CHALMERS

LCA of the Demolition of a Building

An assessment conducted at IVL Swedish Environmental Research Institute

Master's of Science Thesis in the Master's Degree Programme Industrial Ecology

SARA KUIKKA

Department of Energy and Environment
Division of Environmental System Analysis
CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden, 2012
Report No. 2012:17
ISSN No. 1404-8167

LCA of the Demolition of a Building

An assessment conducted at IVL Swedish Environmental Research Institute

SARA L. KUIKKA

Department of Energy and Environment
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2012

LCA of the Demolition of a Building
An assessment conducted at IVL Swedish Environmental Research Institute
Master's of Science Thesis [Industrial Ecology, MPECO]

SARA L. KUIKKA

Cover: Kämpingeskolan photographed by the author.

Department of Energy and Environment
Division of Environmental System Analysis
Report No. 2012:17
ISSN No. 1404-8167

Chalmers University of Technology
SE-412 96 Göteborg, Sweden
Telephone +46 (0)31-772 1000

Gothenburg, Sweden 2012

Abstract

In this master's thesis a LCA of the demolition of a building is conducted. The building is a school with a demolition area of 9000 m^2. Two demolition alternatives; selective and conventional, are assessed in order to determine which alternative is more environmentally preferable. In selective demolition the materials are re-used. In conventional demolition the materials are recycled, incinerated for energy recovery or deposited in a landfill. The studied materials are; glulam beams; windows, teak doors, bricks, steel doors, ceiling tiles, security bars and sinks. The aim of the investigation is to assess the potential environmental benefits of moving up in waste hierarchy. Specifically, the re-use of building materials is compared to recycling, recovery and disposal. The demolition is modelled in Gabi 4 software.

The results of the LCA show that selective demolition is more environmentally preferable in comparison to conventional demolition in all assessed environmental impact categories. The considered impact categories are: acidification potential, eutrophication potential, global warming potential, photochemical ozone creation potential and primary energy demand. It is concluded that selective demolition is environmentally preferable because when it is conducted the materials may be re-used. Since production of new building materials is not needed, the environmental load of production from raw materials is avoided. Furthermore, the large amounts of re-used bricks and windows in comparison to the other re-used building materials have a large effect on the avoided environmental load. Hence, this study shows that the most significant materials to re-use are bricks followed by windows per demolished building. It may thus be concluded that moving up in waste hierarchy is environmentally beneficial in the area of demolition.

Preface

This master's thesis is a LCA of the demolition of a building performed at IVL Swedish Environmental Research Institute. It is the final step of my master programme Industrial Ecology at Chalmers. Demolition of the studied building is planned to proceed in the end of 2012, therefore this study is based on a hypothetical demolition of a building. The thesis is part of the EU project IRCOW, which abbreviates**:***"Innovative strategies for high-grade material recovery from construction and demolition of waste"***.**

I would like to give a special thanks to my supervisor, David Palm at IVL for answering my questions and helping me with the modelling in Gabi. Lisa Bolin has also helped me with the modelling in Gabi therefore I would like to thank her very much as well. I would like to thank Jacob Lindblom at IVL for finding a building that will be demolished and contributing with information in the area of construction. I would like to thank everyone else involved in my master's thesis at IVL whom I have enjoyed working with. A special thanks is given to Maria Ljunggren Söderman for being the examiner of my master's thesis. Finally, special thanks are dedicated to Jenny-Yue Zheng for her input in improving the structure and grammar of the report.

Gothenburg, August 2012
Sara Kuikka

Abbreviations and nomenclature

CML	Characterisation standard for environmental impacts published by the University of Leiden, the Netherlands.
Disposal	Any operation which is not recovery even where the operation has as a secondary consequence the reclamation of substances or energy. (EU, 2008)In Annex I in the EU directive 2008/98/EC landfill is proposed as a disposal operation.
IRCOW	Innovative strategies for high-grade material recovery from construction and demolition of waste
LCA	Life Cycle Assessment
Preparing for re-use	Checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be re-used without any other pre-processing. (EU, 2008)
Recovery	Any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy. (EU, 2008)
Re-use	Any operation by which products or components that are not waste are used again for the same purpose for which they were conceived (EU, 2008). For instance doors from an old building are used again in a new building (Ljunggren Söderman et al., 2011).
Recycling	Any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations. (EU, 2008)
Waste hierarchy	The following waste hierarchy shall apply as a priority order in waste prevention and management legislation and policy: prevention, preparing for re-use, recycling, other recovery and disposal, see *Figure 1*. (EU, 2008)

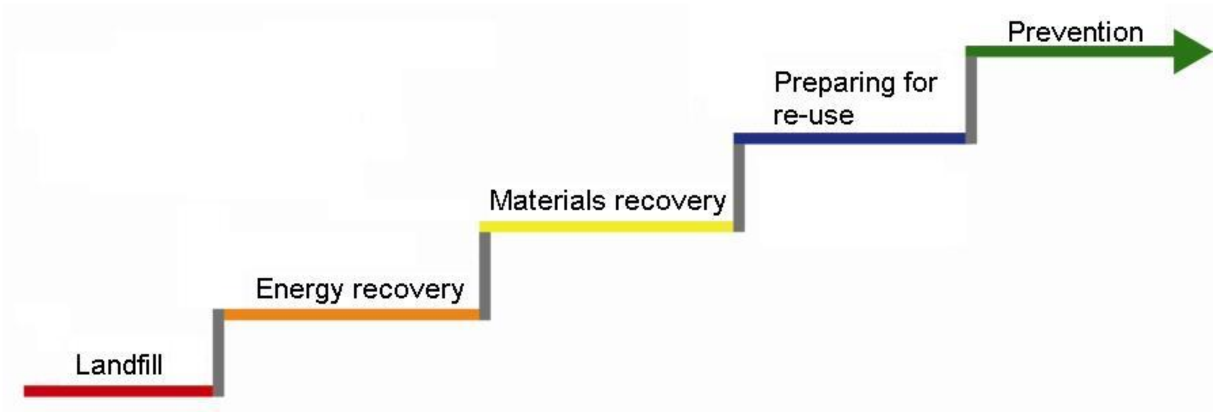

Figure 1 Waste hierarchy (IVL, 2012)

Table of Contents

1. Introduction

In this section the aim of the master's thesis, to conduct a Life Cycle Assessment, LCA, of a demolition of building is explained. The building that will be demolished and the materials that may be re-used are presented. An introduction to LCA methodology is given as guidance for the reader.

1.1 Aim

The aim of this master's thesis is to compare selective and conventional demolition from a life cycle perspective. The two demolition alternatives are compared to assess the possible environmental benefit of re-using construction and demolition material. Specially, when selective demolition is conducted materials may be re-used, and when conventional demolition is conducted materials may be recycled, landfilled or utilized for energy recovery. Furthermore, the possible environmental benefit of moving up in waste hierarchy in the area of construction is evaluated in this master's thesis. Waste hierarchy in the EU directive 2008/98/EC is proposed in the following priority order; prevention, preparing for re-use; recycling, energy recovery and disposal. This master's thesis aims to assess if moving up in waste hierarchy, re-using construction and demolition material, oppose to recycling, landfill and energy recovery is potentially environmentally beneficial.

1.2 Re-use of construction and demolition material

The building is a school located in Tensta, Stockholm's municipality. At the material inventory of the building Michael Joyce[1] from Kompanjonen, a re-use trader, recommended several materials that may be re-used. The materials chosen to be assessed in this study are; glulam beam; wooden windows, teak doors, bricks, steel doors, ceiling tiles, security bars and sinks. These materials are primarily chosen, because of their commercial value – they may be sold again. This is further explained in *Section 3.2 The Building*.

1.3 Life cycle assessment methodology

As stated above the demolition of the building is assessed from a life cycle perspective. LCA of a product or service considers all the activities of the life cycle and evaluates the environmental load of each activity. The life cycle of a product means that it is assessed from its "cradle" where raw materials are extracted from natural resources through production and use to its "grave", the disposal. Activities in between the cradle and the grave are for example manufacturing, transports, use and waste management. (Baumann & Tillman, 2004)

The methodology for LCA is shown in *Figure 1.1*. The dotted lines in *Figure 1.1* indicate that LCA is an iterative methodology. Firstly, the goal and scope is determined and decided upon. Aspects to consider are why the LCA is conducted, who is the intended audience, what product or service is assessed? Additionally, the aim of the LCA is given. Secondly, in the scope the functional unit is explained. All data used later on in the inventory and flows in the life cycle are normalised to the functional unit. System boundaries and the initial flow chart of

[1] Michael Joyce (representative from Kompanjonen) present at the material inventory of the building on March 21, 2012.

the studied system are constructed. At this stage, since LCA is an iterative methodology an interpretation is made and one evaluates if changes of the goal or scope are needed. (Baumann & Tillman, 2004)

Secondly, the inventory analysis proceeds which includes construction of the flow chart, data collection and calculations where all flows are normalised to the functional unit. Thirdly, impact assessment is conducted. The environmental loads of each impact category are assessed. (Baumann & Tillman, 2004)

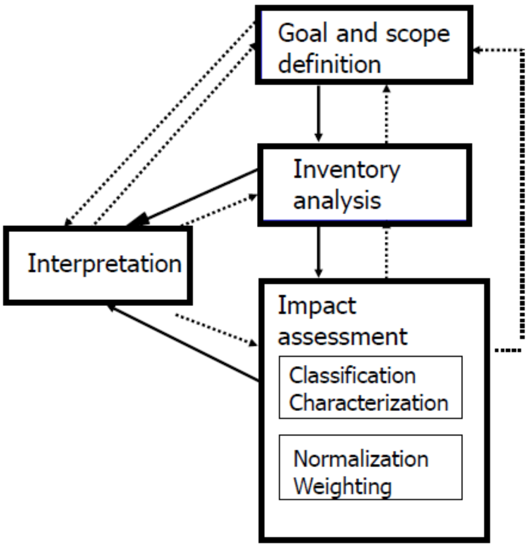

Figure 1.1 LCA methodology (Tillman, 2011)

2. Background

In the following section a background to the master's thesis is given. It is illustrated how buildings are demolished and the waste generated at the demolition site is described. Further, materials that may be re-used are proposed. An overview of the EU project IRCOW is given, in which a case study is conducted. This master's thesis is a part of the case study which aims at selectively demolishing a wood based building and investigate the re-use potential of its construction materials.

2.1 Demolition of buildings

In Sweden it is roughly estimated that approximately 1300 buildings per year are demolished. This estimation is based on data from SCB (2008) and The National Board of Housing, Boverket (2010a). The calculations and assumptions are thoroughly explained in *Appendix A*. The methods of how these buildings are demolished vary. Below is an overview of conventional and selective demolition as well as how these terms are defined in the study.

2.1.1 Conventional demolition

There are several ways to conventionally demolish a building. Buildings may be demolished using an excavator or construction crane (Jonsson & Wallenius, 2006). Johansson M. et al. (2000) states the following demolition alternatives: demolition with hand tools or a hydraulic hammer, demolition using explosives as well as sawing and drilling. The construction and demolition waste is separated to different fractions to be recycled and avoid deposit (AF Group, 2012).

In this study conventional demolition is defined as, the building facades and interior are demolished, without any prior disassembly. Materials consisting of steel, wood and inert material are separated into respective fraction to be recycled, recovered to utilize energy, or landfilled. Finally, the supportive structure of the building is demolished. Typical supportive structure of buildings from 1960's is concrete and this is made to backfilling material.

2.1.2 Selective demolition

A demolition for optimal re-use of construction and demolition materials begins with selective demolition where material that may be re-used is selectively dismantled. Material that may not be re-used is instead recycled. Lastly, conventional demolition proceeds. (Persson-Engberg et al., 1999)

There are also different methods to selectively demolish a building. One method is to build a ladder scaffold around the building and demolish the building from top to bottom (Jonsson & Wallenius, 2006). The material is dismantled from the building and divided into different fractions for re-use, recycling and landfill (Bokalders & Block, 2010).

Aspects to consider when selectively dismantling material according to Persson-Engberg J. et al. (1999):

- A place where the material can be stored safely and sorted at the demolition site.
- Practical opportunities for sorting the material at the building site.
- Transports

- Economically beneficial to sell re-used material
- Demolition cost
- Working environment
- Time frame

In this study selective demolition is defined as the building materials that may be re-used, stated in *Section 3.1*, are selectively dismantled without breaking. The re-used materials are sold again at retailers. After that the building is demolished and the remaining material is treated in the same way as for conventional demolition.

