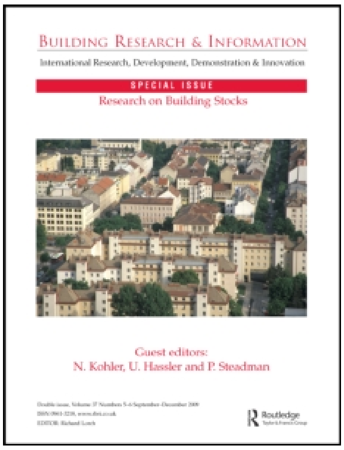

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RESEARCH PAPER

Illustrating limitations of energy studies of buildings with LCA and actor analysis

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Does passive housing really have better environmental performance than conventional housing? Three passive houses and four conventional houses were compared using a life cycle assessment (LCA) methodology. The comparison also provided an actor analysis for the building supply chain and building inhabitants. Results are presented for two scenarios: 'conventional choices' and 'green choices' by the actors. The comparison confirms that passive houses have lower energy use than conventional houses, but when the environmental impact of energy production is taken into consideration, the outcome is less clear. Conventional houses can be equally good environmentally in terms of global warming, acidification, or radioactive waste as typical passive houses with electrical heating depending on the actors' choices. Actor analysis shows that inhabitants' and material producers' electricity choice are very important, while other choices (*e.g.* green transport) are less important. The findings highlight the importance of environmentally responsible decisions throughout the whole life cycle and the need for appropriate behaviours and actions, along with implications for improved communication.

Keywords: actor analysis, environmental assessment, housing, inhabitant behaviour, life cycle analysis (LCA), low-carbon building, passive house

Les logements passifs ont-ils un rendement environnemental vraiment meilleur que les logements classiques ? Trois maisons passives et quatre maisons classiques ont été comparées en utilisant une méthodologie faisant appel à l'analyse du cycle de vie (ACV). Cette comparaison a également fourni une analyse des acteurs concernant la chaîne logistique dans le bâtiment et les habitants des immeubles. Les résultats sont présentés pour deux scénarios, les acteurs opérant dans l'un des « choix classiques » et dans l'autre des « choix verts ». La comparaison confirme que les maisons passives ont une consommation énergétique moindre que les maisons classiques, mais lorsque l'impact environnemental de la production d'énergie est pris en compte, le résultat est moins clair. Selon les choix opérés par les acteurs, les maisons classiques peuvent être aussi bonnes en termes de réchauffement climatique, d'acidification ou de déchets radioactifs que les maisons passives types équipées de chauffage électrique. L'analyse des acteurs montre que les choix faits en matière d'électricité par les habitants et les fabricants de matériaux ont beaucoup d'importance, tandis que les autres choix (par ex. transport vert) sont moins importants. Ces constatations mettent en évidence l'importance de la prise de décisions environnementalement responsables tout au long du cycle de vie, la nécessité de comportements et de mesures adaptés, ainsi que les implications qui en découlent en termes d'amélioration de la communication.

Mots clés: analyse des acteurs, évaluation environnementale, logement, comportement des habitants, analyse du cycle de vie (ACV), bâtiment bas carbone, maison passive

Introduction

In Sweden, as in many other developed countries, the building sector is said to contribute up to 40% of the country's energy and material usage (Byggsektorns Kretsloppsråd (BYKR), 2001; Organisation for Economic Co-operation and Development (OECD), 2003). Saving energy with the help of passive house technology has been presented as the solution to the

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energy and environmental problem in Sweden. Since the building of the first Swedish passive house in 2001, hundreds of apartments have been built. Private building constructors and municipalities in Sweden are using environmental arguments without thorough energy and environmental investigations and without including other actors, such as material producers (supply side) or households (demand side).

First, passive houses are not zero-energy houses. The 'passive house' concept is based on good insulation and effective heat exchange. The heat emitted from household equipment and the residents themselves can be sufficient to keep the indoor temperature comfortable in winter. It is recognized, that some extra energy is needed for cold days, but the energy demand is so small that a heating system is not needed: the limited heat needed can be delivered with different energy technologies, such as an electric cartridge[1] or district heating.

Second, energy studies are no proxy for environmental investigations. Since Adalberth *et al.*'s (2001) influential study, energy use in buildings is interpreted as a proxy for environmental impact in Sweden – building constructors and municipalities do not realize the environmental benefits (rather than just the energy benefits) of passive housing. The problem is that different energy technologies can be used in passive housing and the environmental impacts of different energy sources vary greatly. During the first years, all passive houses were built with an electric cartridge. Current construction practice is for passive housing to have electric cartridges for heating; but some passive housing is supplied with district heating as an alternative.

Furthermore, different energy choices are not exclusive to the builders of passive housing. Material producers, constructors, and households in conventional buildings can also make greener energy choices.

The environmental arguments from Swedish practitioners have led the authors to reconsider energy studies of buildings in the light of life cycle assessment (LCA) and actor analysis. Considering both the differing environmental impacts of different energy technologies and the differing roles of all actors in a building's life cycle, the environmental burden of passive housing needs to be re-evaluated.

Aim

The aim of this study is twofold. The first aim is to find out if passive housing is environmentally better than conventional housing. The second aim is to find out how green choices by different actors influence the buildings' total environmental impact.

Method

For the first aim, a number of existing residential buildings in Sweden are compared (Table 1):

- two traditional passive houses with electric cartridges in Lindås and Värnamo
- one passive house with district heating in Karlstad
- four conventional buildings in Malmö, Helsingborg, Växjö, and Stockholm

A comparison of the buildings' energy demands as well as their environmental burden is made. To create an overall environmental picture (and not only an energy one), an LCA methodology is used. For the conventional buildings, LCA studies exist, while for the passive house buildings solely energy studies exist. These existing studies have been modified and updated for this comparison.

For the second aim, three of these buildings (in Lindås, Karlstad, and Stockholm) are compared in two

Table 1 The studied buildings: energy need for operation includes energy for heating, electricity and hot water

	Building year	Number of floors	Number of apartments	Main materials used	Operation (kWh/m^2)	Heating
Conventional buildings						
Malmö	1996	3	6	Lightweight concrete	100	District heat
Helsingborg	1996	3.5	8	Concrete	121	District heat
Växjö	1996	4	16	Concrete, wood	150	District heat
Stockholm	1996	5	15	Concrete, steel	121	District heat
Passive house buildings						
Lindås	2001	2	20	Wood	68	Electricity
Värnamo	2006	2	8	Concrete, wood	67	Electricity
Karlstad	2006	12	44	Concrete, wood	83	Electricity, district heat

Note: Energy for operation is calculated for the conventional buildings (Adalberth *et al.*, 2001) and measured for passive house buildings (Boström *et al.*, 2003; Beiron *et al.*, 2007; Energy and Building Design (EBD), 2007).

scenarios: one 'conventional choice' scenario and one 'green choices' scenario. Specifically, the focus lies on green material, electricity, and transport choices. Furthermore, results are analysed with help of an actor analysis in order to trace environmental impacts to each respective actor.

