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Environmental analysis of a building with reused building materials

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SUMMARY: In order to reduce the environmental impacts within the building sector, recycling of building materials is on the increase. Projects are carried out on several levels and are often well analysed regarding the economic consequences; however, the actual environmental effects are rarely studied. This paper presents a study of the environmental impacts due to a building from 1997 with a large proportion of reused building materials and components. Two cases were studied; (i) the building as it was built with a large proportion of reused materials and components (ii) the building as if all materials and components had been new. The results showed that the environmental impacts were about 55% of the impacts that would have been caused if all materials had been new. The reuse of clay bricks and roofing clay tiles accounted for the main decrease in environmental impacts. Further, these materials can be transported over quite long distances and still give environmental benefits.

1. Introduction

For the Swedish Building Exhibition 1997, a single-family dwelling was built with a large proportion of reused building materials and components and recycled materials. Building materials were recycled very differently from the recycling practice of today. The building was called 'The recycled house' and attracted great attention. See Fig. 1. The project was supported by the Swedish National Board of Housing, Building and Planning, who wished to promote the growth of a Swedish market of reused building products. The project is documented in (Återvunna huset, 1998) which also includes an economic analysis.

Recycling is here used as an overall concept for reuse, material recycling and combustion with heat recovery. The main benefits of recycling are saving of natural raw materials, saving of energy, decrease of harmful emissions and reduction in space needed for landfills. The degree of benefits varies with the kind of material and form of recycling. Recycling can also have economic consequences but those are not studied here.

The Recycled house represents a frequent topic of discussion at present regarding the environmental impacts from buildings and the way these impacts can be reduced. The aim of the presented study is to analyse the environmental effects of the use of recycled materials in buildings of today.



Figure 1. *The Recycled House, build 1997 (Architect P.Lewis Jonsson.)*

2. Goal of the study

The principal goal of the study was to compare the environmental impacts of a building with a high proportion of reused materials, which is unusual today, with the environmental impacts that would have been caused if all materials and components had been 'new' in that building, which represents the practice of today. The term *new* materials refers here to the way materials are conventionally produced today. *New* materials may contain recycled materials in varying proportions. This is for example the case with steel, gypsum plasterboard and mineral wool. In this way, the environmental effects of extensive recycling may be compared with the environmental effect of the practice of today.

A second goal was to compare the environmental impacts from the transport of recycled clay bricks with the environmental impacts of the transport of new clay bricks. This comparison is described below in section 9, Transport of bricks.

These kinds of analysis are of interest in the increasing discussion in society regarding the assumed benefits due to the reuse of building materials. The intended recipients of the results are mainly the actors in the building sector. The results are also of interest for those who draw up regulations regarding the recycling of building materials.

The processes included for new materials were the production of materials (from extraction of raw materials until the material was ready to be delivered from the factory, cradle to gate) and the transport of materials from the factory to the building site. Processes included for recycled materials were dismantling, upgrading and the transport from the demolition site to a temporary store and finally to the building site.

The building parts included were the foundation, the external and internal walls, the floors and the roof. Experience from a previous study indicates that the parts included account for more than about 97% of the total weight (Thormark, 1997).

References from which data were collected, classification, used characterisation factors, weighting indices, inventory results etc are presented in (Thormark, 1999).

3. Description of the Building

A single dwelling built in 1997 with a net residential floor area of 150 m² was analysed from an environmental point of view. The building also includes a carport and a store room and the total building area is 195 m². The mean U-value for the building was calculated to 0,26 W/m² °K. The foundation is a concrete slab. The external walls in the living part are a clay brick veneer construction with mineral wool. In the part with carport and store-room, the walls are of lightweight concrete. For structural reasons, the building has some load bearing steel elements. The roof is a timber structure with clay tiles, fibre board, mineral wool insulation, polyethylene foil and gypsum plasterboard or wooden panel on the inside. Internal walls are mainly of gypsum plasterboard on wooden studs but there are also clay brick walls. The main reused materials are set out in Table 1 below.

4. Method

The heightened awareness of the importance of environmental protection, and the impacts associated with products manufactured and consumed, has increased the interest in development of methods to better comprehend and reduce these impacts. One of the techniques being developed for this is Life Cycle Assessment, LCA. LCA is the technique for assessing the environmental aspects and impacts associated with a product, or service, in a life cycle perspective. Environmental impacts refer to the demand for natural resources, emissions to air, water and soil and solid waste. The life cycle consists of the processes and transport involved during raw materials extraction, refining of raw materials, production of the product, use of the product and waste management.

An LCA consists of four distinct phases; Goal and Scope (goal and basic definitions for the study), Inventory Analysis (data collections and calculations of input and output of the studied system), Impact Assessment (aimed at evaluating the significance of the environmental impacts using the result from the inventory analysis) and Interpretation (identification of significant environmental issues, supposed to lead to conclusions and recommendations). The Impact Assessment might end with a weighting step which is based on value judgments, not on science.

LCA, as all techniques, has its limitations. One limitation is that the choices and assumptions made in LCA regarding e.g. system boundaries, data sources and impact categories may be subjective. Further, models used for the inventory analysis or to assess environmental impacts are limited by their assumptions and may not be available for all impacts. Also, the accuracy of LCA studies may be limited by accessibility of relevant data and data quality. Finally, as the weighting is based on value judgements, different weighting methods can give different results. For these reasons, it is important to be aware of the limits of the information developed in a study of this kind when assessing the result in a decision process.

LCA is still at the stage of development. However, international standards have been drawn up and established regarding principles and framework, goal and scope definition and inventory analysis [ISO 14040, ISO 10041]. Draft standards have been issued regarding assessment and interpretation [ISO 14042, ISO 10043].

In this study the LCA approach has been used and the paper is largely structured according to ISO 14040:1997, ISO 14041:1998, ISO/FDIS 14042:1999 and 10043:1999.

5. Scope of the Study

Studied systems. The analysed systems are presented in Fig. 2.

Functional unit. The functional unit was the whole building during the phases up to and including the time when all the materials had been delivered at the building site.

System boundaries. The system boundaries are shown in Fig. 2.

Only the production, i.e. cradle to gate, of the building materials and transport from the material producers to the building site were included. Reused materials are packaged and treated in the same way as new materials. In the presented study the type and quality of the reused materials give no indication that the reused materials should be regarded differently from new materials in respect of service life and maintenance. In view of the purpose of the study, the phases after the materials were delivered to the building site, i.e. erection, operation and maintenance, were not included. However, the phases erection, operation and maintenance would not be effected by the use of recycled materials.