2.1.3 Material inventory

According to Swedish law, an environmental inventory of the building must proceed before demolition to find if hazardous material is present in the building (Boverket, 2010b). In the environmental inventory it is investigated if the building contains any hazardous materials such as PCB and asbestos. Hazardous material should be marked in the building. The environmental inventory proceeds to gain legal permission to demolish the building.

No laws in Sweden explicitly state that an inventory of a building should be conducted to evaluate re-use, recycling and recovery alternatives of the construction and demolition material. Nevertheless, municipalities in Sweden have recommendations to recycle and re-use construction and demolition material in a building.

Persson-Engberg et al. (1999) suggests that at an inventory of a building, the amount of material and its composition, quality and possibilities for separation are specified. Regulations and recommendations regarding waste management such as recycling and re-use in the municipality where the building is located should be investigated. Furthermore, the material inventory indicates the economic feasibility of selective demolition. To clarify, if the profit of selling the re-used products will cover the demolition cost. (Persson-Engberg et al., 1999)

2.2 Re-use potential of construction and demolition material

A prerequisite for materials to be re-used is that they are of sufficient quality. Specifically, a re-used product should have similar fire resistance, durability, insulation properties and supportive structure as a product manufactured from conventional raw material (Boverket, 2010). Below are examples of materials that may have commercial value and may be environmentally preferable to re-use.

- Doors and windows (Ljunggren Söderman et al., 2011)
- Wood beams and trusses (Stockholm stad, 2006)(Lennon, 2005)
- Brick (Ljunggren Söderman et al., 2011) (Lennon, 2005)
- Roof tiles of concrete or clay (Stockholm stad, 2006)
- Sanitary goods such as sinks and WC (Ljunggren Söderman et al., 2011)
- Parquet flooring and other types of wood flooring (Stockholm stad, 2006)(Lennon, 2005)
- Stone material such as slate, marble discs and window sills (Stockholm stad, 2006)
- Interior such as wardrobes, kitchen cupboards and shelves (Stockholm stad, 2006)

2.2.1 Wood

In the IRCOW project it is stated that the aim of the demolition is to focus on re-use of wooden materials, hence wood is highlighted. When wood materials are removed selectively they may be re-used. Permanent and lose wood carpentry may be re-used. Construction timber such as wood beams and trusses may be re-used once the nails have been removed. Wood that is contaminated by vermin, mould or rotted may not be re-used. If wood materials are not re-used it may instead be recycled or used for energy recovery. (Bokalders & Block, 2010)

2.2.2 Bricks

Due to the large number of bricks in the building, they are specifically highlighted. A Danish company, Gamle Mursten, has a cleaning facility for bricks. The company is strictly commercialised with no financial support from the government. The company cooperates with architects in the design phase of new buildings. The architects favour the aesthetic traits and historical value of the re-used bricks. (Gamle Mursten, 2012)

When the bricks are re-used they may be demolished conventionally by an excavator and then it is possible to clean the brick and use them again in a new building. A vibrational process is used where the mortar falls of the bricks. Gamle Mursten are able to re-use 50 percent of the bricks in a building, however if the excavator drives on the bricks presumably only 25 percent of the bricks may be re-used. Sides Zimmerman[2] states; “At the moment Gamle Mursten only has the possibility to clean bricks with lime mortar. The cement mortar is harder than the bricks, thus the bricks will break in the vibration process.” However, there is a process to remove cement mortar, yet it is not commercialised. Mulder et al. (2007) have conducted an experiment where the masonry debris is heated to 540 °C. At this temperature the cement based mortar is mechanically and chemical separated from the bricks. In *Appendix C.* an estimation of the energy required to heat the bricks to 540 °C is made. The thermal processes in Mulder et al. methods are fuelled by the combustible fraction of waste, which is defined in their study as wood, plastic, paper and bituminous roofing material.

It is significant to distinguish between facade and interior bricks. Interior bricks are best suitable for interior and are not suitable for outdoor use as facade bricks. The bricks may be damaged due to for example: frost, mechanical influence or contaminates. If bricks are re-used as load carrying structure it is important that the compressive strength of the stones is assessed. When re-using bricks it is significant that they are of sufficient quality such as that they do not have pieces of old mortar or that the pores are not contaminated. If the bricks are of insufficient quality the adhesion between them will be weakened. (Persson-Engberg et al. 1999)

The Swedish standard for bricks (Svensk standard SS 22 2104) has several requirements outlined below;

- dimensions
- bulkiness
- apparent density (bulk density)

[2] Sidse Zimmermann (Employee at Gamle Mursten) email on May 10 2012.

- compressive strength
- frost resistance
- moisture composition

In order for bricks to be re-used they must meet the same requirements as new produced bricks. However, Persson-Engberg et al. (1999) stresses that the requirements for re-used bricks should be limited to compressive strength and frost resistance. Bricks may be re-used in non-load carrying walls or as flooring. (Persson-Engberg et. al. 1999)

2.2.3 Markets for re-use

In Sweden there are retailers, re-use traders, which sell re-used construction and demolition material. An example of a re-use trader is Kretsloppsparken in Gothenburg which offer a wide range of materials, to mention a few; sanitary porcelain, bricks, floor tiles and windows. Kretsloppsparken is supported by financial aid from the municipal government. The re-use trader, Kompanjonen in Stockholm offers a similar wide range of re-used construction material. However, Kompanjonen does not sell supportive construction materials, such as beams and bricks. Kompanjonen is a profit oriented company with no financial support from the government. The web service Blocket is a market for re-used products, including construction and demolition materials.

2.3 IRCOW

This master's thesis is case study of the project IRCOW conducted by IVL Swedish Environmental Research Institute and 12 other European partners. IRCOW is funded under the EU 7th Framework Programme and IRCOW abbreviates: *"Innovative strategies for high-grade material recovery from construction and demolition of waste"***.** (IRCOW, 2011a)

Construction and demolition waste accounts for 30 percent of the total waste produced in EU. When reducing the amount of produced waste, resources are used more efficiently. Thus, welfare and economy may be improved. (IRCOW, 2011b)

The IRCOW project began in January 2011 and continues for 36 months. The project has several case studies, and one of them is a selective demolition of a building in Sweden. To an extent where it is possible the case study focuses on wood material in the building.

3. The building and its materials

The building is a school built in 1968. At the moment the building is utilized as a school and demolition is planned to proceed in the end of 2012. The school was renovated in 1980 (Sisab, 2011). By studying the drawings of the school it is estimated that the demolition area is 9000 m^2 and the school has three floors.

3.1 Materials evaluated for re-use

When Jacob Lindblom, Michael Joyce and the author visited the building on March 21, 2012 materials were found that may be re-used. Glulam beams, windows and teak doors are chosen since the IRCOW case study is aimed to focus on wooden materials. Note the windows consist of a wooden frame and glass. The large number of windows is economically feasible to selectively dismantled and sell according to Michael Joyce. He also stresses that ceiling tiles, steel doors, security bars and sinks are easily dismantled and may be sold again. The facades of the building consist of brick, therefore due to the large amount of brick this is chosen. Below the studied materials are listed:

- Glulam beams
- Windows *see Figure 3.1*
- Teak doors
- Bricks
- Steel doors *see Figure 3.2*
- Ceiling tiles *see Figure 3.3*
- Security bars *see Figure 3.1*
- Sinks

Figure 3.1 Security bars and windows.


Figure 3.2 Steel door


Figure 3.3 Ceiling tiles.

3.2 Materials not evaluated for re-use

Other materials that may be re-used were found in the building during the inventory, yet these are not assessed in the study. The main reason why these materials are excluded is because the study is limited in terms of time and available data.

The supportive structure of the building is concrete beams. Since, there is no conventional method for dismantling and re-using concrete beams they are excluded. In addition, there is no standardised guarantee that a re-used concrete beam will have the same support properties in terms of strength as a newly produced concrete beam. At the moment there are no existing test methods to evaluate if a re-used material has the same compressive strength as a newly produced construction material.

The interior wooden doors and sanitary porcelain were of insufficient quality to be sold and re-used. It is assumed that there is little economic feasibility in dismantling the floor tiles piece by piece according to Michael Joyce.

Materials present in the building which are not chosen to be assessed for re-use potential;

- lamps
- concrete beams
- interior wood doors
- sanitary porcelain
- floor tiles
- roof
- linoleum floors.

3.3 Material inventory of the building

At the visit to the building on March 21 an evaluation of what materials may be re-used was done. The amount of re-usable material is normalised to the functional unit, one piece of demolished school, and presented in the *Table 3.1*.

Table 3.1 Amount of material considered in the building

Material	Amount tonnes/one demolished school
Glulam beam	2.5
Windows	19
Teak doors	0.4
Steel doors	0.35
Ceiling tiles	0.075
Bricks	605
Security bars	2.1
Sinks	0.024
Total	$6.02*10^3$

4. Life Cycle Assessment

In this section the goal and scope of the LCA is stated. The limitations and assumptions are explained.

4.1 Goal and scope

The goal is to assess construction and demolition waste from a life cycle perspective. Two alternatives for demolition are studied, conventional and selective demolition:

1. Conventional demolition – investigate how a building is demolished today. The construction and demolition waste will have different waste management:
   - Material recycling
   - Energy recovery (incineration)
   - Landfill

2. Selective demolition – material that may be used again is dismantled and re-used. The waste management are:
   - Re-use
   - Material recycling of brick

Only materials affected by re-use are included.

4.1.1 Functional unit

The study aims to assess the life cycle of demolition of a building, which is a school. Thus, the function is a demolished building. The functional unit is "one demolished school". All data in the life cycle are normalised to "one demolished school".

The school built in 1968 and located in Tensta, Stockholm. The supportive structure is concrete beams and the facades consist of bricks. The demolition area is estimated to 9000 m^2.

4.1.2 Environmental impact categories

The following impact categories are included in the LCA: eutrophication, acidification, ground level ozone creation, global warming and primary energy demand. These categories are chosen because, they are well established and the data quality is sufficient in these categories. For instance, toxicity is not included due to the low quality of data available in this category. The characterization method used is CML 2001, version December 2007 (University Leiden, 2012).

4.1.3 System boundaries

System boundaries are from the building ready for demolition, including the demolition, the waste management and the re-used material at the retailer. System expansion is utilised to include the alternative production of materials and energy. The waste management is considered for the materials;

- Glulam beam

- Windows
- Teak doors
- Brick
- Steel doors
- Ceiling tiles
- Security bars
- Sinks

The top down model consists of conventional and selective demolition and is presented below.

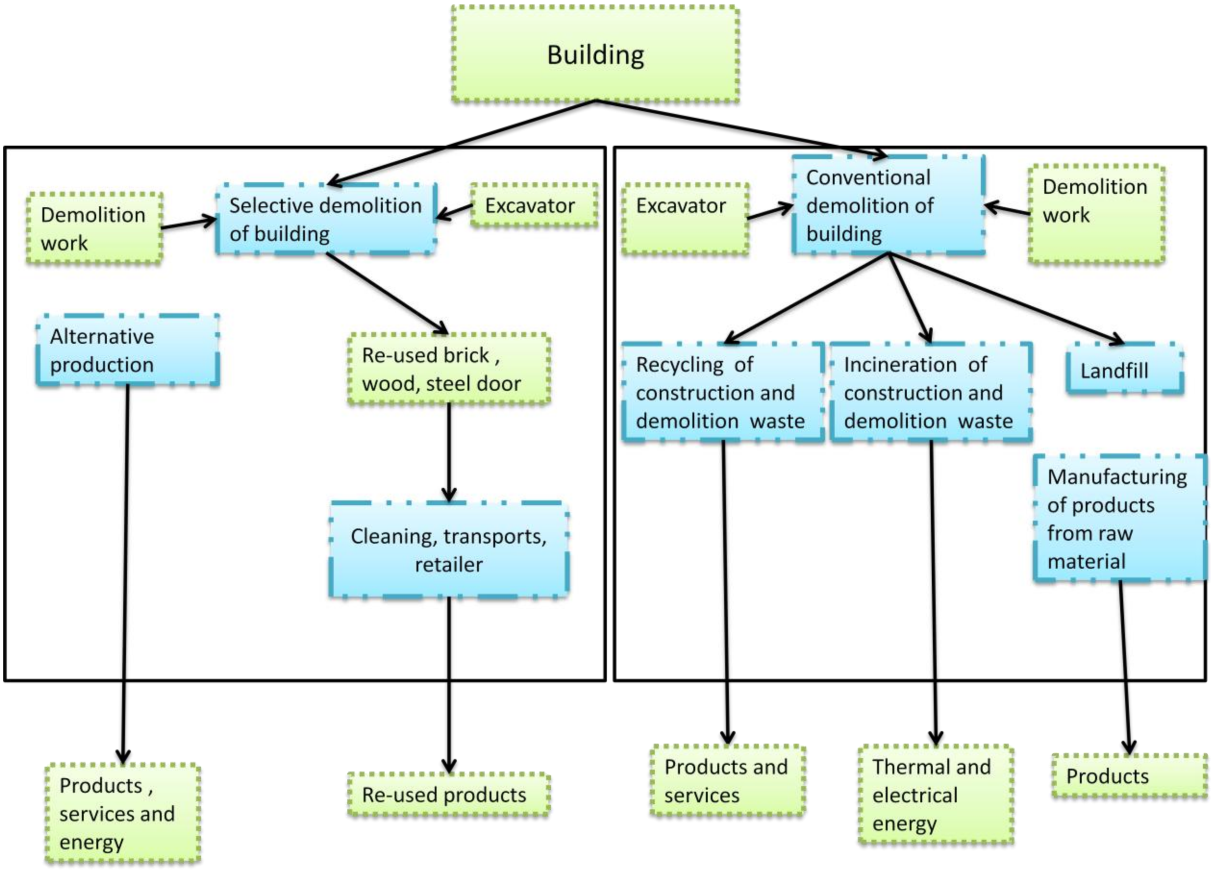

Figure 4.1 Flowchart of the two demolition cases. Processes are represented with blue colour (dashed and dotted border) and products with green colour (dotted border).