Comparative study: buildings and energy perspective

The interest in studies of buildings from an energy perspective, especially life cycle energy, is enormous. A recent literature survey on buildings' life cycle energy resulted in 60 examples of life cycle studies, in both conventional and passive houses (Sartori and Hestnes, 2007). In Sweden there are energy studies of conventional houses (Adalberth *et al.*, 2001; Joelsson, 2008) and energy studies of passive houses (Thormark, 2007). An energy comparison of conventional houses with passive houses exists from as far back as the 1970s (Joelsson, 2008).

The buildings included in this comparison are the Swedish conventional buildings studied by Adalberth *et al.* (2001) and the Swedish passive house buildings studied by Thormark (2007), among others. Table 1 shows the technical specifications, such as building year, number of floors, number of apartments, main construction material, energy use for operation (including heating, electricity and hot water), and the type of heating (district heating or electricity).

In order to compare these buildings, data regarding the energy demand have been partly recalculated or modified.

For the conventional buildings, all energy data regarding operation were collected from Adalberth *et al.* (2001). For the passive house buildings, data on the energy demand for operation were collected from university studies: Lindås (Boström *et al.*, 2003), Karlstad (Beiron *et al.*, 2007), and Värnamo (Energy and Building Design (EBD), 2007). Data for the material production in passive house buildings were partly collected from Thormark (2002, 2007) and partly calculated in the present study.

The energy demand for operation reported for the conventional buildings varies between 100 and 150 kWh/m^2 per year, based on calculated values (due to a lack of measured data). The energy demand for operation reported for the passive houses varies between 67 and 83 kWh/m^2 per year, based on measured values. Because calculated energy demand for heating is often lower than measured energy use (Nilsson, 2003; Bagge *et al.*, 2004; Carl Bro Stockholm Konsult AB, 2006), the energy demand for conventional buildings was modified (it increased by 25%) in the calculations. This means that the passive house buildings use about half the amount of energy in comparison with conventional buildings.

Comparative study: environmental and actor perspective

In order to introduce an environmental perspective to the energy comparison, an environmental analysis with help of an LCA methodology is used. While Adalberth *et al.* (2001) already included an environmental perspective, environmental data for the passive house are calculated especially for this study. In order to introduce an actor perspective, the studied LCA system is presented with its actors and their choices, and the results are analysed with help of an actor analysis.

Studied LCA system, its actors and their green choices

The studied system and the technical processes included in this study are presented in Figure 1. However, changes in this system do not happen on their own. It is necessary to consider the actors and their options within the system, even though there may be many of them. Heiskanen (1997), for example, identifies 28 actors solely to produce a building material. There are energy-related choices, such as choice of electricity generation, and material-related choices, such as reuse or recycling.

This study chooses five main actors and two alternative choices in a Swedish perspective. The main actors are those with possibilities to reduce the environmental burden of a building; in other words, actors with a direct influence (Table 2). Some other actors are represented by one of the five main actors, *e.g.* contractor, architects, and designers are represented by building constructors. The choices these actors can make in this study are energy-related choices regarding material production, transport emissions, and electricity generation (Table 2). Material-related choices are not considered here.

The processes where alternative choices are analysed are presented as shaded boxes in Figure 1, as well as two alternative choices: A, the conventional choice, and B, the green choice. Processes, actors, and their choices in a Swedish perspective (*e.g.* district heating company, EURO 2 and EURO 3) are presented in Table 2.

Some actors influence the technical life cycle indirectly through their demands/recommendations (expressed in brackets in Table 2). The building constructor can put demands on the material producer and material transport companies. The building owner or municipality can put demands on whichever technical system and whichever energy supply system is used,

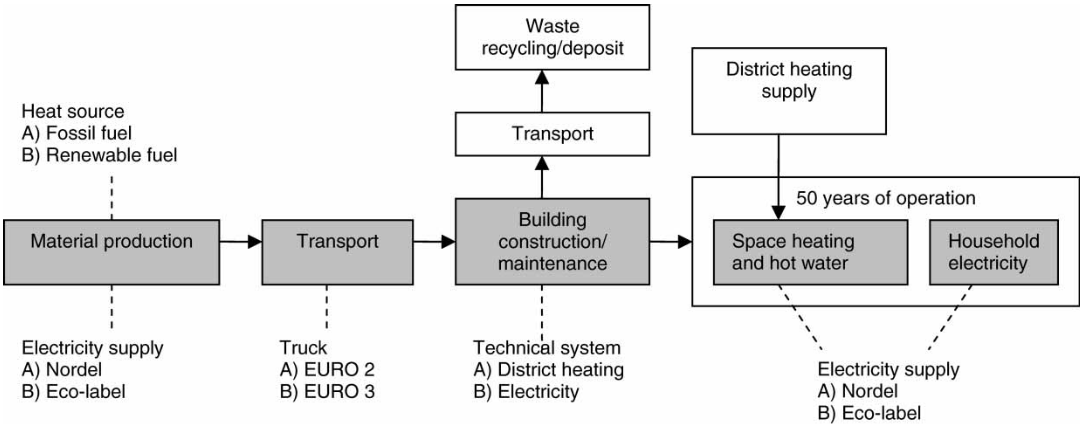

Figure 1 The system analysed for the comparative life cycle analysis of passive and conventional buildings. Shaded boxes represent processes where alternative choices (A and B) are analysed. 'A' represents a conventional choice, while 'B' represents a green choice

Table 2 Processes, actors, and their actions/choices

Process	Actors with direct influence (actors can set demands)	Choices
Material production	Material producer of steel, timber, gypsum, concrete and others. (The building constructor can make a demand)	Electricity supply: (a) Nordic electricity or (b) eco-label Heat source (only for concrete): (a) fossil fuel or (b) renewable fuel
Transport from the production site to the construction site	Transport company. (The building constructor can make a demand)	Truck: (a) EURO 2 or (b) EURO 3
Building construction and maintenance	Building constructor/architects/designer. (The building owner and municipalities can make a demand)	Technical system: (a) district heating or (b) electricity
Space heating and hot water	Residents. (The building constructor, building owner, and municipalities can suggest)	Electricity supply: (a) Nordic electricity or (b) eco-label
Space heating and hot water	District heating company. (The building constructor, building owner, and municipalities can collaborate)	No choices included here
Household electricity	Residents. (The building constructor, building owner, and municipalities can suggest)	Electricity supply: (a) Nordic electricity or (b) eco-label

e.g. electricity or district heating. The building constructor, building owner, and the municipality can recommend that residents choose eco-labelled electricity. The indirect influence becomes interesting first in the actor analysis and recommendations in favour of the whole life cycle.