In order to compare the environmental impacts of the building with reused materials and the environmental impacts in the case if all materials and components had been new, the comparison of the two systems was performed as follows:

(House built with recycled materials + (Products B – Products A)) compared with (House built with new materials).

The system boundary of each system was extended in order to make a relevant comparison of the two cases. The systems also include more building materials and processes than would be needed merely to determine the difference between the case REC and the case All new. This was done in order to determine the relation between the impact of a building with extensive use of recycled materials and the impact of a building with only new materials according to the practice of today.

Reinforcing steel in Sweden is produced from scrap based steel. However, the reinforcing steel in the products B contains scrap based steel as well as ore based steel. This was done in order not to change the total amount of steel in society.

For reused materials, the 'cradle' was the derelict building before the process of dismantling was started. Consequently, dismantling, cleaning and upgrading of dismantled material as well as all transport to the building site were included. It was assumed that the dismantling of the concrete, timber and steel structures and roofing tiles was not considerably affected by the intention of reusing the materials. Owing to this circumstance and lack of good data on dismantling, the processes of dismantling concrete, timber and steel structures were not included.

As pointed out above, reuse of materials and components is not the recycling practice of today. If the materials in this study had not been reused, they would have been recycled in other forms as follows:

Timber would have been burnt and district heat produced. When combustible waste is not enough for the production of district heat in the region, natural gas is used as a fuel complement. The net calorific value for the reused timber was used for calculating the amount of fuel (gas) in system REC. Energy needed for the transport of timber to the incineration plant was taken into consideration, but not the energy needed for any preparation at the incineration plant.

Structural steel would have been recycled and used for the production of scrap steel products.

Mineral materials from demolition (clay bricks, roofing tiles, concrete) would have been deposited on local landfill sites. Materials deposited on local landfill sites are not considered as waste or to cause any environmental harm. In Copenhagen, Denmark, however, in principle all mineral materials from demolitions are recycled (Ludvigsen, 1998). They are crushed and used as sub-base in minor roads etc as a substitute for gravel and sand. One ton of crushed material is considered to be equivalent to one ton of gravel and sand (Ludvigsen, 1998, Arm, 1998, personal communications). It is reasonable to assume that the circumstances will be the same in Sweden in a near future. It has therefore been assumed that sand and gravel will be used as substitute for the shortfall.

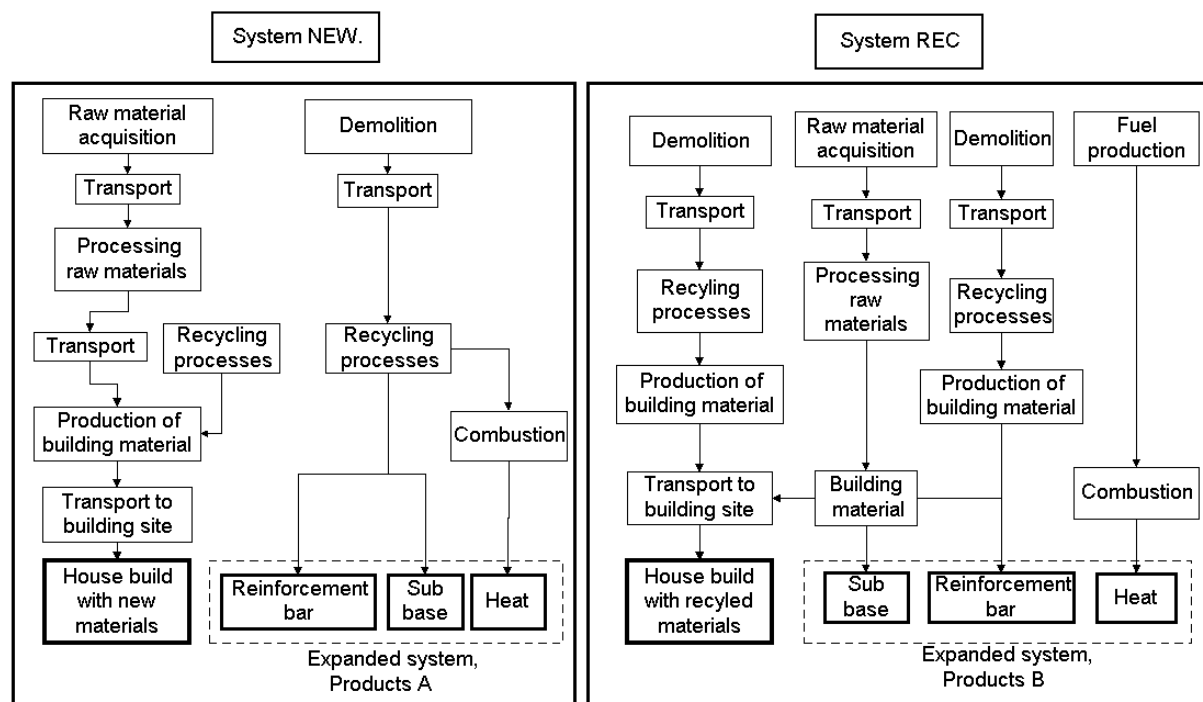


Figure 2. The system boundaries of the analysed systems.

Allocation. Allocation can be defined as the process of assigning material and energy flows as well as associated environmental discharges of a system to the different functions of that system. Recycling is a system where an allocation problem occurs, as the 'waste' from one function constitutes the raw material in a subsequent function.

In this study the allocation was made according to the cut off method, i.e. each product is only assigned the impacts directly caused by that product. The possibility and effects of other allocation methods are discussed below in section 11, *Comments and discussion*.

Data. Data were produced for the environmental load from the dismantling of clay brick walls. For other materials and processes, literature data were used. Literature data were from 1993-1997, with the majority from 1995, mainly representing production in Sweden and Denmark. Data were both industry average data and site specific data. For three materials, no data were available and data for similar materials were then used. For clay roofing tiles, data on clay bricks were used with an addition of 10% of the energy use due to the different drying process (Det Genanvendte hus, 1996). For beams of prefabricated concrete, which were used to a very small extent, data on prefabricated floor elements were used. For fibre board in the roof, data on chipboard were used.

Studied impacts. The following impact categories were studied: global warming, acidification, eutrophication and photochemical ozone formation. Classification and characterisation factors are according to (Hauschild, 1998). Those categories were chosen as there is good agreement on the characterisation factors for those categories. Further, from an environmental and political point of view, those categories are considered to be especially important. The use of natural resources is only presented as a weight. Waste from the production was divided into general waste and environmentally dangerous waste and only presented as a weight.