The "Alternative production" is included to make a system expansion. For example, when wood is removed from the building it is re-used and not incinerated to produce thermal and electrical energy. Hence, alternative production of thermal and electrical energy is included.

"Manufacturing of products from raw material" is included to make a system expansion. The re-used products are compared to products manufactured from conventional raw material. Aspects that are evaluated are avoided emissions, energy consumption and resource use. Note, conventional raw material may be a mixture of recycled material and virgin raw material depending on what product is manufactured. To exemplify, in the production of steel 50 percent of the material is from recycled steel and 50 percent is from virgin iron ore and coal. On the other hand, in the production of glulam beams the wood is from virgin spruce.

The energy needed to demolish the building is referred to as demolition work and it is supplied by an excavator. The same amount of demolition work is assumed to be the used in the selective and the conventional alternative, hence the demolition is set to zero in the model. The demolition work is an estimated figure, used as a comparison in the discussed section. Below in the section demolition work plan it is further explained what demolition work is and how it is calculated.

4.2 Limitations and general assumptions

When the LCA is conducted several limitations and assumptions are made to simplify the calculations and cover data gaps. All data is given and calculated according to the SI system.

4.2.1 Geographical limitations

The geographical system boundary is Sweden. Aspects of demolition and construction waste in other EU countries are not assessed. The waste management in Sweden is considered and not in other countries. Yet, to make the necessary system expansion the following processes in other countries will be included:

- Transports of construction material imported to Sweden.
- Electricity consumption in Sweden imported from other counties.
- Production of goods abroad used in Sweden.

4.2.2 Assessed construction and demolition materials

The amount of analysed re-used products in the building is limited to eight, due to time limitations and that a brief material inventory was conducted.

The life length of a re-used product is assumed to be of the same life length as a product produced from conventional raw material. This simplification is made to be able to compare a re-used product with a new product produced from raw material. Moreover, the re-used products are estimated to have the same material composition as corresponding materials produced today, even though the products in the building were produced during the 1960's.

The materials studied in the selective and conventional demolition alternatives are assumed to be of the same amount. To exemplify, if 2.5 tonnes glulam beams are selectively dismantled and re-used, it is assumed the same amount of glulam beams are incinerated to utilize energy in the conventional alternative. This assumption applies for all the materials except for the bricks. In selective demolition only 50 percent of the bricks are assumed to be re-used while 50 percent is recycled to backfilling material.

4.2.3 Hazardous material

It is not yet decided when the building will be demolished. As a consequence, it is not possible to conduct an environmental inventory within the time frame of this master's thesis. It is a legislative requirement that an environmental inventory must proceed before the building is allowed to be demolished. Therefore, hazardous materials in the building are not assessed in the study. Additionally, if a thorough investigation did proceed, a demolition expert might have recommended that more materials may be re-used than the ones assessed in this study. To add, a demolition expert could have helped determine the quantity of each material present in the building. Consequently, assumptions are made about the amount of re-useable materials in the building.

5. Description of the model

A detailed description of the model proceeds to show the life cycle of the demolished building. Specific assumption and simplifications regarding each process are explained.

5.1 Gabi software

Processes, flows and plans, in Gabi are used to construct a model where the aim is to represent a selective and conventional demolition. A process is for example production of diesel, brick or incineration of wood. Processes have inputs, for instance crude oil, as well as outputs, such as diesel and carbon dioxide. Flows connect the processes to each other, for instance energy and weight of cargo. Finally, plans are where the processes and flows are incorporated to flowcharts. Plans may be connected to one another. In figures below, the white boxes with black boarders are plans, the green boxes with dotted boarders are products, the blue boxes with dashed and dotted boarders are processes and the purple arrows are flows.

5.2 Data collection and data gaps

The LCA data is collected from; Gabi databases, literature and from the inventory of the building. Transport distances are found by using Google road directions function. In the model cargo is transported by the readymade process representing a truck with European environmental standard 4. If the cargo is not transported by this process it is stated. If a transport distance is unknown due to data gaps, the transport distance is assumed based on experience and what seems reasonable.

5.3 Demolition plan

The school is either selectively demolished or conventionally demolished. The reference flow is the demolished building, the school. Thus, the functional unit is “one demolished school”.

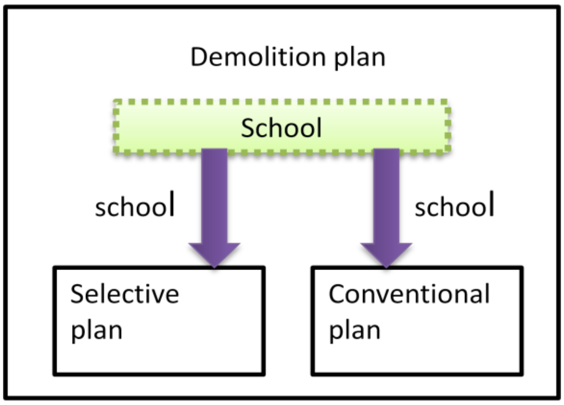

Figure 5.1 Demolition plan

5.4 Selective plan

The school is selectively demolished and the materials are selectively dismantled without breaking.

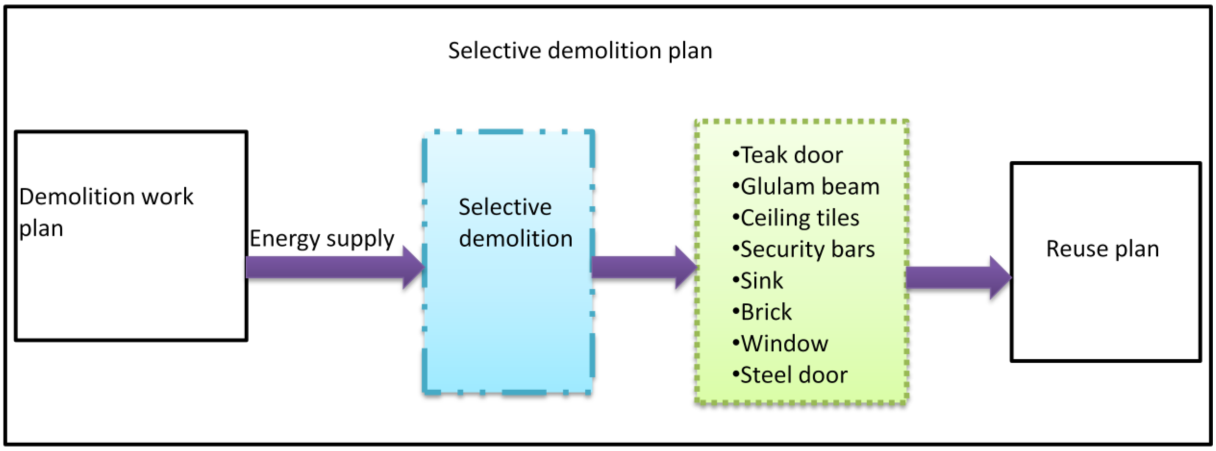

Figure 5.2 the selective plan. The products glulam beams, wooden windows, teak doors, brick, steel doors, ceiling tiles, security bars, sinks are selectively dissembled and re-used.

5.4.1 Re-use

The selective plan is connected to the re-use plan. The wooden windows, teak doors, steel doors, ceiling tiles, security bars and sinks are assumed to be transported, 26 km by trucks, to the retailer of re-used products, Kompanjonen.

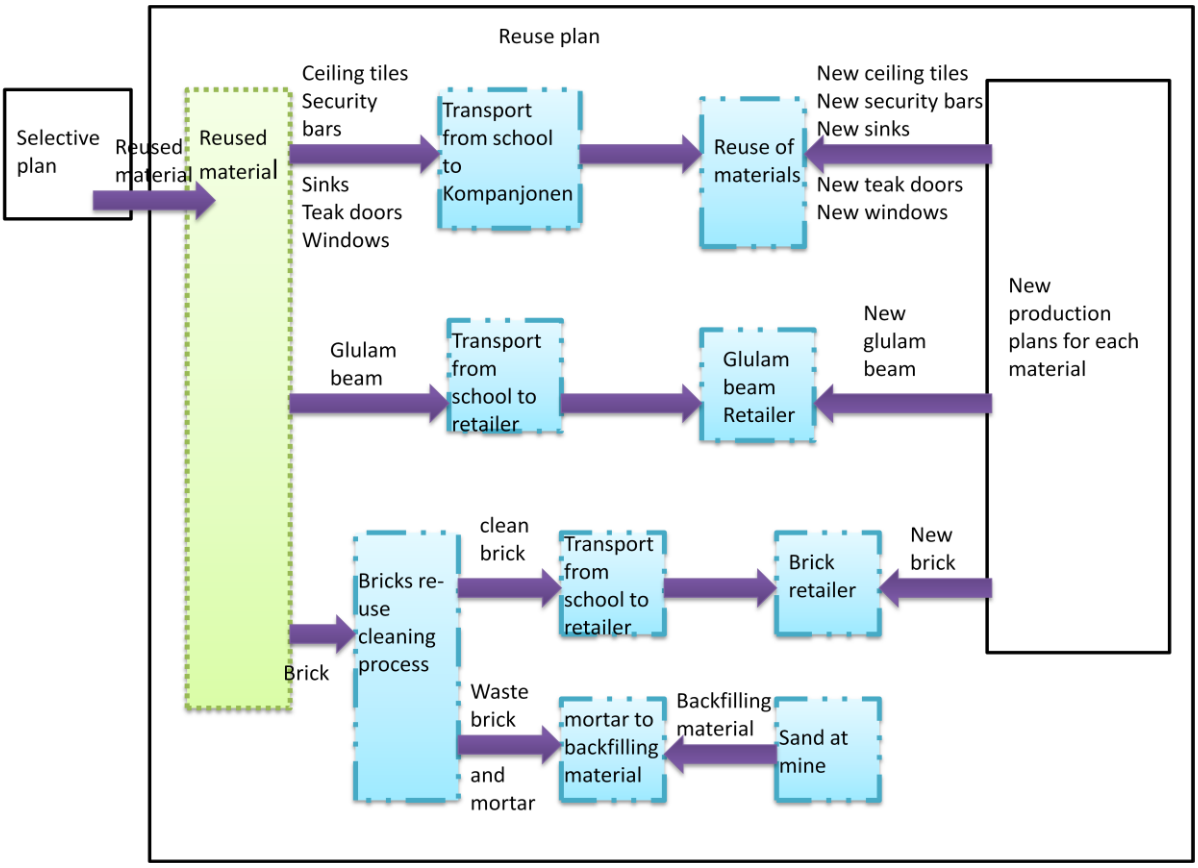

Figure 5.3 the reuse plan. The diesel transport plans to supply the trucks with diesel are not shown in the figure.

The aim of the new production plans is to represent the building and construction products produced from conventional raw materials. Note, as stated in the section “system boundaries” conventional raw materials include both virgin and recycled materials.

The arrows pointing to the left in the in the figure illustrate the system expansion which includes the production of goods from conventional raw material. The resource use and environmental impact of producing a product from raw material is subtracted from a re-used material.