Functional unit

In the comparison, the functional unit[2] is 1 m^2 floor area of the building, normalized per year, calculated with an operation period of 50 years. (This is similar to the LCA study of conventional buildings by Adalberth *et al.*, 2001.)

Data sources for building material production

Similar to the energy comparison, environmental data for conventional buildings are used from an existing study by Adalberth *et al.* (2001). For passive house buildings, environmental data are collected from recent LCA-based environmental product declarations (EPD), LCA studies, and companies' own environmental declarations (see Table A1 in the Appendix). Some modifications are made regarding material data, electricity data, and maintenance data. For material data, where no environmental data were available, data for similar materials are used. The alternatives regarding heat source are collected only for concrete production (Gäbel, 2001). When the electricity mix is not specified, especially in environmental declarations, a Swedish electricity mix is used: 40% hydropower and 50% nuclear power (Swedish Energy Agency, 2005). Maintenance intervals are based on the periodic maintenance guide of the Swedish municipal housing organization (Swedish Municipal Housing Organisation (SABO), 1998).

Data source for energy supply

For data on energy supply to the studied buildings, an average Nordic electricity mixture is used for both building types (Table 3a) and an average of three Swedish plants for district heating (Table 3b). For the green choice in the actor analysis, eco-labelled electricity according to the Swedish Society for Nature Conservation (SSNC) is used consisting of 95% hydropower and 5% wind power (SSNC, 2007).

There is a discussion within the LCA community about marginal versus average electricity. Ekvall *et al.* (2005) suggested that the average electricity mix is useful when the aim is to ascertain environmental relevant flows and to avoid processes with undesirable environmental impacts, while a marginal electricity mix is useful when the aim is to assess the consequences of changes of a product system. In this study, it is not the product system, but environmental-relevant actors and their choices, that are in focus. Therefore, the average electricity approach appears relevant for both the environmental analysis of the buildings and the analysis of the actors' environmental influence on them.

Table 3a Nordic electricity mix and used data sources

Energy	%	Data sources
Nuclear power	26	EPD, Vattenfall (Vattenfall Ringhals, 2004; Vattenfall Forsmark, 2005)
Water	48	EPD, Vattenfall (Vattenfall Norden, 2005)
Wind	2	EPD, Vattenfall (Vattenfall Vinkraft, 2003)
Biomass	5	EPD, Vattenfall (Vattenfall Uppsala, 2004)
Coal	9	LCA on electricity produced in Denmark (Anon., 2000)
Oil	1	LCA on electricity produced in Denmark (Anon., 2000)
Gas	6	LCA on electricity produced in Denmark (Anon., 2000)
Other	3	EPD, Vattenfall (Vattenfall Uppsala, 2006)

Note: EPD, environmental product declarations; LCA, life cycle assessment.

Table 3b Average of three Swedish plants for district heating and used data sources

Energy	%
Biomass	5
Coal	1
Oil	8
Gas	23
Waste	21
Electricity	13
Peat, pine oil	28
Other	1

Notes: EPD, environmental product declarations. Pine oil is a by-product of wood pulp manufacture.
Data Sources: Average of three Swedish plants for district heating: EPD, Vattenfall (Vattenfall Uppsala, 2004, 2006) and EPD (Göteborg Energi, 2001)

In this study, the Nordic electricity mix is used, since it best represents the current electricity situation in Sweden. The Swedish electricity mix and the OECD mix used by Adalberth *et al.* (2001) do not represent the current situation. Currently, most of the electricity (about 97%) used in Nordic countries is also produced there (NordEl, 2007). Hence, data from Adalberth *et al.* (2001) are modified accordingly.

Data sources and calculations for transports

For conventional buildings, the transport distances (material production to building sites, building sites to the waste-disposal site during renovation and demolition) are collected from the study by Adalberth *et al.* (2001). The environmental impacts of different transport types are taken from the Network for Transport and the Environment (NTM) (2007), which provides data on energy demands and produced emissions.

For passive house buildings, the same transport distances from building sites to the waste-disposal site were used, while different transport distances from material production to building sites are assumed. Crushed stone 'Macadam' was assumed to be transported 25 km with a truck of 24-ton load capacity, filled to 70%. All other materials were assumed to be transported 250 km also in a truck of 24-ton load capacity, filled to 70%. In order to take account of local distributions of materials, 50% of all materials (except Macadam) were also assumed to be transported 10 km in a truck of 8.5-ton load capacity, filled to 50%.

Among others, actors can make choices regarding transport and the change of emission standards, in this study from EURO 2 to EURO 3. Transport emissions – carbon dioxide (CO_2), carbon monoxide (CO), sulphur dioxide (SO_2), hydrocarbons (HC), and nitrous oxide (NO_x) – on these alternative standards are collected from the NTM (2007) and are presented in Table 4.

Environmental impact categories and calculations

LCA results are calculated as various environmental impacts. The use of any of the existing weighting indicators was avoided because a comparison of impact categories is more transparent for present purposes.

Emissions are classified according to environmental impact categories in the Centre of Environmental Science's (CML) handbook (Heijungs *et al.*, 1992). Impact categories and factors considered in this study are global warming potential for 100 years (GWP), acidification potential (AP), eutrophication potential (EP), and photochemical ozone creation potential

Table 4 Transport emissions based on lorries, emission standards, and load capacities

Lorry (load capacity/total weight)	Emission standard	CO_2 (g/ton-km)	CO (g/ton-km)	SO_2 (g/ton-km)	HC (g/ton-km)	NO_x (g/ton-km)
8.5/14 ton	EURO 2	176	0.170	0.043	0.160	1.60
8.5/14 ton	EURO 3	176	0.150	0.043	0.160	1.10
24/40 ton	EURO 2	52	0.049	0.013	0.047	0.46
24/40 ton	EURO 3	52	0.046	1.500	0.047	0.33
Lorry	**Load capacity (%)**	**kWh/ton-km**				
8/24 ton	50	0.67				
24/40 ton	70	0.20				

Source: Network for Transport and the Environment (NTM) (2007).