Limitations. The study was limited to the following:

- In the Recycled House, lime mortar was used in order to facilitate future reuse of the clay bricks. As the use of lime mortar was not necessitated by the use of reused clay bricks and in order to ensure that the use of different types of mortar would not affect the result of the study, only lime cement mortar was considered in this study.

- Electricity was accounted for in two ways. A minor part, about 2% of the total energy use, was Swedish electricity production, mainly based on nuclear and hydroelectric power. All other electricity was average data for European electricity. The fuel sources for the average European electricity were about 40% nuclear power, 38% coal, 10% fossil oil, 8% gas. The remaining sources were hydroelectric power and biofuels [Frees, 1996].
- The study was limited to the effects on the external environment. Parameters included were the use of raw materials, use of energy, emissions to air and water and soil.
- Cradle to gate data was used. The transport distance from the supplier of building materials to the building site was calculated as if the nearest supplier had been chosen in order not to overestimate the benefits from using recycled materials.

6. Impact assessment

The impact assessment phase here includes modelling of inventory data within four impact categories, i.e. characterisation. The characterisation was performed on the basis of characterisation factors collected from (Hauschild, 1998).

In order to provide further aspects on the inventory and characterisation results, weighting was also used. In this study, weighting factors were applied directly on the full inventory results, not limited to the four impact categories. By weighting, the result is further aggregated and ranked. Weighting is based on value judgments, different for different individuals, organisations and societies, and consequently different weighting methods can give different results. Altogether three weighting methods were used. Two weighting methods were chosen in order to achieve aspects regarding assumed Swedish ecological critical loads and Swedish political goals. A third method was chosen to achieve aspects on the assumed willingness of the average OECD citizen to pay for avoiding negative impacts. Each of these weighting methods results in one single overall score by the use of weighting factors. The methods used were as follows:

- The Environmental Theme Method, ET. This method (developed in Netherlands (Heijungs, 1992)) is adapted to Swedish conditions in two index series, political goals and ecological critical loads (Miljömässiga skillnader mellan återvinning/återanvändning och förbränning/deponering, 1993). The indices used here were based on assumptions regarding ecological critical loads. The contributions are weighted against each other on a long-term basis. Weighting factors were collected from (Lindfors, 1995).
- The Ecological Scarcity Method, Eco. This system starts out from political goals (was presented by Ahbe et al, 1990). Indices for Sweden can be found in (Miljömässiga..., 1993). In this system, emissions are weighted against each other directly. The ecological scarcity is defined as the ratio of the total environmental impacts to the critical impact within a geographically defined area. The method has also been used with authority goals. The weighting factors used in this paper were based on the goals for reduction presented by the Swedish Environment Protection Agency in a scenario study regarding Sweden 2021 (Bengtsson, 1997).
- The Environmental Priority Strategies in product design, EPS, developed in Sweden (Steen and Ryding, 1992). In this method, the willingness to pay (within the OECD countries) to restore five defined safeguard objects is assessed. The objects are: biological diversity, human health, production, aesthetic values and natural resources. The weighting factors have been updated and in this paper version 1996 was used (Steen, 1996).

7. Calculation Model

The calculation was made using the computer program LCA Database and Inventory Tool, version 2.38, developed at the Danish Building Research Institute (Petersen, 1999). The calculation model is structured into four levels: raw materials, building products, building elements and the building itself. In the tool, the user

defines all data regarding emissions. The user can also make the classification and define the characterisation factors. The tool enables full insight over applied calculation models.

8. Results

8.1 The use of Building Materials, Energy and Resources and Production of Waste

The amount of materials as well as the proportion of recycled materials used in the Recycled House and in the case All new are presented in Table 1. The total amount of timber is higher in the Recycled House because the reused structural timber had larger dimensions. The total quantity of clay brick is also higher in the case of reuse. The reused clay brick was a solid brick while new clay brick was assumed to be a hollow clay brick. The required amount of mortar when using old clay bricks was assessed by the bricklayer to be the same as the amount required when new hollow clay bricks are used.

The total weight of all materials used was 389 tons. The reused materials accounted for about 30 % by weight of all the materials and 40 % by weight if the crushed stone in the foundation was excluded. The total requirement of clay bricks and roofing tiles was supplied by reused clay bricks and tiles. Of the total requirement of timber, 32% was supplied by reused timber. As regards the requirement of steel, 70% was supplied by reused steel.

The use of energy in the case Rec was about 60% of case All new. The energy use, broken down by fuels, is presented in Fig. 3. The total energy saving corresponds to a calculated energy requirement for heating the building for about thirteen years. (If the feedstock energy had not been included the energy use in the case Rec would have been about 54% of case All new, which corresponds to about nine years of heating.)

The Recycled house reduced the use of raw materials for production of building materials and also decreased transport. The main primary raw materials conserved were bedrock, sand and clay and timber (the use decreased by about 30%) and fossil resources for energy production (the use decreased by about 25 %). The use of different chemicals decreased by about 80%. As nearly all steel is recycled today, reuse of steel means almost no change in the amount of primary raw materials.

With the assumption made that in a near future mineral waste will be crushed and used as sub-base (see above under *System boundaries* in section 5), the reused materials in Recycled house would not have been driven to landfill if not reused. Therefore, the recycled house caused a change in the *form* of recycling but did not decrease the amount to landfill.