In the “Bricks re-use and cleaning process” it is estimated that 50 percent of the bricks may be re-used (Gamle Mursten, 2012). The eventual environmental impacts, specifically, energy use and emissions, to clean the bricks from mortar are neglected. The simplification is made due to data gaps and at the moment no existing commercial method to remove the cement mortar from bricks. Yet, suppose a commercial method did exist, the bricks are cleaned at the demolition site and transported to a retailer in the Stockholm region. The distance from the school to a retailer of re-used brick is assumed to be 50 km by truck.

The separated mortar and broken bricks are produced to backfilling material at the demolition site. To make the necessary system expansion the readymade Gabi process for sand production (Ecoinvent, 2008) is subtracted from the process of making “mortar to backfilling material”. This is done to compensate for the backfilling material that would otherwise have been added to the area. The eventual transports of this procedure are neglected, because they are assumed to cancel out.

The glulam beam is transported, 50 km from the school to a retailer. In a similar way, as explained above, the production of a glulam beam from virgin raw material is subtracted from the re-used glulam beam.

5.4.2 New production of each material

Due to data gaps and time frame limitations simplifications are made in the plans representing the production of goods from virgin raw material. In general, energy in some parts of the production and the energy to pack the materials are neglected.

5.4.2.1 Production of new windows

According to a building product declaration from Elitfönster windows consist of 62 weight percent glass, 29 weight percent spruce and 9 weight percent other material which includes galvanized steel, titanium dioxide, PVC, polysulphide and EPDM-rubber (Elitfönster, 2007). In the model the new windows are assumed to have this composition.

The windows are covered in white paint. Due to a lack of data for white paint in the IVL database a process producing white spirit is used (Ecoinvent, 2008). White spirit, is an organic solvent used in paints.

The wood, paint and window glass are transported from respective production site to Edsbyn where there is a manufacturing facility of windows (Svenska Fönster, 2012). The transportation distances are estimated to 1000 km from the glass and the paint production site to Edsbyn. The wood is transported 592 km from Vimmerby sågverk to Edsbyn.

Lastly, the paint, glass and wood are present at the window manufacture plant in Edsbyn. At the plant the energy, emissions and waste produced are neglected. As stated above, apart from wood and glass, the window consists of 9 weight percent other material. In the model the paint, galvanized steel, titanium dioxide, PVC, polysulphide and EPDM-rubber are aggregated to 9 percent other material to simplify calculations in the model. Finally, the “new window production” plan has an outflow of a new window produced from raw material.

5.4.2.2 Production of new teak doors

The doors in the existing building are made from teak. Producing teak doors have a negative environmental impact on the rainforest, which is today publicly known. A more environmentally preferable door is made of oak. Both oak and teak are classified as hard wood which are suitable construction materials.

Due to a lack of data oak wood production, a general process for hard planed wood is chosen. The life cycle is assessed from the seed, to the saw mill and planing, including drying the wood to a moisture content of 10 percent. The oak wood is assumed to be produced in Sweden and transported 500 km by truck to a retailer of oak doors in Stockholm.

5.4.2.3 Production of new steel doors

The steel doors are modelled as Dalocs S60 Steeldoor consisting of steel sheets and isolation of mineral wool. Dalocs S60 Steeldoor is chosen because it is one of the most common steel door on the market. It is assumed that the door consists of 20 percent mineral wool and 80 percent steel.

The Gabi process representing the steel production comes from industry data, and includes emissions and energy use from cradle to factory gate. The steel sheet production is assumed to be in Oxelösund, Sweden. The door is manufactured in Töreboda, Sweden (Daloc, 2010). The steel sheet is transported 228 km by truck from Oxelösund to Töreboda.

As mentioned above, the door consists of mineral wool. However since there is a lack of mineral wool data, the mineral wool is assumed to be rock wool (ELCD/PE-Gabi, 2010). These products are fairly similar. The mineral wool is produced in Askim, Norway and transported 283 km by truck to Töreboda.

In the activity, where the steel and mineral wool are constructed into a door simplifications are made due to data gaps. These simplifications are the following;

- energy to manufacture the door is neglected
- the expected environmental impact of the manufacturing activity
- other products such as, glue to adhere the steel sheets to the mineral wool, are neglected.

5.4.2.4 Production of new ceiling tiles

The ceiling tiles consist of glass wool and are assumed to be produced at the same production site as the mineral wool used in the steel door. They are transported 471 km by truck from Askim, Norway to Stockholm. The energy to cut the glass wool into ceiling tiles is neglected, due to data gaps.

5.4.2.5 Production of new security bars

The security bars are assumed to be produced from steel galvanised with zinc. The Gabi process represents a cradle to gate inventory of galvanised steel (ELCD/PE-Gabi, 2010). It is estimated that the transport distance from the steel plant to the security bar manufacturing is 100 km by truck. The energy and expected environmental impact to manufacture the security bars are neglected due to data gaps.

5.4.2.6 Production of new sinks

The sinks consist of stainless steel (Onninen, 2012). A process in Gabi represents the production of stainless steel from cradle to gate (ELCD/PE-Gabi, 2010). The steel is assumed to be transported, 100 km by truck, from the stainless steel plant to a sink manufacturing plant which is represented by a process producing an average steel product.

5.4.2.7 Production of new bricks

The production of bricks is represented by a process in Gabi where the raw material acquisition and manufacturing, is considered. Further described in the results and analysis section the bricks are of great importance for the results. Therefore, two production cases of bricks are constructed.

In the original case the bricks are produced in Europe. The electricity input to produce the bricks comes from coal, crude oil and natural gas (The Visegrad Group, 2012). The bricks are assumed to be transported 1000 km by truck from the production plant in Europe to Stockholm.

In the other case the bricks are assumed to be produced in Sweden. The electricity supply is a Swedish composition, mainly made up of hydro and nuclear power. The bricks are assumed to be transported 100 km by truck.

5.4.2.8 Production of new glulam beams

The modelled glulam beam consists of 99 weight percent spruce and 1 weight percent MUF glue (Gross & Fröbel, 2007) (Erlandsson, 2009). The process used to represent spruce for the glulam beam is a process representing planed soft wood (Ecoinvent, 2008). The process includes the life cycle of a tree from a seed to sawn wood and planing. The drying activity of wood to a moister content of 10 percent is included in the process.

Since, there is a data gap of MUF glue a similar process is chosen. It is a process where urea formaldehyde foam is produced which MUF glue mainly consists of (Gross & Fröbel, 2007).

The planed wood and the MUF glue is estimated to be transported 500 km each by truck to a manufacturing plant of glulam beams. The energy and expected environmental impact at the manufacturing plant are neglected. Additionally, the presumed environmental impact of the protective coating that covers the glulam beam is neglected.

5.5 Conventional plan

The school is conventionally demolished. At the demolition site material is sorted as follows; materials consisting of wood are put in one container, steel materials in a second container, inert materials in a third container and bricks are crushed to backfilling material. *See Figure 5.4.*

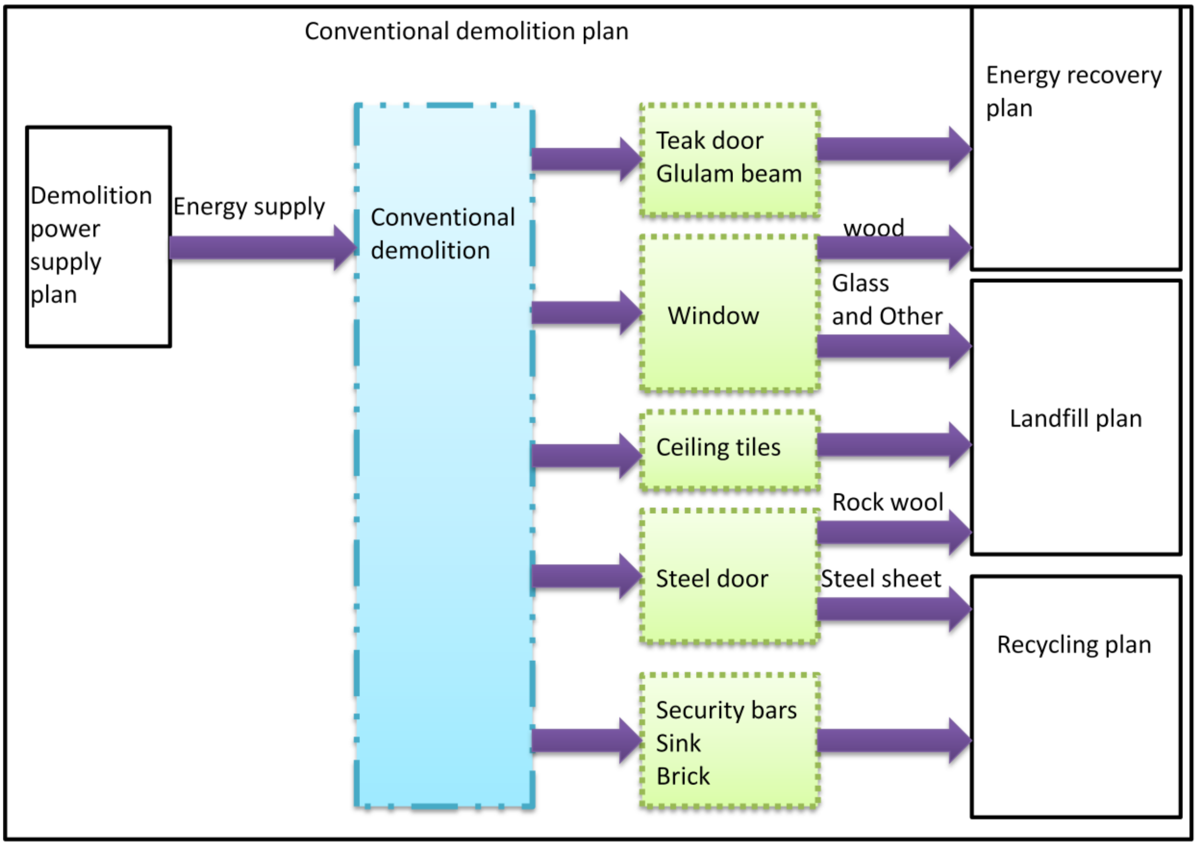

Figure 5.4 conventional demolition plan.

The energy demand to separate the parts, steel sheet and mineral wool, in the steel door is neglected. Similarly, the energy demand to separate the windows different parts, wood, glass and other, is neglected. As explained above, 9 weight percent of the window is other material, including galvanized steel, titanium dioxide, PVC, polysulphide and EPDM-rubber (Elitfönster, 2007). It is assumed that the 9 weight percent other material goes to landfill.

5.5.1 Energy recovery plan

The wooden materials are assumed to be transported 8.3 km by truck from the school to Hässelbyverket, a combined heat and power plant located in Stockholm.

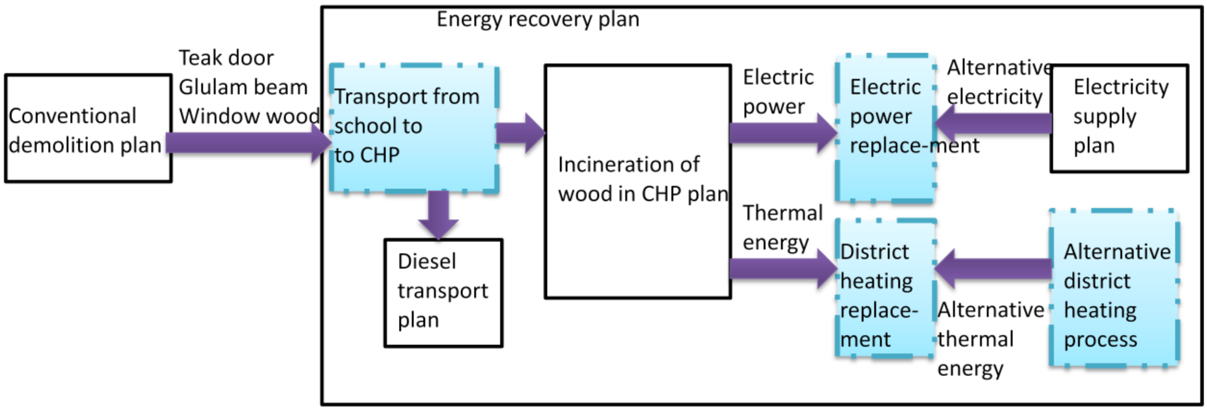

Figure 5.5 Energy recovery plan.