(POCP). These are the same as in the study of conventional buildings by Adalberth *et al.* (2001). Also, radioactivity and land use are considered, but only where these impacts come as a result of modelled effects of the green choices in this study. This is similar to what Kohler *et al.* (2004) did in a study on passive houses with various electricity supply systems.

There is a discussion in the literature about the importance of carbonation in the calculation of the overall CO_2 emissions of concrete (Kjellsen *et al.*, 2005). Traditionally, only the production of concrete is considered. In this study, the buildings are built with different amounts of concrete and the issue becomes more important. Therefore, the rate of carbonation was included to account for GWP in the calculation. Two concrete qualities were used in the buildings, K30 and K40. They contain 12 and 15 weight-% cement, respectively. Based on the data provided by Pade and Guimaraes (2007), the total CO_2 uptake after 70 years' service life will be about 3.3% of the total CO_2 emissions for K30 and 3.4% for K40, and after demolition it will be 8.9% of the total CO_2 emissions for K30 and 9.1% for K40.

Interpretation of results using actor analysis

Even though there are different types of analysis possible within the interpretation phase in LCA, the 'dominance analysis' is the most common for studies of buildings (Sartori and Hestnes, 2007). The 'dominance analysis' is used to investigate which technical process of the life cycle gives rise to the greatest environmental impact. This has led to the identification of operation as the most polluting technical process in buildings' life cycle (Adalberth *et al.*, 2001; Sartori and Hestnes, 2007). In Sweden, this has also led to the promotion of passive housing as the preferred solution.

However, experiences from previous studies of actors in the Swedish building sector (Baumann *et al.*, 2003; Gluch *et al.*, 2007) and within the concept of environmental assessment of organizing (EAO) (Baumann, 2004; Brunklaus, 2005, 2007) have led the present authors to rethink the otherwise very technical LCAs in light of the actors' inputs. Technical LCAs encapsulate too many assumptions about actors and who should do what. This is especially problematic when passive housing is promoted with environmental arguments, and risks underestimating the environmental value of various actors' choices in the chain.

In this study, special emphasis is placed on actors in the interpretation phase. LCA results are analysed with help of actor analysis to trace environmental impacts to each respective actor. Instead of the dominance analysis that traces technical processes, this analysis is inspired by the decision-maker analysis (Baumann and Tillman, 2004). The life cycle is understood as a chain of actors and LCA results are understood as the sum of choices within this chain.

By highlighting the actors in the life cycle instead of technical phases, the intent is to clarify certain dimensions of the problem. One concerns the value of various actors' choices in the context of the life cycle as a whole; the other illustrates/visualizes that energy choices entail different types of environmental problems and by so doing allow people to make informed value choices.

Results

As expected, the results for energy use show that passive housing is on average better than conventional housing (Figure 2). However, unexpected are the results for environmental impacts, where traditional passive housing with electricity is on average no better than the conventional housing. This applies to most of the environmental categories, such as GWP, AP, EP, land use, and radioactive waste (operation), except POCP. Both energy and environmental results are presented on average and as the relative difference from conventional to passive housing in Figure 2.

Going into more detail uncovers new aspects about the comparison between conventional housing and passive

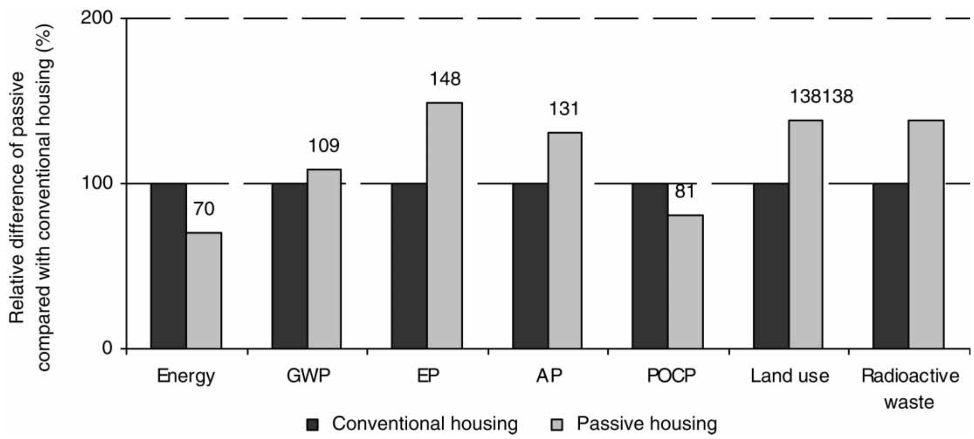

Figure 2 Relative difference of passive compared with conventional housing. Values are normalized results based on average data from four conventional buildings with district heating (normalized to 100%), and based on average data from two typical passive house buildings with electricity for extra heating (relative to conventional buildings). GWP = global warming potential, EP = eutrophication potential, AP = acidification potential, POCP = photochemical ozone creation potential.

housing. In 2007, practitioners in the Swedish building industry made a comparison of the CO_2 emissions for a conventional building in Stockholm with typical passive housing with electricity for extra heating in Lindås (Swedish Building Industry, 2007). They found that both housing types are emitting CO_2 to the same extent. The current paper takes their discussion further by looking more comprehensively at environmental impacts and at the importance of the actors involved. As expected, the results for energy use (Figure 3) show that passive housing, especially when the energy for extra heating is supplied by district heating, is better than conventional housing. However, the difference becomes smaller when environmental impacts are considered more broadly (Figure 4). Typical passive housing and conventional housing contribute to global warming to almost the same extent.