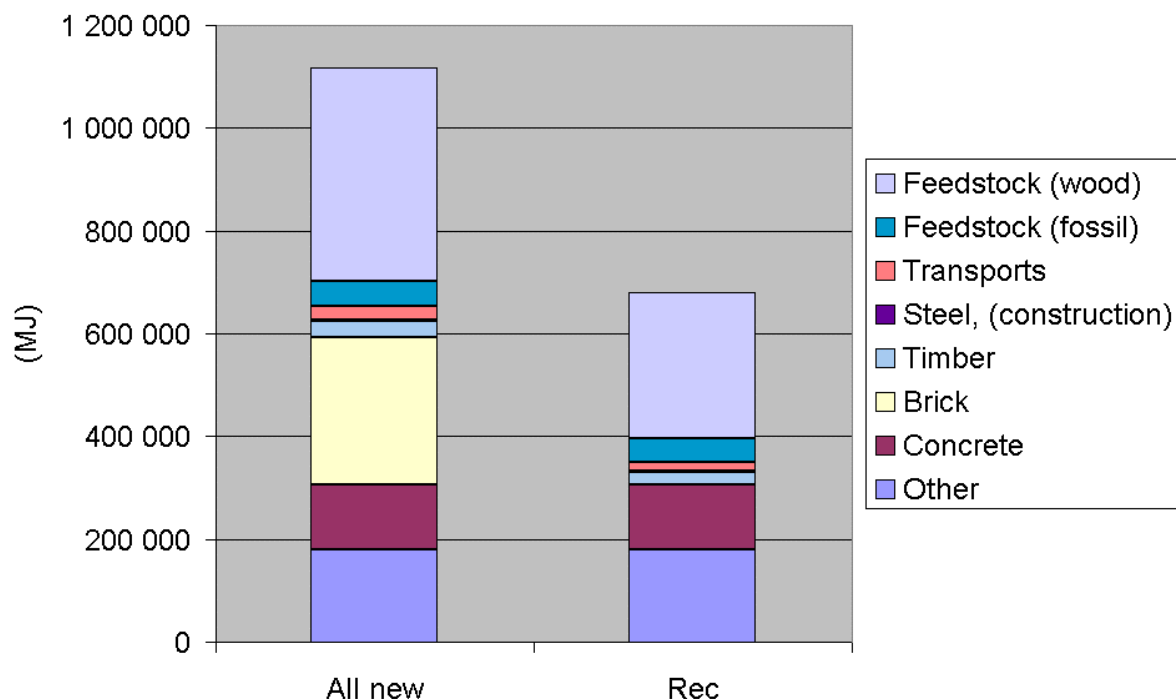


Figure 3. Survey of the total use of primary energy.

However, waste from the material production decreased due to the use of recycled building materials. The environmentally harmful waste decreased by about 50% and undefined waste by about 30%.

Table 1. Quantity survey of new and recycled building materials in the two cases.

Material	Unit	The Recycled House		Case All new
		Reused	New	New
Crushed stone	ton		110	110
Reinforcement	ton		0,454	0,454
Concrete, aggregate partly of crushed concrete	ton	94,5 (material recycling)		
Concrete, aggregate of crushed stone			94,5	
Prefabricated concrete element	ton		2,28	2,28
Clinker concrete block	ton		7,78	7,78
Lightweight concrete	ton		8,7	8,7
Clay brick	ton	90,576	83,028	
Roofing tile, clay brick	ton	12,510	12,510	
Mortar	ton		38,6	38,6
Timber	m ³	10,656	17,151	11,624
Steel structure	ton	1,015	1,015	
Fibre board in roof	m ³		1,286	1,286
Plywood	m ³		0,09	0,09
Gypsum plasterboard	ton		2,683	2,683
Mineral wool	ton		1,909	1,909
Insulation, EPS	ton		0,625	0,625
Vapour barrier, PE	ton		0,028	0,028

8.2 Characterisation

Characterisation was based on characterisation factors from (Hauschild, 1998).

The results from the characterisation are presented in Fig. 4-7. 'Changes' accounts for the difference between the expanded system of the case recycled house and the expanded system of the case All new. See Fig. 2. As mentioned above under *System boundaries* in section 5, the reuse of timber in the Recycled House caused an increase in the consumption of natural gas in the region. Consequently, it caused a change in the emission output due to the different emission profiles for combustion of biofuel and natural gas. The emission to air of CO₂ from combustion of biofuel was set to zero due to the circulation of biomass and because the net emissions from combustion can be regarded as negligible (Brännström, 1996). Combustion of natural gas causes the emission of considerably less CO than combustion of biofuel. Further, some transport did not occur owing to reuse. The change in emission output due to combustion of natural gas and the absence of some transport is presented as 'Changes' in Fig. 4-7.

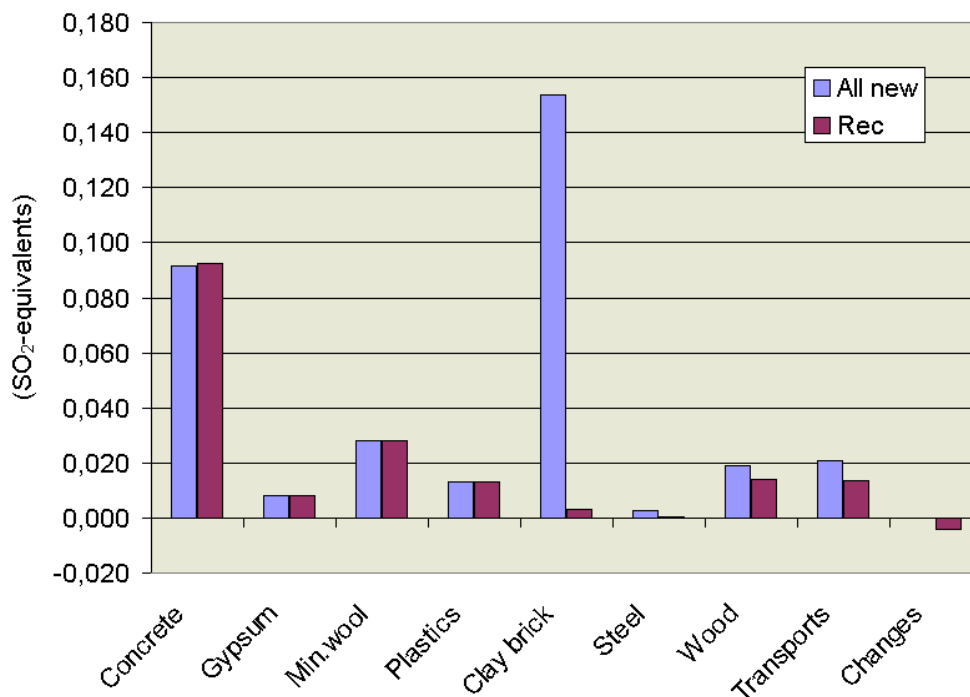


Figure 4. The contribution to acidification, broken down by materials and transport. 'Changes' represents the difference between product B and product A of the expanded systems, see Fig.2.