The "Incineration of wood in CHP" plan *in Figure 5.5* includes a processes incinerating untreated wood. The treated woods; teak doors, window and glulam beam are assumed to be incinerated in this process. The fact that the wood is treated is neglected. Furthermore, the "Incineration of wood in CHP" plan also has inflows consisting of several chemicals such as ammonia, sodium hydroxide and lime. The outflows of the plan are electric power and thermal energy in the form of steam.

To be able to assess the electric power produced from the wood in the building, a negative flow of alternative electric power is included (arrow pointing to the left). In the same manner, to be able to assess the thermal energy produced from the wood in the building an alternative district heating process is subtracted from it.

5.5.2 Landfill plan

As illustrated in *Figure 5.4* of the Conventional plan; the ceiling tiles, mineral wool from the steel door and other material from the windows are inflows to the landfill plan. In the landfill plan the materials are transported, 18.8 km by truck, to a landfill located in Upplands Väsby (D.A. Mattsson AB). A readymade process in Gabi represents the landfill (Ecoinvent, 2008). The emissions from the landfill are neglected, they are considered to be relatively small for the environmental impact categories considered.

5.5.3 Recycling plan

In the recycling plan the bricks are assumed to be recycled into backfilling material at the demolition site. To account for the potential environmental gain of recycling the bricks, a readymade sand process in Gabi is subtracted from the recycled bricks.

The three steel materials (the steel sheets of the doors, the security bars and the sinks) are transported 452 km by truck, to a steel recycling facility located in Nybro (Stena Stål). Ideally, the recycling process for the stainless steel, containing chrome, and the recycling process of the chrome free steel differ. However, to simplify the model the three steel materials are recycled in the same facility. Furthermore, a process representing steel in Gabi is subtracted from the recycled steel to account for the potential environmental gain.

5.6 Electricity supply plan

The electricity supply plan is used both in the selective and conventional demolition alternative. The electricity outflow of the plan may be varied between Swedish composition, hard coal and natural gas. The Swedish composition is mainly nuclear and hydro power. The hard coal and natural gas comes from Danish power plants.

5.7 Demolition work plan

Energy is needed to demolish the building and it is referred to as demolition work. The demolition work is performed by an excavator using diesel. It is assumed the same amount of energy is needed to either selectively or conventionally demolish the building. *Figure 5.6* shows how the demolition work is modelled in Gabi:

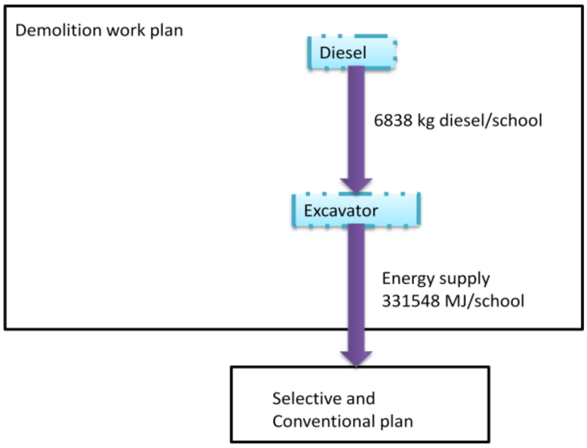

Figure 5.6 In Gabi the energy to demolish the building is modelled as the plan "demolition work" and connected to it is the selective and conventional plans.

The energy supply, 331548 MJ/school, estimation is based on Gustavsson L. et al. (2010) results of a LCA of a building where they assume demolition accounts for 10 kWh/m^2 building primary energy. Gustavsson et al. (2010) assume that the energy is consumed as diesel fuel. Hence, the same assumptions regarding energy use to demolish the building are made in the study. Since, 1 kWh is equivalent to 3.6 MJ, this equates the primary energy of demolition to 36 MJ/m^2. By studying the drawings of the school it is estimated that the demolition area is 9000 m^2. Thus, the energy supply to demolish the building should correspond to approximately $36 * 9000 = 324000\ \mathrm{MJ/school}$. This is confirmed by demolition employee, Börje Åbinger[3] who proposes an excavator operates 240 hour to demolish the building. The calculation is further explained in the appendix.

When finding the results of the LCA the demolition work inflow to the selective and conventional demolition plans are set to zero. It is assumed the amount of energy required to either demolish the building selectively or conventionally is the same. This assumption is made due to that the facades of the building, the bricks, are demolished by an excavator in the same way for both conventional and selective demolition. The calculated demolition work is used as a comparison to the results in the discussion and conclusion section.

[3]Börje Åbinger (employee at demolition company Globax AB) contacted via telephone on May 15, 2012

5.8 Calculation methods

The following calculation methods were used to estimate the amount of material in the building. The data was used in the plans. The amount of materials considered in the study is presented in *Table 3.1*.

5.8.1 Windows

By studying construction drawings of the building, the number of windows is found to 558 pieces. According to Elitfönster (2007) a whole window including window frame and glass weighs 34 kg. Hence, the total mass of the windows is: 18972 kg.

5.8.2 Security bars

On the entrance floor of the building there are a total of 104 windows, which all have security bars. Due to data gaps, the weight of one security bar is estimated to 20 kg. The total mass of bars is: 2080 kg.

5.8.3 Steel doors

The school has five steel doors and one steel door weighs 70 kg (Daloc, 2010). The total weight of the steel doors is 350 kg. The door frame and other material contributing to the weight of the doors are neglected. The materials that are considered in the doors are the steel sheets of the doors and the insulation material, mineral wool, inside the doors. As stated in the plan for new production of steel doors the assumption is made that the door consists of 80 percent steel and 20 percent mineral wool. As a result the total amount of steel in the doors accounts to 280 kg and the total amount of mineral wool accounts to 70 kg in the doors.

5.8.4 Glulam beams

By studying construction drawings of the building the amount, 6 pieces, and dimensions of a glulam beam are found. The density is 380 kg/m^3 (Gross & Fröbel, 2007).

$$V_{glulam\ beam} = 10 * 0.667 * 0.165 \qquad (1)$$

$$V_{glulam\ beam} = 1.10055\ m^3$$

$$m_{glulam\ beam} = 6 * 1.10055 * 380 \qquad (2)$$

$$m_{glulam\ beam} = 2509.254 \approx 2500\ kg$$

5.8.5 Bricks

The surface area, 2900 m^2, of the building is found by studying the construction drawings. A normal sized brick has dimension 250x120x62 mm (Beijer Byggmaterial, 2012). The density of a brick is 2403 kg/m^3 (SI metric, 2011). The mortar is assumed to be 9 mm on each side of the brick.

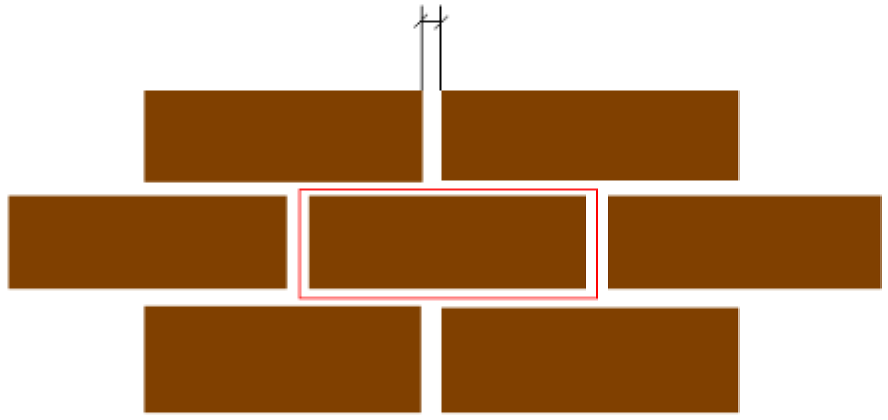

Figure 5.7 The red border shows the mortar.

The area of a brick and a mortar, is given by:

$$A_{red} = (0.25 + (2 * 0.009)) * (0.062 + (2 * 0.009)) \quad (3)$$

$$A_{red} = 0.02144\ m^2$$

$$Pieces\ bricks = \frac{2900}{0.02144} \quad (4)$$

$$Pieces\ bricks = 135261.194$$

$$m_{bricks} = 0.25 * 0.120 * 0.062 * 135261.194 * 2403 \quad (5)$$

$$m_{bricks} = 604560.7\ kg \approx 605 * 10^3\ kg$$

5.8.6 Teak doors

The school has 8 teak doors and one door is assumed to weigh 50 kg. The total weight of the teak doors are 400 kg.

5.8.7 Ceiling tiles

The ceiling of the entrance is estimated to 30 m^2. The area of a ceiling tile is estimated to 0.25 m^2. Hence, the amount of ceiling tiles is assumed to be: 120 pieces. The thickness is 55 mm and the weight per area is 2.5 kg/m^2 (Bullerbekämparen, AB)

$$m_{ceiling\ tiles} = 120 * 0.25 * 2.5 \quad (6)$$

$$m_{ceiling\ tiles} = 75\ kg$$

5.8.8 Sinks

It is assumed the school has 6 sinks in stainless steel. A sink weighs 4 kg (Onninen, 2012). The total weight of the sinks is 24 kg.

6. Results

In this section the environmental impact load is described. Firstly, the results of the total demolition within the system boundaries for the selective and conventional demolition alternatives are presented. Secondly, the results of each material are given.

Generally, the results are presented as a negative value since the system boundaries are given as a building ready to be demolished. The construction and use phase of the building are not included.

The negative values in the results represent avoided environmental impact. Hence, the more negative a result is the more environmentally beneficial process. A positive value represents an environmental load, in other words an environmentally unbeneficial process. Results are given per impact category according to the CML 2001 – version December 2007 standard (University Leiden, 2012).

6.1. Results of demolition including all considered materials

Table 6.1 shows the results of conventional and selective demolition. The system starts at the building ready for demolition, including, the waste management and the re-used material at the retailer. The waste management is considered for the materials; glulam beams, wooden windows, teak doors, bricks, steel doors, ceiling tiles, security bars and sinks.

The difference between selective and conventional demolition is presented. The negative values in the difference column represent avoided environmental impact if selective demolition is conducted.

Table 6.1 Results for one demolished school.

Environmental impact categories	Conventional	Selective	Difference
CML2001 - Dec, 07, Acidification potential (AP) [kg sulphur dioxide equivalents]	-15	-480	-460
CML2001 - Dec, 07, Eutrophication potential (EP) [kg phosphate equivalents]	-2	-66	-64
CML2001 - Dec, 07, Global warming potential (GWP 100 years) [kg carbon dioxide equivalents]	$-3.4*10^3$	$-1.20*10^5$	$-1.17*10^5$
CML2001 - Dec, 07, Photochemical ozone creation potential (POCP) [kg ethene equivalents]	-2	-67	-65
Primary energy demand from renewable and non renewable, resources (net cal. value) [MJ]	$-3.7*10^5$	$-2.0*10^6$	$-1.9*10^6$

6.2 Results of each material

The environmental load per material varies significantly. Of all the materials bricks contribute the most to the large difference between conventional and selective demolition. Likewise, windows are of similar importance, yet not of the same magnitude as bricks. Therefore, the results for each impact category are first presented including all materials. Then the results are presented excluding both bricks and windows.

6.2.1 Acidification potential of each material

Of the materials evaluated in the building, the re-use of bricks results in the greatest avoided environmental load. When selectively demolishing the building and re-using brick 480 kg sulphur dioxide equivalents are prevented from being emitted. This is due to the large amount of bricks in the building, 605 tonnes/demolished school. The process, brick production from raw materials, contributes to a large environmental impact. In the brick production the acidifying substances; sulphate, sulphide and sulphur dioxide are emitted which lead to acidification of soil and water. Additionally, nitrogen oxides are emitted in the production of the bricks which results in acidification.