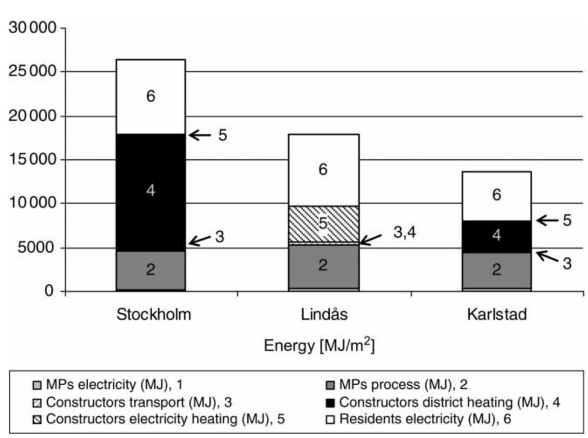

Figure 3 Actor analysis for energy use. Buildings presented are Stockholm (conventional building), Lindås (traditional passive house), and Karlstad (passive house with district heating)

This is because of the relatively great use of electricity for extra indoor heating in the passive house. Only when that electricity is replaced by district heating, as in the Karlstad building, does passive housing become distinctly better than conventional buildings. The typical passive house fares even worse in the comparison when looking at the buildings' contribution to acidification, land use, and production of radioactive waste (Figure 4, left column). In other words, conventional buildings (at least Swedish ones) are not necessarily worse than the environmentally argued passive buildings. It depends on residents in conventional buildings making a green choice of electricity supplier. If residents in conventional buildings take this action, then conventional buildings become the better environmental alternative.

In the actor analysis, energy use and environmental impacts are traced to each respective actor, such as material producer, buildings constructor, and residents. The importance of these actors is illustrated for three buildings: Stockholm (conventional); Lindås (passive, electricity), and Karlstad (passive, district heating) (Figures 3 and 4). Additionally, the effects of green 'material, electricity and transport' choices are presented in two scenarios: 'conventional choice' (Figure 4, left column) and 'green choice' (Figure 4, right column).

The actor analysis for energy use and 'conventional scenario' shows several things:

- Construction companies are most important for choosing the energy source (Figure 3), while environmental impacts for heating can be traced back to either district heating companies or residents (Figure 4, left column). A high consumption of energy from district heating can have a low environmental effect on global warming.

- Residents are contributing the most to buildings' environmental pollution, independent of the type of building. Their importance becomes greater when choosing passive housing with electricity for extra heating, but becomes less when choosing passive housing with district heating for extra heating.
- Together, material producers are almost equally contributing to buildings' environmental pollution. Timber, steel, and concrete producers stand out among the material producers with notable contributions to environmental impacts.

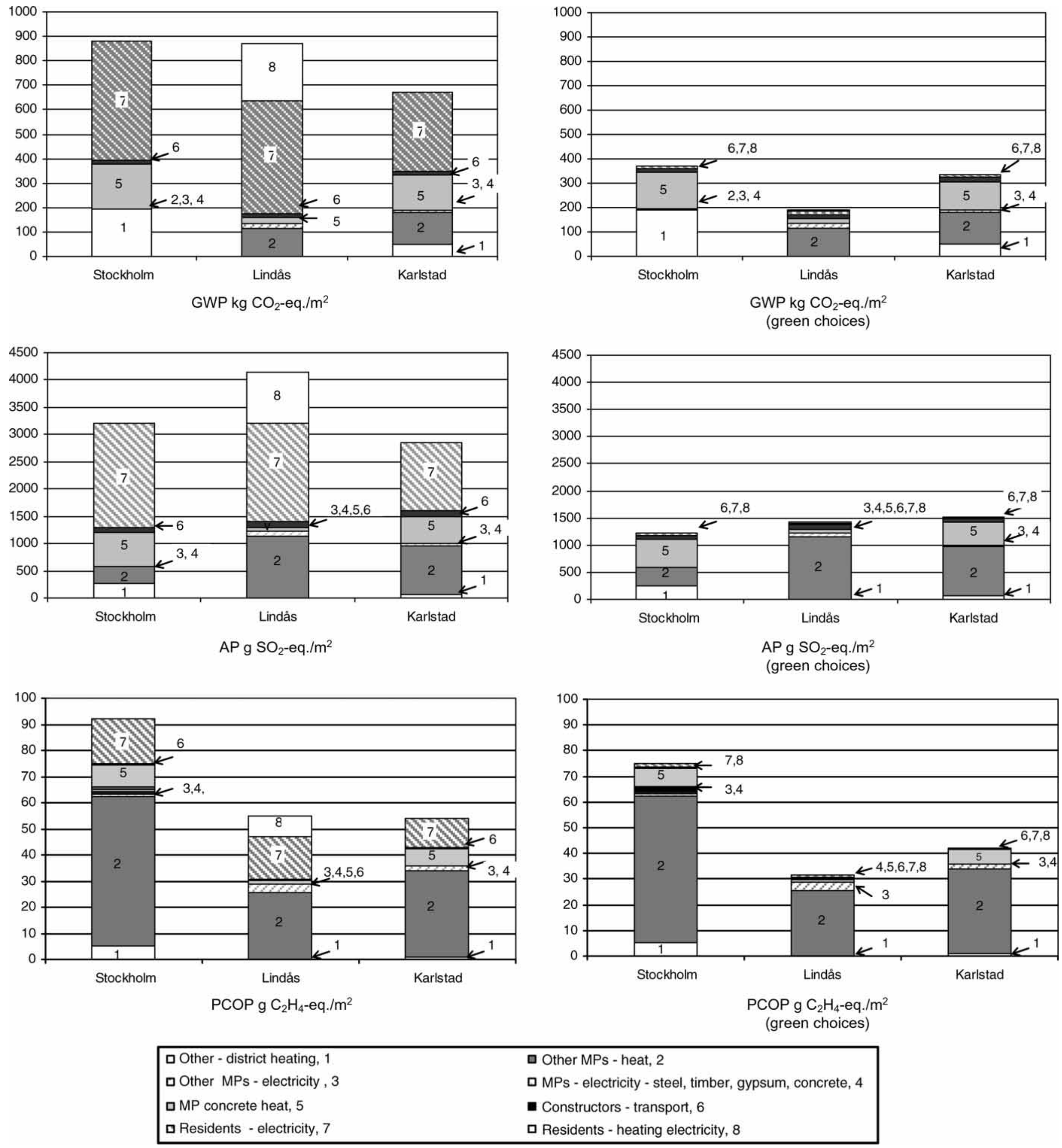

Figure 4 Actor analysis of the conventional scenario (left) and green choices scenario (right) along the building chain. Buildings presented are Stockholm (conventional building), Lindås (traditional passive house), and Karlstad (passive house with district heating). Environmental impacts presented are global warming for 100 years (GWP), acidification (AP), photochemical ozone creation (POCP), land use, and radioactive waste. Constructors means building constructors/construction companies; MPs means material producers