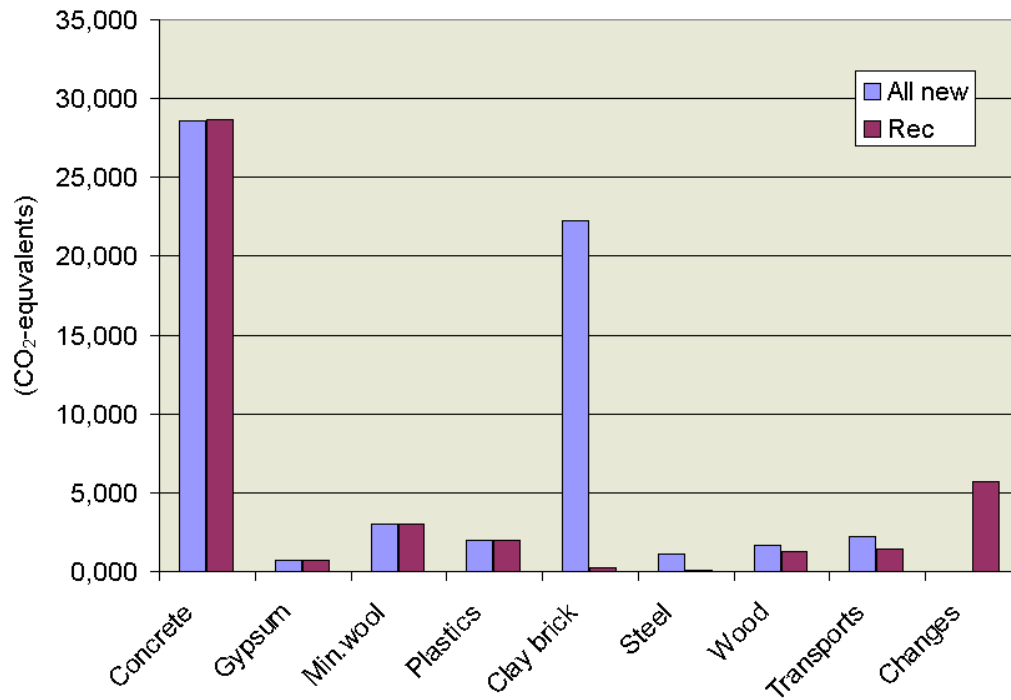


Figure 5. The contribution to global warming, broken down by materials and transport. 'Changes' represents the difference between product B and product A of the expanded systems, see Fig.2.

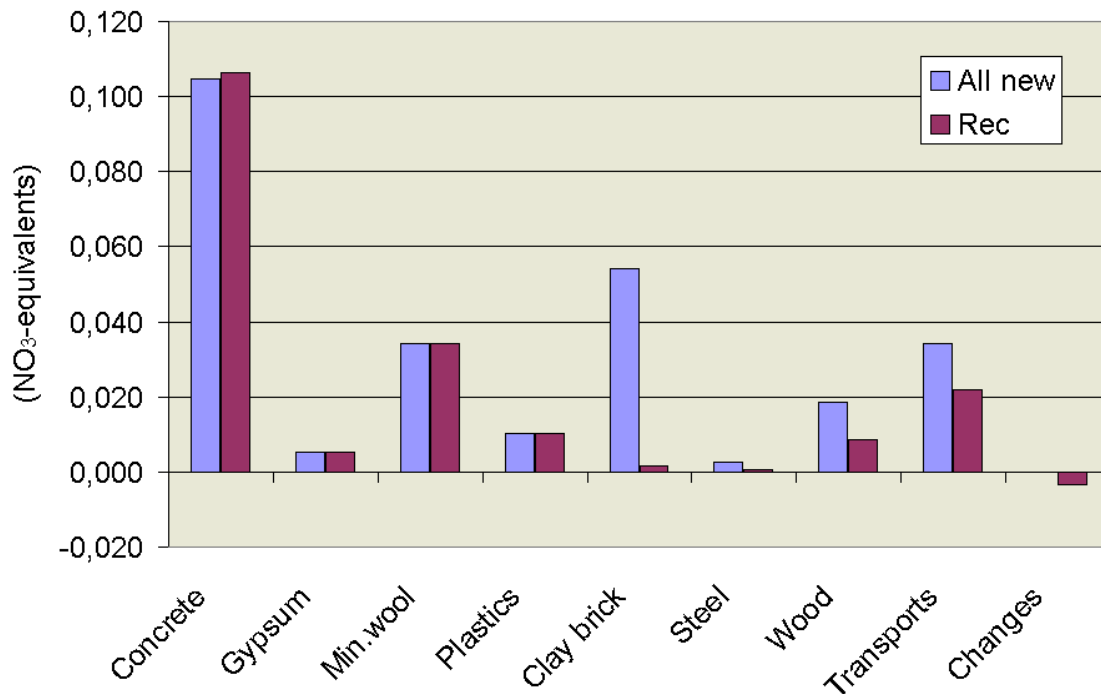


Figure 6. The contribution to eutrophication, broken down by materials and transport. 'Changes' represents the difference between product B and product A of the expanded systems, see Fig.2.

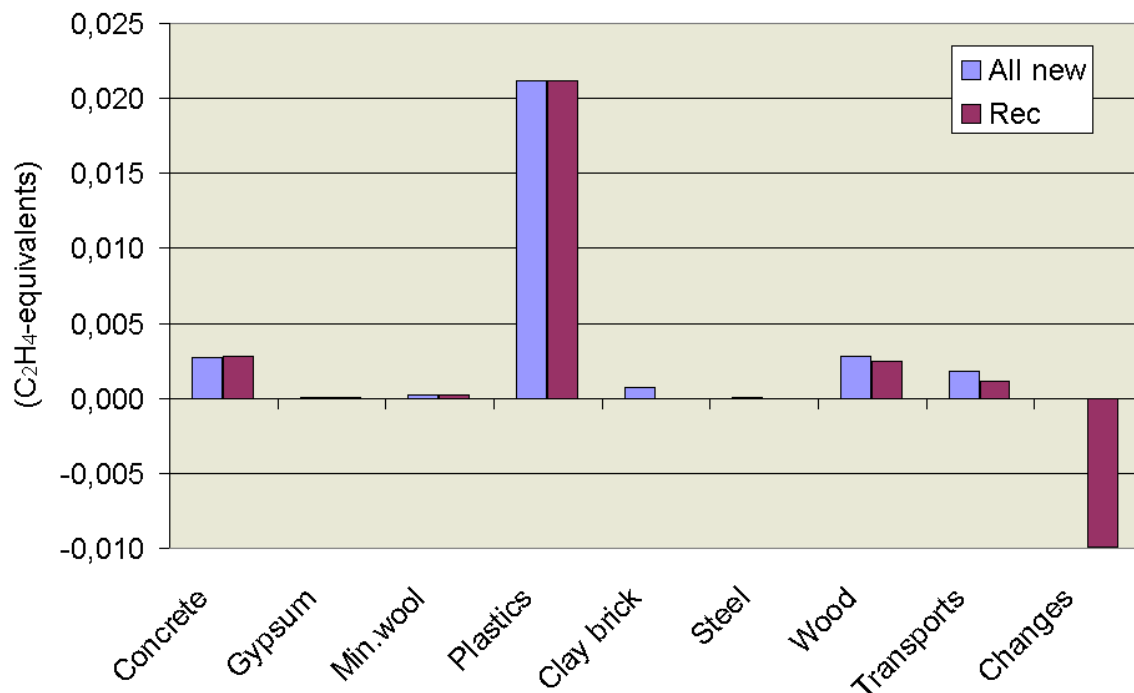


Figure 7. The contribution of photochemical oxidants, broken down by materials and transport. 'Changes' represents the difference between product B and product A of the expanded systems, see Fig.2.