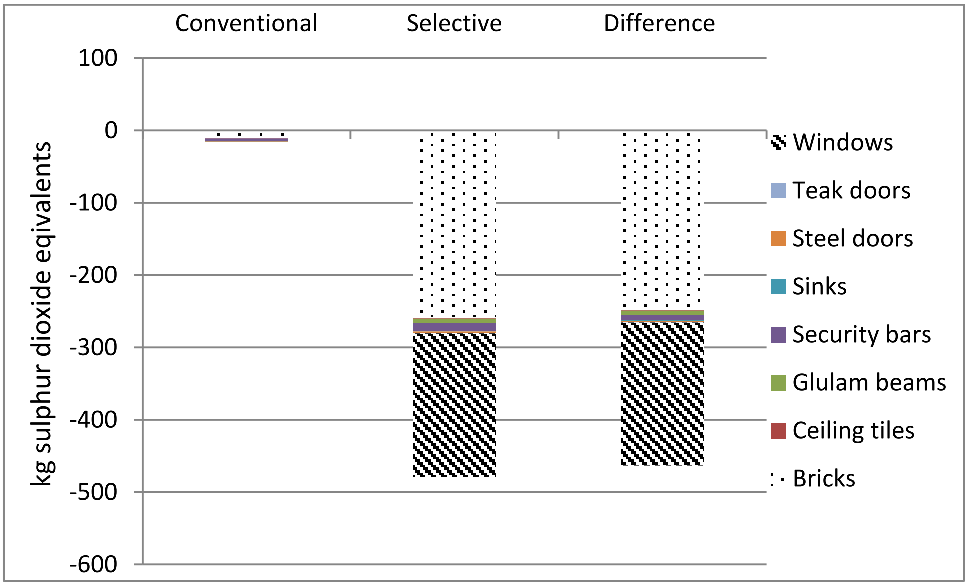

Figure 6.1 Acidification potential for one demolished school.

Re-use of windows is the second most important material after bricks, resulting in a large avoided acidification potential. If windows are not re-used, then new windows are produced from raw material. The production of the window parts, glass and frame emit sulphate, sulphide, sulphur and sulphuric acid. In *Figure 6.2* the results are presented without bricks and windows.

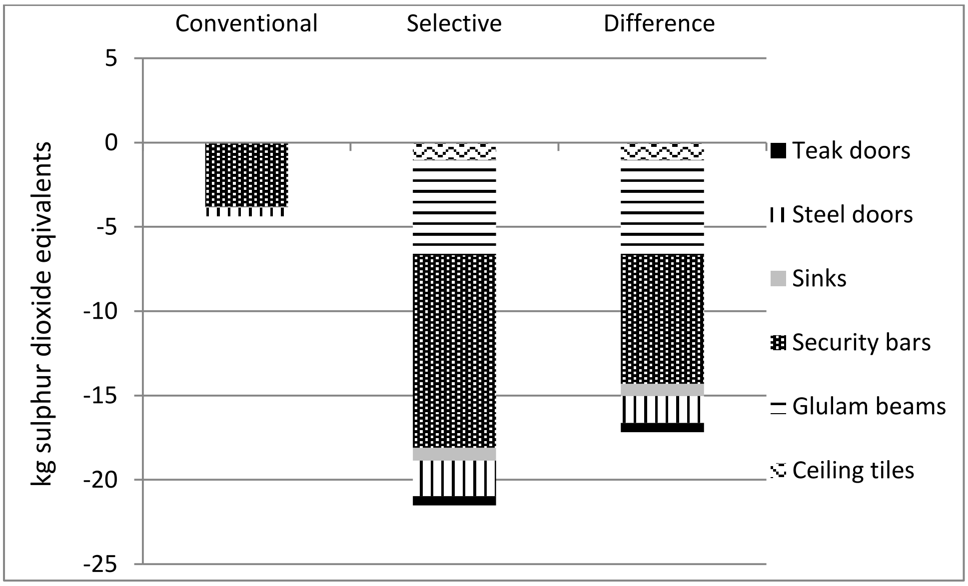

Figure 6.2 Acidification potential excluding brick and windows for one demolished school.

6.2.2 Eutrophication Potential of each material

In terms of acidification potential the production of bricks have the greatest environmental load and the same applies for eutrophication potential. The major eutrophicating substances emitted in the process, production of bricks from raw material are; nitrogen oxides, nitrogen, phosphate and phosphorus.

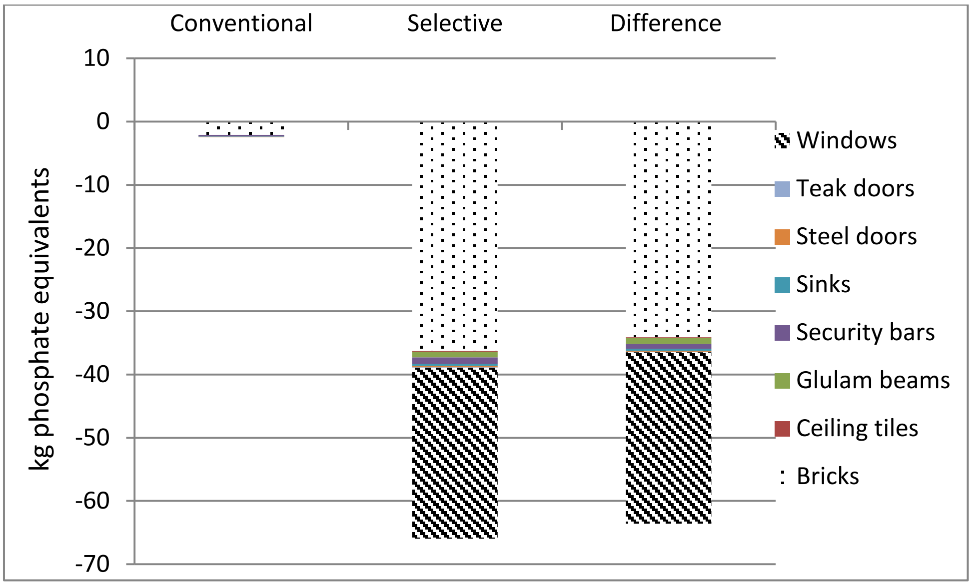

Figure 6.3 Eutrophication potential for one demolished school.

Similar to acidification potential, the greatest avoided eutrophication potential when re-using bricks is achieved, followed by windows. The eutrophicating emissions, phosphate and phosphorus from the window production are avoided when windows are re-used. In *Figure 6.4* the results are presented without bricks and windows.

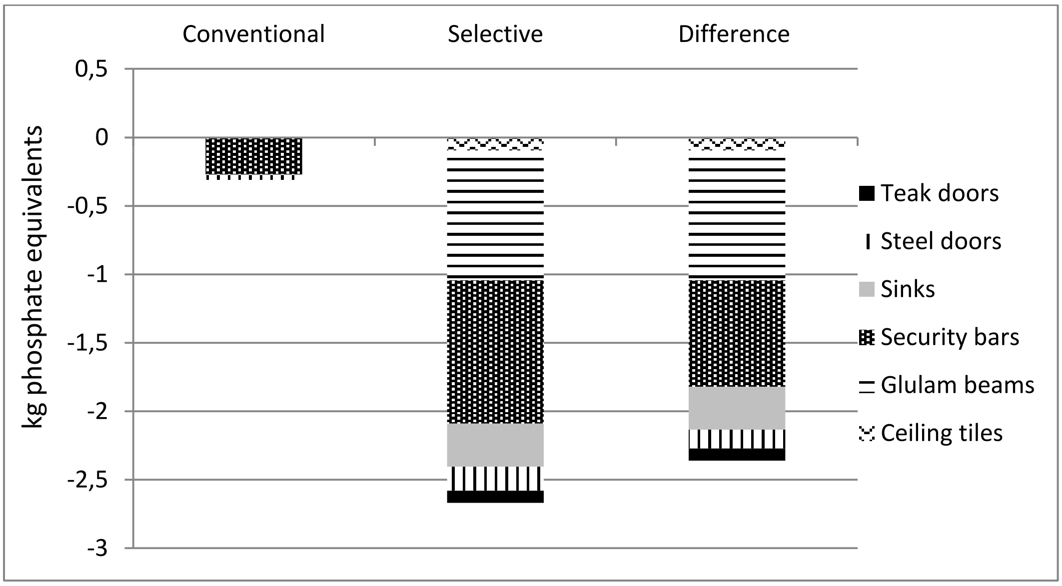

Figure 6.4 Eutrophication potential excluding brick and windows for one demolished school.

6.2.3 Global warming potential of each material

Shown in *Figure 6.5* the bricks contribute to the largest avoided environmental load of global warming potential of the materials. Emissions leading to global warming are avoided when bricks are re-used. In the process, brick production from raw material, the avoided emissions are carbon dioxide, methane, nitrous oxide, sulphur hexafluoride and carbon tetrachloride.

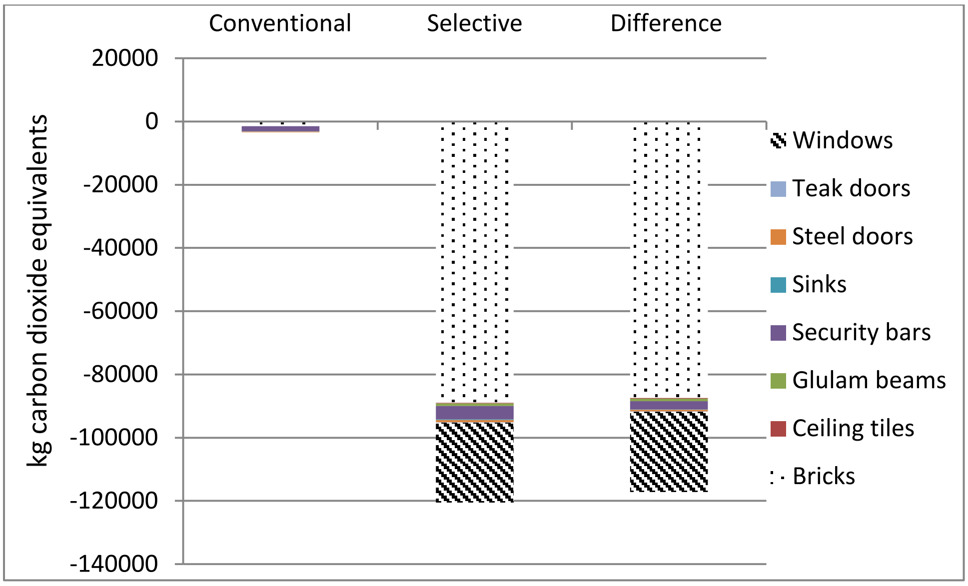

Figure 6.5 Global warming potential for one demolished school.

Below bricks are excluded from the results. Similar, to both eutrophication and acidification potential, windows are the second most dominant in terms of avoided global warming potential. When re-using windows the emissions; carbon dioxide, carbon tetrachloride and methane from the glass and wood frame production are not emitted. Global warming potential without bricks and windows is presented in *Figure 6.6*.

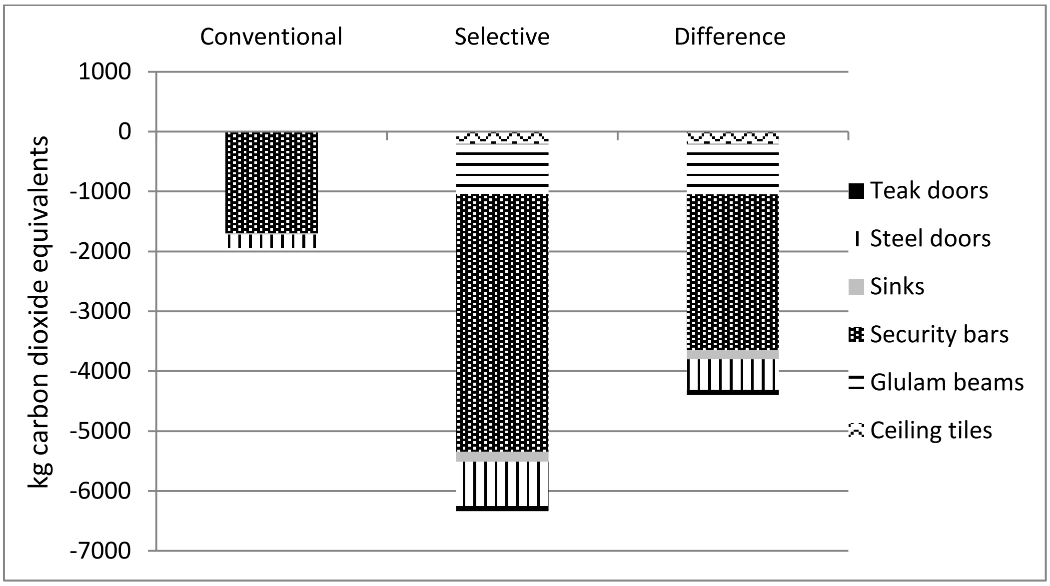

Figure 6.6 Global warming potential excluding bricks and windows for one demolished school.

6.2.4 Photochemical ozone potential of each material

Re-using bricks and not producing them from raw materials results in avoided photochemical ozone emissions.