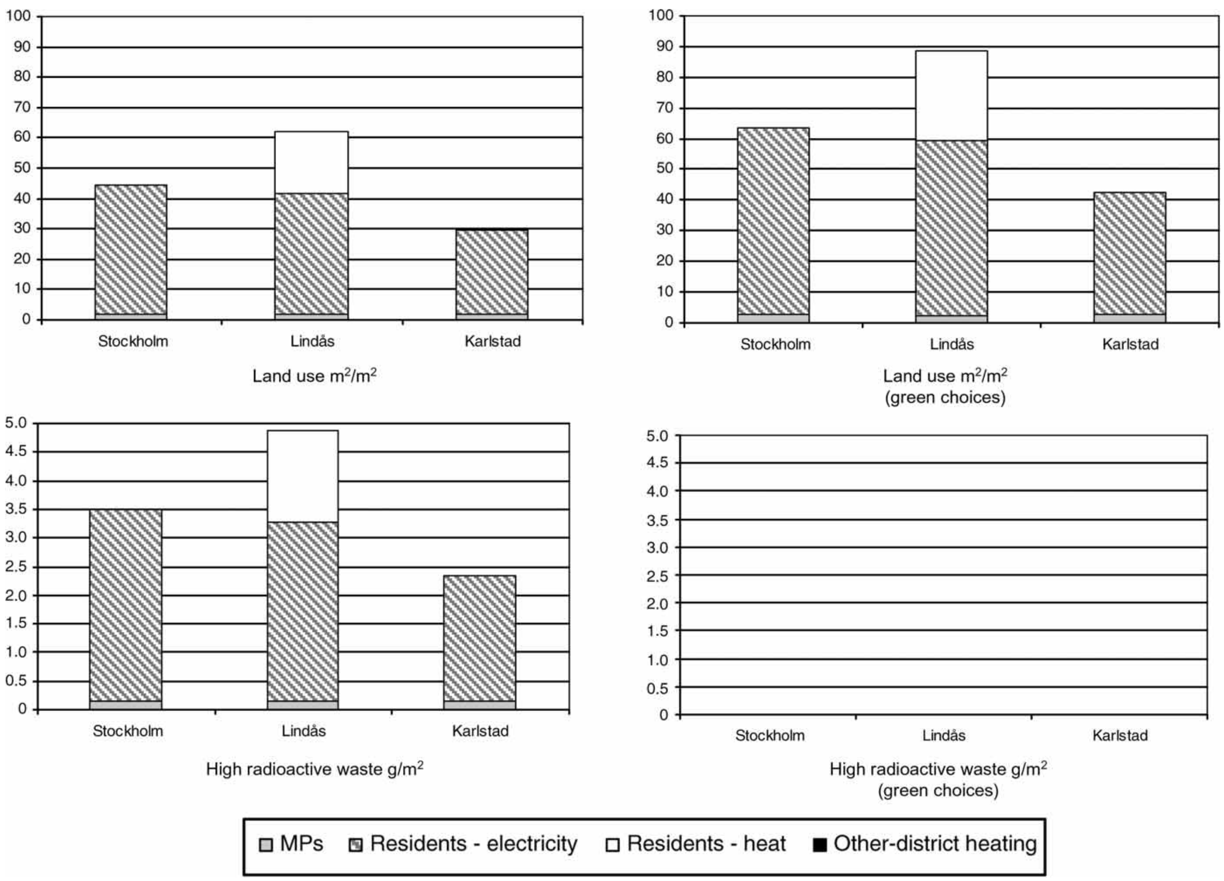

Figure 4 Continued

The actor analysis for the 'green choices' scenario shows other things (Figure 4, right column):

- Residents have the most environmental influence by choosing eco-labelled electricity.
- Construction companies have the least influence with their green transport choices. However, construction companies can recommend that residents choose eco-labelled electricity.
- The material producer's importance becomes even greater when residents and construction companies start making greener energy choices.

To conclude, it is not possible to say if passive houses or conventional houses are environmentally preferable because it depends upon the effect of the various choices made by the different actors. However, it is clear that it is not sufficient solely to rely on energy analysis and passive housing technology in the efforts to reduce the environmental burden of the building sector. The interest for passive housing as such tends to make construction companies the central and most important actor, but the present analysis shows that residents and material producers can also be equally important for the overall environmental impact of the building. In comparison with previous research, this means that the (absolute) focus on building construction should be downplayed and put into context.

Discussion

The results show that many actors need to be considered when making a building 'green' – residents' and material producers' choices in addition to what the building constructors do. Using a simple sensitivity analysis, some reflections and comments are offered on the results and how method and data may have affected the results. Then the methodological approach is discussed and findings compared with other related studies.

Sensitivity analysis

In this study, the service life was set to 50 years. How would the results be with an assumed service life of 75 years? More maintenance would be needed. A 50% increase in maintenance showed that the relative difference of passive housing and conventional housing did not change much. An increase in maintenance for passive housing means an increase use of high-impact materials, such as plastic covering. This changes the relative difference rather than favour conventional housing.

The energy sources for heating in this study mirror the common situation for residential buildings in Sweden. The use of electricity for heating in passive houses, however, is not connected to the construction of passive houses in themselves; any other source of energy can be used. However, as the need for bought energy for heating is low per housing unit, it might be economically inefficient to provide district heating to an area with single-family houses. Here small-scale district heating might be of interest.

The study conducted was limited to only three to four passive and conventional buildings, respectively. The buildings differ regarding their main construction material and insulation standard. Even so, the results are similar within each category of building type, which indicates that the results have some generality.

Further studies would be of interest regarding end-of-life impacts and the substitution of materials in order to minimize the environmental impact from the production part. End-of-life impacts are relatively problematic since they occur in the future, but recent studies show relatively low values compared with production and operation (Adalberth *et al.*, 2001; Thormark, 2002, 2007). Also, material studies can in some way be connected with problems. For example, data on ‘alternative’ building materials, such as insulation material, are very limited. It would be of great interest to generate LCA on, for example, wool insulation or hemp insulation.

Methodological approach and other related studies

The comparison revealed that energy analysis and passive house technology are insufficient to reduce the environmental burden of buildings. The introduction of environmental and actor perspectives is important for the comparison of passive and conventional buildings. What is the contribution of this study’s methodology and the results? What are its strengths and weaknesses? To address these points, the results are compared with other related studies: other energy studies, those with an environmental perspective, and those with an actor perspective.