8.3 Weighting

Three different methods were used: The Environmental Theme method, The Ecological Scarcity method and The Environmental Priority Strategies in product design, EPS. The methods (and sources from which weighting factors were collected) are described above in section 6. The result of the weighting is presented in Table 2.

When the Environmental Theme method was applied, it was mainly a reduction in the emissions CO₂, SO₂, NO_x but also the decreased production of special waste and the decreased use of electricity that affected the result.

When the Eco Scarcity method was applied, it was also mainly a reduction in the emissions CO₂, SO₂ and NO_x but also the decreased production of special waste and the decreased use of electricity that affected the result.

The emissions which affected the result in the Environmental Theme and the Eco Scarcity methods were not at all the most highly ranked factors, but due to their magnitude they had a great influence.

When the EPS method was applied it was the reduction in VOC emissions that dominated the result. The CO₂ emissions and the reduction in the use of oil also contributed. In the EPS method, VOC is among the most highly ranked factors. If VOC were excluded, the reduction in CO₂ emission would have dominated, but the reduction in the use of oil and coal and the reduction in NO_x emissions would also have strongly affected the result.

Table 2. The result of weighting with three different methods.

	All new, (indices)	Rec, (indices)	Rec in % of All new
Eco	62 532 856	38 200 324	61
ET, long	5 881 116	3 754 346	64
EPS	588 646	480 053	82

9. Transport of Reused brick

In an analysis of the environmental benefits of recycling, the environmental impacts caused by transport are an important issue. Therefore, the environmental effects due to the production and transport of reused bricks were compared with the environmental impact due to the production and transport of new bricks. In the study, environmental impact refers to the following effect categories: global warming potential, acidification, eutrophication and photochemical ozone creation.

Reused clay brick is in general heavier than new clay brick. The reuse of brick is for the moment not very common and it is therefore difficult to make any general statement on the means of transport for reused brick. However, so far reused brick is often transported fairly short distances compared with new brick and therefore smaller lorries are mainly used.

A comparison was made of transporting 435 bricks. This number was chosen as about 435 hollow clay bricks weigh 1 ton. Reused brick had an average weight of 3,6 kg/brick. New brick was assumed to have a weight of 2,3 kg/hollow brick and 3,2 kg/solid brick.

The means of transport was assumed to be the same for both new and reused brick. A medium heavy lorry with a total weight, when full, of 24 tons, was assumed for distances 0-200 km. It was assumed 50% full. A heavy lorry with trailer with a total weight, when full, of 40 tons, was assumed for distances of 300 km or more. It was assumed 70% full. The degrees of filling are in accordance with guiding principles in (NTM, 1999).

Data on litres of fuel/km and emissions/litre were collected from (NTM, 1999) and is valid for diesel, environment class 1, time period 1993-1995. Data used for new clay brick refers to brick produced in Denmark in 1993 and comes from an, at that time, modern factory (Petersminde, 1993). The factory used natural gas and electricity. The electricity accounted for about 6% and was assumed to be an average European electricity.

In all cases, the eutrophication and photochemical ozone creation effects of reused bricks is equal to those from new bricks at a much shorter distance compared to the global warming potential and acidification effects. Therefore, only the results of the eutrophication and photochemical ozone creation effects are presented. The results are shown in Fig. 8-9.

No data is available on brick produced in Sweden. A corresponding calculation was made with data from the factory in Petersminde but with the average European electricity changed to electricity from Svenska Vattenfall (Brännström, 1996). Photochemical ozone was still the decisive factor and the crossing point was at a slightly shorter distance than in Fig. 8-9.

When studying the figures, it should be remembered that in Sweden there are only three brickyards left. Besides, local brickyards are often subject to strong competition by foreign brickyards. For example, the brickyard outside Stockholm is considerably rivalled by Danish brickyards. This means that, in general, new brick is often transported quite long distances.

The above arguments are also mainly valid for roofing tiles. There are some differences, however. The weight difference between new and reused clay tiles is less than for brick. Besides, tiles are more energy intensive to produce than bricks. Both factors might make it more worth while to reuse tiles. On the other hand, an observation must be made regarding the remaining service lifetime of the tiles.

To reach the best benefits, reused bricks should of course be taken from a place within the region of the new building site. The benefits are further increased in the cases when it is possible to transport the bricks directly from the derelict building to the new building site.

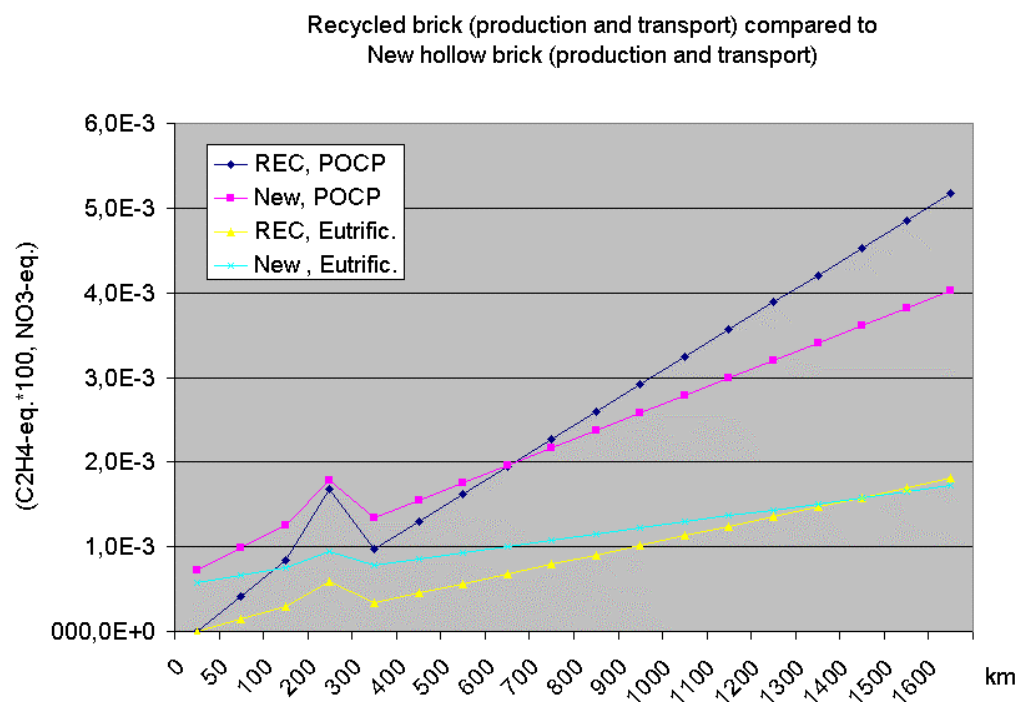


Figure 8. The contribution to eutrophication and photochemical oxidation from recycled bricks and new hollow bricks.