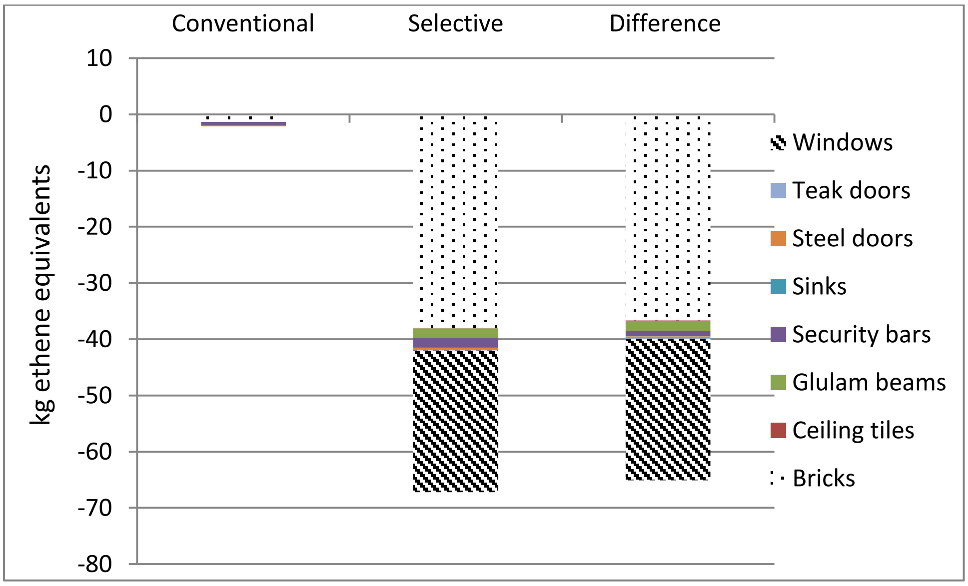

Figure 6.7 Photochemical ozone creation potential for one demolished school.

Re-use of windows are significant in photochemical ozone creation potential, because when producing windows from raw materials emissions causing photochemical ozone are avoided. Photochemical ozone creation potential without bricks and windows are presented in *Figure 6.8:*

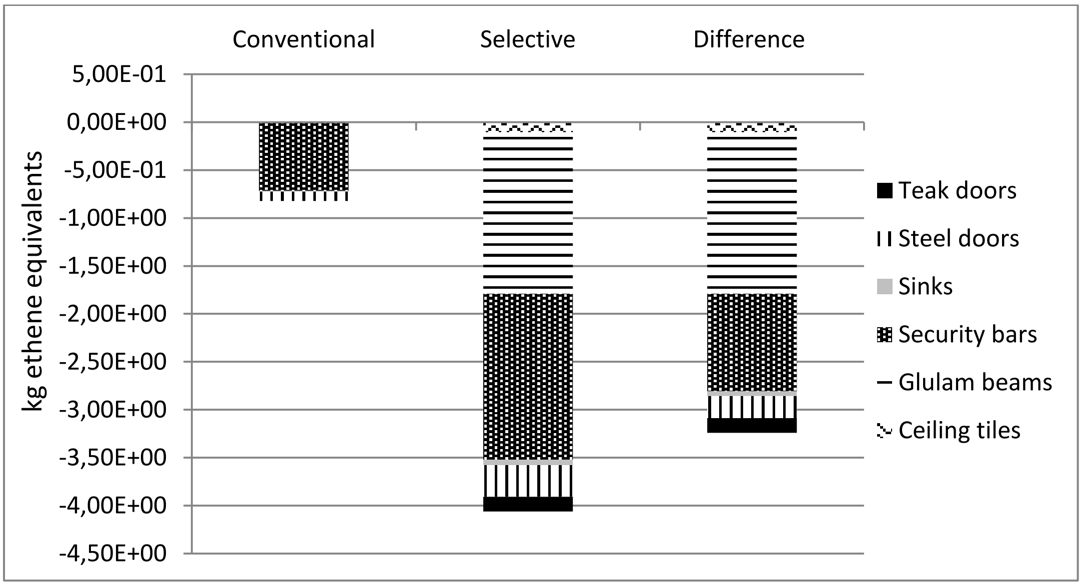

Figure 6.8 Photochemical ozone creation potential excluding bricks and windows for one demolished school.

6.2.5 Primary energy demand

The large amount of bricks results in the great primary energy demand. The primary energy sources are organic substances, wind power and hydropower.

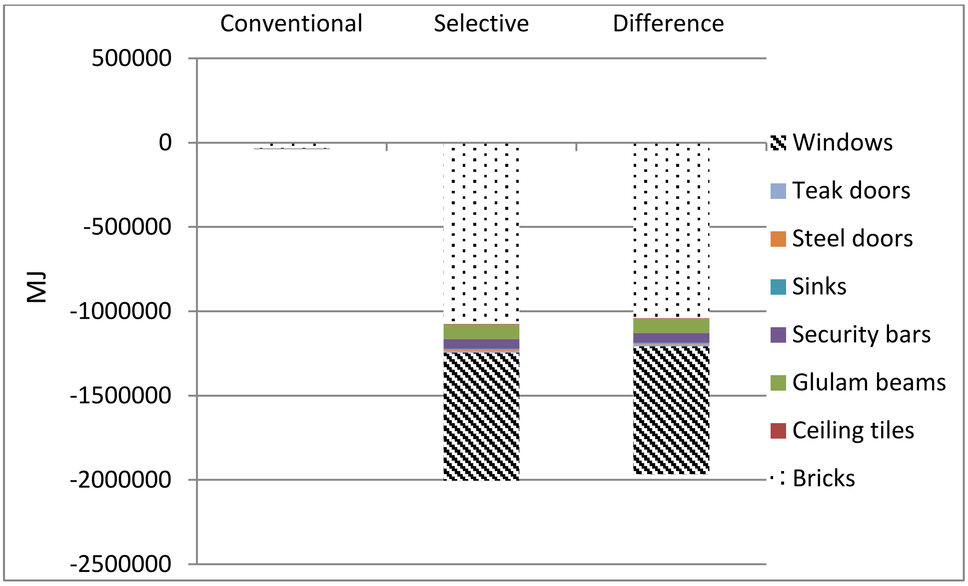

Figure 6.9 Primary energy demand for one demolished school.

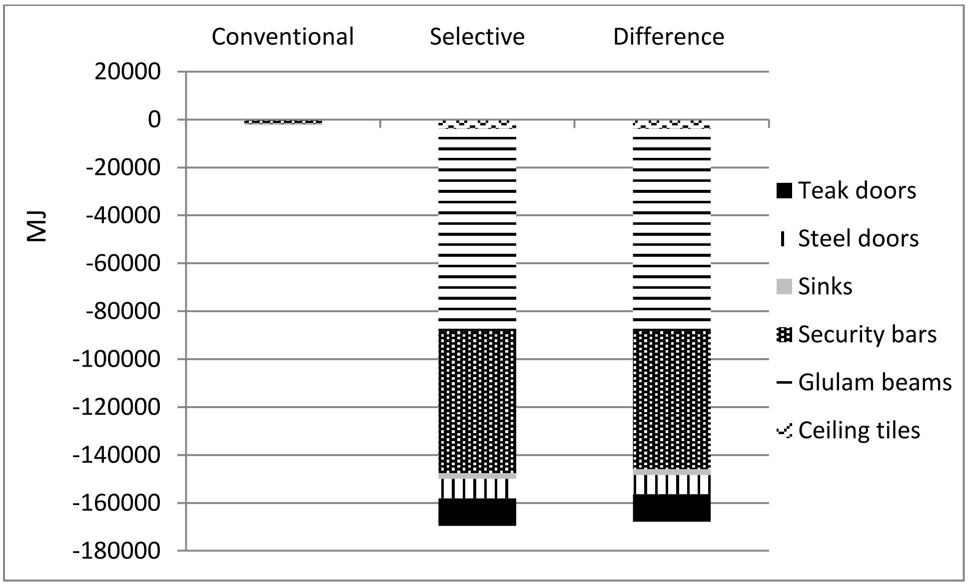

Figure 6.10 Primary energy demand excluding bricks and windows for one demolished school.

7. Analysis of results

To analyse the results a dominance analysis and a sensitivity analysis are performed. The dominance analysis shows which material is dominant and in the sensitivity analysis critical parameters are varied.

7.1 Dominance analysis

The re-use of bricks is highly significant and contributes to the largest difference between selective and conventional demolition. For instance considering global warming potential, bricks results in a difference of $-8.7*10^4$ kg carbon dioxide equivalents (*Figure 6.5*) and the other materials; glulam beams, ceiling tiles, sinks, steel doors and teak doors all result in a difference of approximately $-4.4*10^3$ kg carbon dioxide equivalents each (*Figure 6.6*). After bricks, windows are the second most important material to re-use. In terms of global warming potential, windows results in a difference of approximately $-2.5*10^4$ kg carbon dioxide equivalents (*Figure 6.5*).

7.2 Sensitivity analysis

A sensitivity analysis proceeds to assess two different production cases of brick, produced in Europe or in Sweden. Another sensitivity analysis shows the effect of re-using 25 percent and 50 percent of the bricks. Lastly, a sensitivity analysis is done to evaluate if different sources of electricity have an effect.

7.2.1 Different production cases of bricks

The dominance analysis showed that re-use of bricks is highly significant, hence; two cases of brick production are made to investigate if there is a difference in environmental load. The first case is the original case, where the bricks are assumed to be produced in Europe and transported 1000 km by truck to Sweden. The electricity input to produce the bricks is from coal, crude oil and natural gas. In the other case, bricks are produced in Sweden. The transportation is 100 km by truck. The electricity input to produce the bricks is Swedish composition, mainly hydro and nuclear power. Below the results for global warming potential are presented.

Table 7.1 Sensitivity analysis of bricks for the different cases.

		CML2001 - Dec, 07, Global warming potential (GWP 100 years) [tonnes carbon dioxide equivalents]
	Conventional	-3.39
EU Case	Selective	$-1.20*10^2$
	Difference between Selective and Conventional	$-1.17*10^2$
Swedish Case	Selective	-99.8
	Difference between Selective and Conventional	-96.4
Difference between Cases		-20.7

By replacing the re-used bricks with bricks produced in Europe a greater environmental gain is achieved than in the case with bricks made in Sweden. The Swedish case also results in an avoided environmental load yet not of the same magnitude as the European case. The transportation has a greater effect on the environmental load than the electricity use. This is due to the small amount of electricity used in the model to produce the bricks.

7.2.2 Varying amount of re-used bricks

A sensitivity analysis of varying the amount of bricks is conducted. Gamle Mursten proposes that 50 percent of bricks in a building may be re-used. Yet, if the excavator demolishing the building drives on the bricks and the bricks break, then only 25 percent of the bricks may be re-used.

Table 7.2 Sensitivity analysis of amounts of re-used bricks. 50 percent is re-used compared to if 25 percent is re-used.

		CML2001 - Dec, 07, Global warming potential (GWP 100 years) [tonnes carbon dioxide equivalents for one demolished school]
	Conventional	-3.39
EU Case and 50 percent of the bricks are re-used	Selective	$-1.20*10^2$
	Difference between Selective and Conventional	$-1.17*10^2$
EU Case and 25 percent of the bricks are re-used	Selective	-76.8
	Difference between Selective and Conventional	-73.4
Difference between Cases		-43.7

A more negative value is obtained from the case of re-using 50 percent than the case of re-using 25 percent. The results show that it is more environmentally beneficial to re-use a larger amount than a smaller amount of bricks.

7.2.3 Sensitivity analysis of varying electricity source

A sensitivity analysis is done to vary the electricity supply used in the demolition. The Swedish composition of electricity used in the original case is replaced by hard coal. The sensitivity analysis shows that the results of demolition do not differ significantly depending on which electricity supply is used. This is due to lack of electricity consumption data in the processes in the model. For instance, in the process where the mortar is removed from the bricks there is a lack of energy consumption data. To add, in the manufacturing of the products from raw material there is a lack of data of electricity utilised in the manufacturing plants. The main reason for this is that electricity is an aggregated flow in the data sets used. This means that it is accounted for automatically and one cannot change the type of electricity used.

7.3 Reasonability check

A reasonability check is conducted in the impact category global warming since, the amount, mass of materials assessed in the building have a large effect on the magnitude of the environmental load. Thus, the global warming potential of the difference between selective and conventional is normalised per kg material and the results are presented in *Table 7.3*.

Table 7.3 Global warming potential is normalised per kg.