Most of the 60 life cycle studies on buildings are limited to energy use (Sartori and Hestnes, 2007), even though global warming has become popular recently (Joelsson and Gustavsson, 2008). Only two studies include a more comprehensive environmental perspective (Adalberth *et al.*, 2001; Scheuer *et al.*, 2003). These indicate similarities between energy and environmental impact. Joelsson (2008) compared conventional buildings from the 1970s (effective district heating based on a combined heat and power production) with a passive house in Lindås (conventional electricity and photovoltaic). This indicates the importance of the supply system and production of materials. However, Joelsson’s argument is based solely on energy use, global warming, and marginal electricity. Only some studies identify the importance of the social nature of energy use, such as the importance of residents’ behaviour. Among such studies are Browne and Frame (1999), and recently Ellegård (2008).

Among the studies with a more environmental perspective are those on buildings’ energy supply for Germany (Kohler *et al.*, 2004) and Switzerland (Citherlet and Defaux, 2005). The German study compares conventional and passive houses regarding energy use and environmental impact on gas- and electricity-based heating (European Union coal, French radioactivity, and photovoltaics). The choice of heating system is shown to be important. Photovoltaics had the best results, but such a choice may not be realistic on a large scale. Kohler *et al.* also stress the problem of comparing different environmental impact categories, such as radioactivity and global warming. Citherlet and Defaux compare insulation variants regarding energy use and environmental impact comparing different electricity mixes, *e.g.* Union for the Coordination of the Transmission of Electricity (UCTE) instead of the Switzerland mix. The choice of building material and electricity mix is shown to be important for buildings with low energy consumption. Also, Adalberth *et al.* (2001) point to the importance of the electricity mix, *e.g.* the Swedish mix instead of the OECD mix, and district heating source, *e.g.* biomass instead of fossil fuel. However, these studies show the technical nature rather than the social nature of energy supply systems. None of these studies includes an overall actor perspective. Recommendations were made for technical solutions (and for constructors) rather than for different actors in the chain, *e.g.* residents or district heating companies.

A handful of studies exist that also stress the need for an actor perspective (Cooper *et al.*, 2008; Heiskanen, 1997; Berlin *et al.*, 2008). Cooper *et al.* (2008) suggest that LCA can be used as framework for identifying impacted sectors and organizations. They found that life-cycle stakeholder forums are important because they help people to understand and avoid impact shifting among them. The present study’s actor analysis of conventional to passive housing indicated the different actors responsible for each housing type, such as the district heating actor for conventional and residents for passive housing. Heiskanen (1997) showed that LCA can help different actors to see the indirect consequences of their actions. LCA can be described as chain of (responsible) actors, which may turn out to be surprisingly long; as many as 28 actor groups can be responsible for the production of construction materials. LCA can distribute responsibility among actors. Its message is that everybody is responsible. LCA makes complex human–environmental links look very simple. However, general recommendations (such as passive house is always better) are difficult to make. It must always be kept in mind that LCA and its chain of responsibility is a construction of material and energy linkages that depends on the analyst's choices. One example is the study of Berlin *et al.* (2008) which includes an actor perspective. Their study is made with an industrial perspective including households. The present study has a building constructor perspective including households. Their study includes actors and their possible actions, but excludes the most important actor, agriculture with its 94–99% of environmental burden.

The strength of this methodology is that more emphasis is placed on the interpretation of results and it is therefore more usable for actors. The methodology focuses on the environmentally important actors and actions instead of technology and production phases. Recommendations are usable for more than one actor and may foster collaboration. The weakness of the methodology is that it is hard to include all actors' choices, but this can be viewed as more realistic to present the variety of both actors and actions. Environmental problems are complex: every actor and individual is part of them and the choices and actions shape the environmental outcomes.

Conclusions

Care is needed when drawing environmental conclusions from energy studies. Although passive houses have a low energy use; the environmental impacts are not automatically lower. Additionally, the life cycle is changeable. All actors in the life cycle, such as the building constructor, municipalities, material producer, and residents, can improve a building's environmental burden.

In order to make an environmental difference, it is not enough to set energy requirements and build 'low-energy' buildings such as passive houses. One has to set requirements for the source of energy in the whole life cycle chain, for material production, space heating (electricity or district heating), and household electricity. The building constructor needs to cooperate with the material producer, municipalities, and residents in order to create a building with a low environmental burden. Building constructors need to ask for low-impact environmental products. Municipalities need to require low-impact environmental district heating. Residents are recommended to use eco-labelled electricity. Municipalities need to think about their future energy supply and the appropriate regime for electricity supply (free market, local provision, feed-in tariffs, etc.).

Importance of an actor perspective

Within a life cycle framework there is not only one actor and one solution. The link between actors and environmental burden is complex, as Heiskanen (1997) points out. There is an actor–energy link, frequently studied for buildings, but there is also an energy–environment link, frequently forgotten for buildings. The present paper has connected the actor–energy link and the energy–environment link, which have brought surprising results. Adalberth *et al.* (2001) suggested the importance of the energy source in the district heating and electricity mix, but an interpretation of that work was reduced to energy efficiency in the operation phase and the similarities between energy use and the environmental burden of buildings.

An actor perspective has been shown to be vital in the LCA study, especially in the interpretation phase. This is demonstrated by presenting:

- a chain of actors instead of technical processes
- environmental impact per actor instead of technical phases
- a variety of choices for each actor instead of one choice for one actor
- recommendations for each actor in favour of the whole chain

Recommendations to actors in the building chain

Including an actor perspective shows the social nature of technical systems. For different actors, it reveals the consequences of their actions and indicates which actor has the largest direct influence and which has the largest indirect influence. For buildings, both conventional and passive house styles, the largest direct influence is the resident/household's green electricity choice. Since the introduction of a liberal electricity market in 1996, electricity is probably the simplest product to choose in an environmentally friendly manner (Konsumentverket, 2007). This might be surprising for residents, as few choose eco-labelled electricity today (Dagens Nyheter (DN), 2007; Ek and Söderholm, 2005, 2006). The influence of material producers is underestimated as well, while building constructors' direct influence (active choice) is overestimated and constructor's indirect influence (set demand on supplier) is underestimated. Therefore, advice is offered for actors in the building chain:

- Residents/households should learn that their choice of eco-labelled electricity influences the environmental burden of the building to a large extent.

- Material producers should learn that their choice of energy source influences the environmental burden of buildings more than their green electricity choice.

