704,0
Sawn timber, soft wood, air dried	structure	7,1	530 (5)	3763	5	18,8
Sawn timber, hardwood, planed, air / kiln dried. U=10%		3,68	630 (6)	2318,4	5	11,6
sand-lime brick	wall	17,45	1900 (7)	33155	500	16577,5
Expanded polystyrene	wall	53,63	30 (8)	1608,9	500	804,5
Stucco	wall	1,13	2162 (3)	2443	150	366,5
Cement mortar	wall	1,5	2162 (3)	3243	150	486,5
gypsum board	wall	1,24	2787 (9)	3455,9	100	345,6
Base plaster	wall	0,77	2787 (9)	2146	50	107,3
Alkyde paint, white, 60% H2O	paint	0,0566	1057 (9)	59,9	25	1,5
Window				632,6	300	189,8
Steel, ETH + zinc coated	roof	0,132	7800 (3)	1029,6	200	205,9
				64976,2		24080,1

(1) Buildesk (2007)
(2) www.sonotube.com
(3) The Physics factbook (2007)
(4) Marley Eternit 2007 www.marleyeternit.co.uk
(5) for Douglas fir, www.simetric.co.uk
(6) for high quality , www.simetric.co.uk
(7) Texas AM Library http://txspace.tamu.edu
(8) Ecoinvent database
(9) www.simetric.co.uk

APPENDIX 5

Source, year of application and geography of LCI data

Material	source	Technology mix	geography
Concrete, sole plate and foundation	Ecoinvent	2001	Switzerland
Solid Unbleached Board	Ecoinvent	2000	Finland, for Europe
Steel ETH S	ETH-ESU 96	unknown	Germany
Oriented Strand Board	Ecoinvent	2000	Germany, for central Europe
Fiber cement facing tile, at plant	Ecoinvent	2000	Swtizerland
Sawn timber, soft wood, air dried	Ecoinvent	1986	Germany, for central Europe
Sawn timber, hardwood, planed, air / kiln dried. U=10%	Ecoinvent	1986	Germany, for central Europe
Straw IP, at farm	Ecoinvent	unknown	Switzerland
Limestone, milled, packed, at plant	Ecoinvent	unknown	Switzerland
sand-lime brick	Ecoinvent	1991-1996	Germany
Expanded polystyrene	Ecoinvent	2003	Switzerland, for Europe
Stucco	Ecoinvent	2000	Switzerland
Cement mortar	Ecoinvent	actual	Austria
flat glass coated, at plant	Ecoinvent	2000	Germany, extrapolated fo RES
Base plaster	Ecoinvent	actual	estimates for EU
Alkyde paint, white, 60% H2O	Ecoinvent	unknown	Germany
Processes			
Baling	Ecoinvent	1999-2001	Switzerland
Loading bales	Ecoinvent	1999-2001	Switzerland
Sheet rolling, steel	Ecoinvent	1996	EU
phosphating, (Zn s) I	ISEMAT 2001	1992	Netherlands
Transport			
Transport, tractor and trailer	Ecoinvent	1999-2001	Switzerland
Transport, lorry 16t	Ecoinvent	unknown	Switzerland
Transport, lorry 28t	Ecoinvent	unknown	Switzerland
Transport, muncipal waste collection,lorry 21 t	Ecoinvent	2000	Switzerland and Germany
Transport, van<3,5t	Ecoinvent	unknown	Switzerland
Energy			
electricity, hard coal, at power plant CZ	Ecoinvent	2000	Czech Republic
Electricity, natural gaz, at power plant CENTREL	Ecoinvent	2001	Czech Republic
electricity, lignite, at power plant CZ	Ecoinvent	2000	Czech Republic
electricity, nuclear, at power plant CZ	Ecoinvent	1995-1999	Czech Republic
heat, hardwood logs, at wood heater 6 kW	Ecoinvent	unknown	Central Europe
Waste scenarios			
Landfill/ CH U	Ecoinvent	unknown	for Ecoinvent data
Recycling steel and iron/ RER U	Pré consultants	unknown	for Ecoinvent data