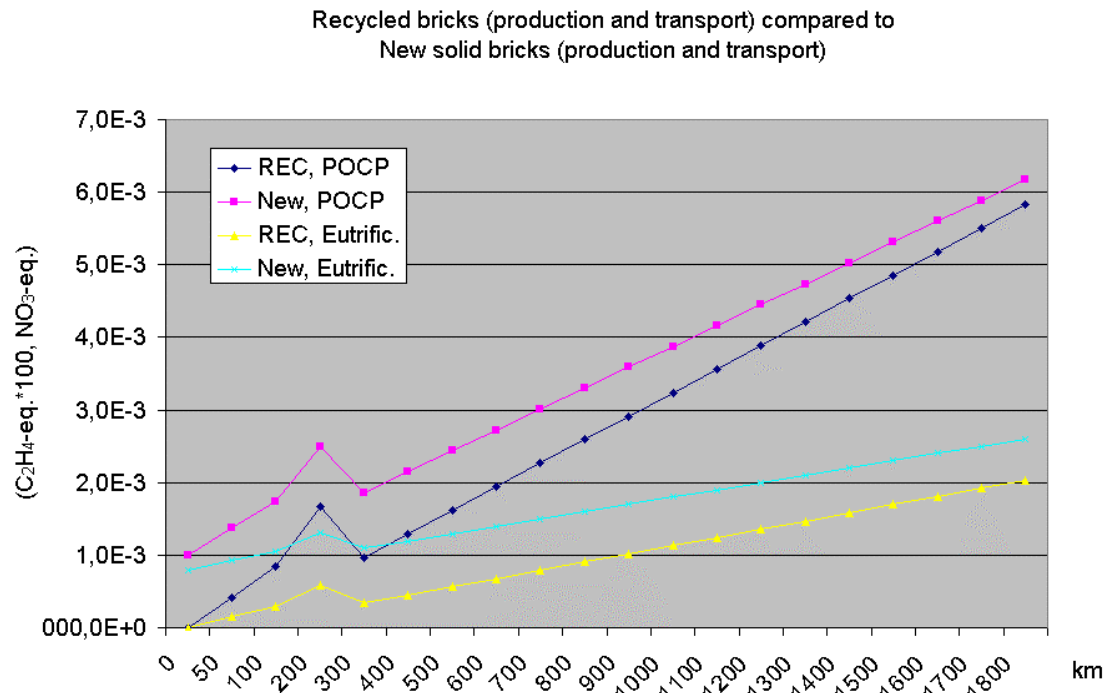


Figure 9. The contribution to eutrophication and photochemical oxidation from recycled bricks and new solid bricks transported.

10. Summary of Results

The aim of the study was to compare the environmental impact due to production of materials up to and including the delivery at the building site for a building with a high proportion of recycled building materials and components, case Rec, with the impact due to that building if only conventional materials and components had been used, case All new.

The use of energy, feedstock energy included, was for the case Rec about 60% of the case All new. The figure when feedstock energy was excluded was about 54%.

The main primary raw materials conserved by the use of recycled materials were bedrock, sand and clay and timber (the use decreased by about 30%) and fossil resources for energy production (the use decreased by about 25%). The use of different chemicals decreased by about 80%.

With the assumption made that mineral waste in a near future will be crushed and used as sub-base (see above in *System boundaries* section 5), the recycled house did not decrease the amount of material to landfill. Only the form of recycling changed, i.e. from material recycling or combustion to reuse.

The result regarding the impact categories, in percentages of the case All new, was as follows for the recycled house: global warming potential 70%, acidification 50%, eutrophication 70% and photochemical ozone formation 61%.

The result with the applied weighting methods, in percentages of the case All new, was as follows for the recycled house: for the Ecoscarcy Method, Eco, 61%, for the Environmental Theme Method, ET_{long}, 64% and for the EPS method, 82%.

How long the feasible transport distance is for reused brick ought to be assessed in each case. When reused brick from the local region is used, there always seems to be considerable environmental benefits.

11. Comments and Discussion

11.1 General

Use of reused materials

In an analysis of the use of reused materials, some things have to be remembered. Reused materials might have a shorter service life than new materials. Maintenance might also differ between reused and new materials. In the presented study, however, the type and quality of the reused materials give no indication that the used materials should be regarded differently from new materials.

Reuse of clay bricks and roofing tiles

Clay bricks and roofing tiles seem to be the building materials whose reuse provides very good environmental benefits. Reuse of bricks is possible when lime mortar or other weak mortar is used for laying, even if lime-cement mortar was used for the plaster. This is also true for hollow clay bricks. The results of this study show that reuse of clay bricks may confer considerable environmental benefits. Despite the possibilities and benefits, reuse of clay bricks is for the time being fairly rare. There are several reasons for this. One is the lack of rational and economic methods for cleaning the bricks. Another reason is the lack of non destructive test methods. Methods, however, are constantly developing.

A survey was made of the total quantity of building material in the existing building stock and the waste from construction and demolition produced in 1996 (Kartläggning av materialflöden, 1996). Clay bricks accounted for about 12 % by weight of the material in the existing building stock. Of the waste, clay bricks accounted for about 7 % by weight. However, it is difficult to assess how much of this clay brick can be reused. Generally, all kinds of brick can be reused except brick from chimneys (Tegel, 1998). The possibility to reuse brick mainly depends on the grade of mortar used for laying. When hard lime-cement mortar is used, reuse seems for the moment impossible. The use of lime-cement mortar began at different times in different regions of Sweden. For the time being, there are no investigations to assess the number of the existing buildings in which bricks were laid with lime mortar or other rather weak grades of mortar. However, generally it can be said that the quantity of reusable brick shows a gradual decrease in the building stock built after world war two. Besides, the proportion of brick as a building material is also on the decrease in these buildings. Consequently, reusable clay bricks in the existing building stock are in the future a diminishing 'resource'.