- Building constructors and municipalities should learn that saving energy through passive house technology is not enough. They need to include the energy supply. They must not forget to put demands on material producers, make suggestions to residents, and collaborate with district heating companies. Alternatively, they need to access their own green energy (solar cells, wind turbines).

To create a building with a low environmental burden, requirements need to be made for the source of energy in the whole chain, from material production to space heating (electricity or district heating) and household electricity.

Meeting the future

It is unwise to reduce the environmental impacts of buildings to energy (kWh/m^2) and global warming. It is also unwise to reduce environmental solutions to passive house technology. The introduction of passive house technology shifts responsibilities from district heating producers to residents, which is not currently communicated. To avoid shifting responsibility within the building chain and to meet future trends, such as the recent trend of building passive housing in sheet metals or with district heating (Byggvärlden, 2008), communication needs improvement. One way of doing this is a multi-actor forum within the framework of LCA (Cooper *et al.*, 2008); another way is the introduction of an environmental energy label for buildings and communication with various actors and also with national institutions (Brunklaus and Lundberg, 2007).

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Endnotes

[1]An electric cartridge is a small heating element connected to the electricity supply system.

[2]The functional unit of floor area is defined in this study as the usable floor area within the apartments, staircases, cellar and attic. Areas excluded from the usable floor area are larger shafts, external walls and internal walls separating apartments.

Appendix

Table A1 Environmental data for materials/equipment collected for passive house buildings and conventional buildings. Information is included about the type of study – life cycle assessment (LCA)/environmental product declarations (EPD) or company/sector – year, and references

Material	Passive house buildings	Conventional buildings
Concrete	LCA, 1997[a,b] (Björklund and Tillman, 1997)	LCA, 1997 (Björklund and Tillman, 1997)
Lightweight-aggregate concrete blocks		Company, 1997 (Leca, 1997)
Crushed stone 'Macadam'	Sector, 1995 (Danish Technological Institute (DTI), 1995a)	Sector, 1995 (DTI, 1995a)
Brick	Sector, 1995 (DTI, 1995b)	Sector, 1995 (DTI, 1995b)
Gypsum wallboard	LCA, 1997[a] (Björklund and Tillman, 1997)	Company, 1996 (Gyproc, 1996)
Mortar	LCA, 1997[a] (Björklund and Tillman, 1997)	LCA, 1996 (Björklund *et al.*, 1996)
Glass wool	LCA, 1993 (Ceuterick, 1993)	LCA, 1993 (Ceuterick, 1993)
Stone wool	LCA, 1993 (Ceuterick, 1993)	LCA, 1993 (Ceuterick, 1993)
Aluminium	Sector, 1996 (European Aluminium Association, 1996)	Sector, 1996 (European Aluminium Association, 1996)
Copper	LCA, 2003 (PRe Consultants, 2003)	LCA, 1996 (Sunér, 1996)
Steel (from scrap)		Sector, 1996 (Danish Steel Works, 1996)
Steel studs (from ore)	LCA, 1997[a] (Björklund and Tillman, 1997)	
Steel reinforcement (from ore)	LCA, 1997[a] (Björklund and Tillman, 1997)	
Steel, stainless	LCA, 2003 (Strand, 2003)	
Water down pipes, gutters	Company, 2006 (Planja, 2006)	
Expanded polystyrene (EPS)	Sector, 2005 (Boustead, 2005a)	Company, 1995[c]
Polyethane (PE), Polypropane (PP)	Sector, 2005 (Boustead, 2005b)	Sector, 1993 (Boustead, 2003)
Polyvinylchloride (PVC)		Sector, 1993 (Boustead, 2003)
PVC film	Sector, 2005 (Boustead, 2005c)	
PVC pipe	Sector, 2005 (Boustead, 2005d)	
PVC flooring	EPD, 2000 (Golvbranschens riksorganisation, 2000c)	
Chipboard	Sector, 1995[d]	Sector, 1995[d]
Glulam wood	EPD, 2007 (Erlandsson, 2007)	Sector, 2007 (Erlandsson, 2007)
Planed timber	LCA, 1997[a] (Björklund and Tillman, 1997)	Sector, 1997 (Building Planning System (BPS), 1997)
Plywood	EPD, 1999 (Vänerply, 1999)	EPD, 1999 (Vänerply, 1999)
Veneered laminated beam product, KERTO	EPD, 1999 (Vänerply, 1999)	EPD, 1999 (Plyfa, 1999)
Masonite beams	Sector, 2005 (Erlandsson, 2005)	
Wooden flooring	EPD, 2000 (Golvbranschens riksorganisation, 2000a)	
Equipment		
Kitchen cupboards	Sector, 1997 (Sterner, 1997)	
Wardrobes	EPD, 2006 (SAIB, 2006)	
Linoleum floor covering	EPD, 2000 (Golvbranschens riksorganisation, 2000b)	LCA, 1995 (Jönsson, 1995)
Underlay felt	EPD, 2008 (Icopal, 2008)	Company, 1999 (Mataki, 1999)
White goods: refrigerator, freezer, stove, drying cupboard		Company, 1998 (Electrolux, 2003)
Freezer	EPD, 2003 (Electrolux, 2003)	
Refrigerator	EPD, 2005 (Electrolux, 2005a)	
Washing machine	EPD, 2005 (Electrolux, 2005b)	
Windows, product Elit window EFH12*12 M	EPD, 1997 (Noren, 1997)	EPD, 1997 (Noren, 1997)
Bath tub	Data for steel studs (Björklund and Tillman, 1997)	
Fittings	Data for steel studs (Björklund and Tillman, 1997)	
Ceramics	Sector, 2003 (PRe Consultants, 2003)	
Doors	EPD, 1998 (Henriksson, 1998)	
Glass	Sector, 1993 (Button and Pye, 1993)	
Paint	Sector, 1999 (Axelsson *et al.*, 1999)	
Taps	EPD, 1999 (Gustavsberg, 1999)	

Notes: [a]Electricity data given by Björklund and Tillman (1997) are without emissions. Here, Nordic electricity data from NordEl (2007) are used.
[b]'Fossil fuel' data given by Björklund and Tillman (1997) are without emissions. Here, 'Oil' data with emissions from Baumann and Tillman (2004) are used.
[c]Data collected by Neste Thermisol Ltd (Hedenstedt, Denmark), 1995.
[d]Data collected by Novopan Traeindustri A-S (Ryomgaºrd, Denmark), 1995.