Reused materials on the increase

In the Recycled House, a high proportion of reused material was used. This could, however, have been increased. Lightweight concrete and lightweight aggregate blocks are not reused today, but this would be possible if other types of mortar were used. Further, all construction timber could have been reused. This can be considered as the maximum use of reused material in the Recycled House. The result regarding the energy use would then have been about 55% of that in the case All new.

The benefits of using recycled materials are in this study compared with the use of 'new' materials. The term *new* materials refers here to the way building materials are generally produced today. However, if it is assumed that the use of both recycles in material production and the use of reused materials in buildings becomes the general situation in the future, it is obvious that the result of a corresponding study in such a situation would show less difference between the case Rec and the case All new. Consequently, the environmental impacts caused by a building with increased use of recycled materials, in *proportion* to a 'general building', will evidently always depend on how much recycled materials there are in the general building.

Other substitutes for timber as fuel

Timber would have been burnt with energy recovery if it had not been reused. It was assumed that natural gas was used as a substitute for the shortfall in timber. A calculation was also made with the assumption that oil, coal or some other biofuel was used as substitute for the shortfall in timber. The result of the characterisation is presented in Table 3 in percentages of what it would have been in the case All new.

Table 3. The result of the characterisation, in percentages of what it would have been in the case All New, with different fuels for heat production in the expanded system of the Recycled house.

	Gas	Oil	Coal	Biofuels
Acidification	50	61	61	51
Global warming	70	74	76	62
Eutrophication	70	70	70	70
Photochemical oxidation	61	63	62	94

11.2 The method

The method used is limited in many ways. For several issues, for example noise, vibrations, risk of accidents etc, there is at present no agreement on how these are to be assessed. The use of recycled materials presupposes a demolition method different from today which may cause a considerable increase in those issues.

In this study, the factors in the method used which are likely to affect the result are the method for allocation and the quality of data. These factors are discussed below.

Allocation

A building and most of its materials has a very long service life and is very complex compared with most consumer goods. For this reason it is more or less impossible to predict how many times a material will be recycled or if it will be recycled at all. If parts of the impact caused by production were allocated to the recycled product, no product would assume responsibility for these parts if no recycling occurred in the future. Therefore, a cut off allocation was used in this study.

However, many different methods for allocation are available and it is generally known that the result of an LCA can change considerably with the allocation method used. If the result of an LCA is to be relevant in a decision situation, it requires use of an allocation method which seems intuitively reasonable and fair to the users of the result. Also, the method must be consistent for a material whether it is reused or new.

As the result can change considerably with the allocation method used, it can be of interest to see what other methods would be available and how the result would then change.

In this study, the allocation problem in recycling is mainly relevant for three materials; steel, brick and timber. Three lifetimes were assumed for these materials with the following functions in each lifetime: structural steel (steel, steel, steel), brick (brick, brick, sub-base) and timber (timber, timber, fuel). It was also assumed that there is no appreciable quality change for brick and timber between the first and second lifetime.

An overview of eight allocation methods is given by Ekvall, 1997. With the assumptions made above regarding lifetimes and quality, the impact from production, in all eight methods, either burdened the first lifetime or was shared about equally between the first and the second lifetime. However, it is quite unlikely that anyone, except maybe the brick and timber industry, would accept an allocation method in which reused products, here brick and timber, are assigned any part of the impacts from a production that occurred hundred years ago.

Regarding steel, the situation is different. Steel can be recycled over and over again without any appreciable quality change. Further, ore based steel products contain some recycled steel. Therefore, an allocation where all three lifetimes equally share the impacts from primary production and the recycling processes can be argued to be reasonable and fair. When this allocation was used, the result for the whole house changed by less than one percent for all the different impact categories except for eutrophication. Eutrophication in case Rec was 73% of that in the case All new instead of 70% when the cut off allocation was used.

11.3 Data quality

Literature data was used and differs in some aspects, see above under *Data*, section 5. It can be seen from Fig. 4-7, that the materials which contributed most to the environmental impact were concrete, plastics and clay bricks. A sensitivity analysis was made with the data for those materials varied by $\pm 10\%$. With changed values for concrete and plastics, the total result changed only slightly except for the photochemical ozone formation which

changed by about 3%. With changed values for clay bricks, the total result changed by about 2%. As the primary purpose of the study was mainly to compare the two cases, the data can be regarded as sufficient enough.

Owing to the data quality, the result can not to be regarded as a result of the actual impact from either of the cases. The result should instead be regarded as an indication of how the two cases are related to each other.

A sensitivity analysis was also made regarding the effect of different classes of electricity. Instead of the average European electricity, the electricity from Svenska Vattenfall was used (Brännström, 1996). This only slightly affected the relation between the case Rec and the case All new.

It should be noted that the average European electricity and the electricity produced from Svenska Vattenfall are not comparable. For example, in the inventory data on the European electricity, no allocation was made regarding heat and electricity. There is also no information regarding the proportion of produced heat and electricity. About 55% of the fuel for this electricity is fossil fuel and it can therefore be assumed that the proportion of heat is not negligible. Data on Swedish electricity are, however, allocated to heat and electricity.

12. Conclusions

All techniques for assessing the impacts caused by an object, or a process, have their limitations. It is important to be aware of the limits of the information developed in a study of this kind when assessing the result in a decision process.

The results of the study show that there are considerable environmental benefits to be derived from the use of reused clay bricks and roofing tiles instead of new bricks and tiles. Reuse of these materials can contribute to a considerable reduction of the environmental impact from a whole building. An important issue, however, is how far the bricks are transported. The length of the feasible transport distance for reused bricks ought to be assessed in each case. The main factors that affect the reasonable distance are distance to the producer of new bricks, the quality of the new bricks and all means of transport. When reused bricks from the local region are used, however, there seems always to be considerable environmental effects.

As regards the environmental benefits due to reusing materials which would otherwise have been used as fuel for district heating, these greatly depend on the combustion capacity and the fuel substitute in the region.

The amount of waste is not always decreased by extended recycling when the region has a well developed handling of building 'waste'. Only the *form* of recycling changes and consequently the environmental benefits.

The proportions and kind of natural resources that are saved by recycling building materials vary considerably with the building material that is recycled. They also depend on the resource used as substitute for the reused material.

As the reuse of building materials affects a complex system, it can be difficult to make broad generalisations. Each material has to be assessed separately.

Consideration of the potential benefits to be derived from recycling and a recycling approach ought to form an integral part of the design phase of new buildings, in order that buildings should be designed so as to offer the opportunity of future recycling.

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