Material	Global warming potential [kg carbon dioxide equivalents]	Amount of material [tonnes]	Normalised material [kg carbon dioxide equivalents / kg material]
Bricks	$-8.7*10^4$	605	-0,14
Ceiling tiles	-200	0.075	-2,7
Glulam beams	-840	2.5	-0,34
Security bars	-2600	2.1	-1,3
Sinks	-150	0.024	-6,1
Steel doors	-510	0.35	-1,5
Teak doors	-87	0.4	-0,22
Windows	$-2.5*10^4$	19	-1,3

Table 7.3 shows that generally the avoided environmental load of re-using building materials is 0-2 kg carbon dioxide equivalents per kg material. A similar value of 0-2 kg carbon dioxide equivalents per kg material is also found by Palm et al. (2012) in their study of re-used building materials.

The re-use of sinks has the greatest avoided environmental load per kg materials, because the sinks consist of stainless steel. Chrome is used as a raw material in the stainless steel production and when refining chrome ore the carbon dioxide emissions are large because of an extensive energy use (Norgate et al., 2004).

8. Conclusions and discussion

It is concluded that the selective demolition of the studied school is more environmentally preferable than conventional demolition. The results show that the environmental load of selectively demolishing the building is smaller than when it is conventionally demolished. In the selective demolition, construction and demolition materials may be re-used. Production of new construction and demolition materials is then not needed and the environmental impacts that new production implies are avoided. Furthermore, it is concluded, when moving up in EU's waste hierarchy an environmental gain is achieved. It is environmentally preferable to re-use building materials in comparison to material recycling, energy recovery and landfill.

If the environmental benefit of selective demolition is compared to the environmental impact of a passenger car 120 tonnes of carbon dioxide equivalents *(Table 6.1)* are avoided when selectively demolishing the building and re-using construction materials. In Sweden it is assumed that 1300 buildings are demolished every year. If all buildings in Sweden were selectively demolished and the materials assessed in this study were re-used, the total avoided environmental load would be$1.56*10^5$ tonnes carbon dioxide equivalents per year. This corresponds to the emissions from $5 *10^4$ cars driven 1500 metric miles each year. The calculation is based on that a car driven 1500 metric miles per year emits approximately 3 tonnes carbon dioxide equivalents (Ljunggren Söderman et al., 2011). Further, the estimated demolition work to demolish the building has a global warming potential of 2.5 tonnes carbon dioxide equivalents per building, which is very little in comparison to the avoided environmental impact of the selective demolition.

Moreover, it is concluded that the amount of material in the building has an effect on the magnitude of the environmental load. Specifically, in the building bricks and windows account for 605 and 19 tonnes respectively. The other materials are of a magnitude of thousand to a hundred kg. Evidently, to produce the total quantity of bricks and windows from raw materials has a greater environmental load than producing for instance the steel doors which only have a total weight of 350 kg.

In section *5.4.1 Re-use* it is explained that the energy to remove the mortar from the bricks is neglected due to data gaps. However, the results shows that re-use of bricks are highly significant in comparison to the other materials assessed. Therefore, a rough estimation is done to find the energy required to remove the cement based mortar using Mulders et al. (2007) method. The calculations and assumptions are thoroughly explained in *Appendix C*. It is found that the thermal energy required to remove the cement based mortar of the total amounts of bricks is approximately $2.7*10^5$ MJ. If this energy is fuelled by coal the carbon dioxide emissions are 24 tonnes which reduces the difference between conventional and selective demolition to $-6.2*10^4$ kg carbon dioxide equivalents. The selective demolition still gives a more negative result than conventional demolition, thus it is environmentally preferable to re-use bricks. The selective demolition still gives a larger amount of avoided emissions than conventional demolition. Mulders et al. proposes that the combustible fraction from demolitions is used as an energy source, while coal is used in the calculation. This may have an effect on carbon dioxide emissions calculated.

The reasonability check of the global warming potential normalised per kg of material showed that the results are reasonable in comparison to Palm et al. (2012) who proposes a similar value for global warming potential per kg building material. Thus, the conclusions is drawn that the assumptions and simplifications made have a small effect on the results. Yet, a limitation worth highlighting is the studied materials, limited to eight different types. The building contains several more materials that may be assessed. Perhaps the results would have been different or similar if other materials were studied for re-use.

8.1 Re-use in society

From an environmental perspective it is beneficial to re-use construction and demolition materials as shown in this study. However, another question remains; will re-use of construction and demolition materials occur? It is important to focus on the building and construction stakeholders due to their influence over the industry. To begin with, there are re-use businesses such as Gamle Mursten and Kompanjonen that are strictly commercial without financial support from the government. According to themselves they are successful due to their focus on customer demand. These customers are beginning to have a growing demand for goods with reduced environmental impacts. Additionally, Gamle Mursten cooperates with, architects, to design new buildings with the re-used bricks.

The economic aspects of demolition are briefly discussed. One may assume selective demolition is more expensive than conventional demolition. Presumably, more working hours are needed to demolish selectively which is more expensive. Nevertheless, as stated above, there are businesses such as Kompanjonen, making a profit from selling re-used building and construction materials. One may argue that the extra cost of selective demolition will be covered when the re-used materials are sold again.

Legislative and economic policies from the government are significant to implement re-use of building and construction materials according to the author. Gamle Mursten suggests a law is passed to insure five percent of the materials in a building are re-used. Additionally, the author recommends a law is passed to make material inventories mandatory before demolition of the building proceeds. The aim of the material inventories is to evaluate re-use possibilities. Finally, the author proposes economic policies are needed to increase the amount of construction materials re-used at a demolition site. This may be reduced tax on re-used building and construction materials as well as increased fees to deposit waste.

9. Future studies

In this study, conventional demolition is compared to selective demolition of a school, and in the selective demolition the re-use potentials of eight different materials are assessed. A first proposed future study is to evaluate the re-use potential of more materials, in the building. If more materials are assessed, this may give a more holistic view of demolition.

The re-use traders request a standardised guarantee for re-used products, because they have an issue with guaranteeing that their products have sufficient properties in terms of quality and supportive structure. New test methods for re-used products need to be further developed. Thus, a proposed research topic is to create a standardised guarantee and new test methods for re-used building materials. A further recommended future study is to assess the economic profit of selling re-used materials.

The importance of re-using bricks is shown in this study hence; further research on technologies to re-use bricks is recommended. The commercialised existing technology only removes lime mortars and not cements mortars from the bricks. It is therefore suggested to investigate and develop technologies such as Mulders et al. (2007) method to remove cement mortar. Another possible approach is to avoid using cement mortar when constructing new buildings and to use lime mortar instead.

It is suggested at the IRCOW project meeting (May 29, 2012) and by the author that the building industry may in the near future lease out building materials, to have a closed loop of material flows. Further, Catharina Thormark (2001) proposes guidelines to design buildings for disassembly to increase re-use. More studies of how the building industry may increase re-use of materials as early as in the design and construction stage are recommended.

References

AF Group (2012) Selektive rivning, *AF Group* http://www.afgruppen.se/Rivning-och-atervinning/Selektiv-rivning/ (2012-06-15)

Azar C. (2010) *Thinking about energy systems – Concepts and tools*, Sustainable energy futures course compendium – autum 2010. Chalmers, Göteborg 2010

Beijer Byggmaterial (2012) Tips liten ordlista, *Beijer Byggmaterial* http://www.beijerbygg.se/templates/bb_byggradlistitem.aspx?id=12111 (2012-05-08)

Baumann, H. & Tillman, A. (2004) The Hitchhikers Guide to LCA – An orientation in life cycle assessment methodology and application Studentlitteratur, Lund.

Bloch M. (2012) Carbon dioxide emissions calculator, http://www.carbonify.com/carbon-calculator.htm (2012-06-16)

BKV Thermal (2007) Mineral wool http://www.bkvthermal.com/mineralwool.html (2012-05-08)

Bokalders V. & Block M. (2010) The whole building handbook: how to design healthy, efficient and sustainable buildings. Published by Earthscan in the UK and USA in 2010

Boverket (2010a) Teknisk status i den svenska bebyggelsen, *Swedish National Board of housing, building and planning,* http://www.boverket.se/Global/Webbokhandel/Dokument/2011/BETST-Teknisk-status.pdf (2012-08-28)

Boverket (2010b) Rivning. *Swedish National Board of housing, building and planning,* http://www.boverket.se/Bygga--forvalta/Bygglov-och-bygganmalan/Rivning/ (2012-02-17)

Bullerbekämparen AB (2012), Parafon Bullerskiva, *Bullerbekämparen AB* http://www.bullerbekamparen.se/parafon-bullerskva.aspx (2012-05-08)

Börje Åbinger (2012) Globax AB

D.A. Mattsson AB, Kontakta oss. *D.A. Mattsson AB* http://www.damattssonab.se/index.asp?page=1 (2012-05-21)

Daloc (2010) S60 Ståldörr/branddörr A60, A120, Dörrkatalogen, Daloc http://www.dorrkatalogen.daloc.se/staldorrar/S60/ (2012-05-07)

Galva, http://www.glava.no/naeringsbygg/ (2012-05-19)

Gross H. & Fröbel J. (2007) Limträ Guide, *Svenskt Limträ AB*. http://www.svensktlimtra.se/Upload/File/publikationer/SV_Limtra_WEB.pdf (2012-03-28)

Gustavsson L., Joelsson A. & Sathre R. (2010) Life cycle primary energy use and carbon emissions of an eight-storey wood-framed apartment building. *Energy and Buildings*, Volume 42, Issue 2, pg. 230-242.

Elitfönster (2007) Byggvarudeklaration BVD 3, *Elitefönster* http://www.elitfonster.se/Documents/Byggvarudeklarationer/BVD_MF.pdf (2012-05-07)

Erlandsson M. (2009) Byggvarudeklaration BVD 3 Limträ, *Martinson Group AB, IVL Svenska Miljöinstitutet.* http://www.martinsons.se/Allm%C3%A4n/Filer/Byggsystem/U2179%20%20EPD_BVD_%20Limtr%C3%A4_Martinsons%20_reviderad%20sep.pdf (2012-05-07)

EU (2008) Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives, Official Journal of the European Union.

Gamle Mursten (2012) The re-brick project, http://www.gamlemursten.dk/uk (2012-04-20)

Heavy equipment (2008) Fuel consumption, http://www.heavyequipmentforums.com/showthread.php?5804-Fuel-Consumption (2012-05-14)

Hitachi (2012) ZX350LC-5, Hitachi Construction Machinery, http://www.hcme.com/en/content/view/full/5420 (2012-05-14)

IRCOW (2011a) Project general details, Project details http://www.ircow.eu/Basis.aspx?Tid=2&Sid=32&Hmi=32&Smi=0&artid=4 (2012-02-02)

IRCOW (2011b) IRCOW Newsletter 1 http://www.ircow.eu/media/downloads/IRCOW_news_letter_01.pdf (2012-02-02)

Johannsson M., Hietala P., Larsson K., Karlsson H., Hedlund M. & Eriksson L. (), *En handbook – Rivning med Brokk* [Electronic] Brokk AB http://www.brokk.ru/pdf/Rivningshandbok%20sv.pdf (2012-06-28)

Jonsson G. & Wallenius M. (2006) Miljöaspekter vid rivning av betongstation, Examensarbete vid Institionen för samhällsbyggnad avdelningen för geoteknologi, Luleå tekniska universitet. http://epubl.ltu.se/1404-5494/2006/021/LTU-HIP-EX-06021-SE.pdf (2012-03-01)

Lennon, M. (2005) Recycling Construction and Demolition Wastes – A Guide for Architects and Contractors, The Institution Recycling Network, Boston Society of Architects, Massachusetts Department of Environmental Protection http://www.mass.gov/dep/recycle/reduce/cdrguide.pdf (2012-02-02)

Ljunggren Söderman M., Palm D., & Rydberg T. (2011) Förebygga avfall med kretsloppsparker. Analys av miljöpåverkan, IVL Swedish Environmental Research Institut, rapport B1958

Mörstedt S-E. & Hellsten G. (2005) Data och Diagram Energi- och kemitekniska tabeller, seventh edition, printed in Malmö by Liber

Mulder E., de Jong T. & Feenstra L. (2007), Closed Cycle Construction: An integrated process for the separation and reuse of C&D waste, Waste Management volume 27, Elsevier, pg. 1408-1415.

Norgate T.E., Jahanshahi S. & Rankin W.J. (2004) Alternative Routes to stainless steel – A life cycle approach, *Document Transformation Technologies* http://www.pyrometallurgy.co.za/InfaconX/010.pdf (2012-06-15)

Onninen (2012) Tvättställ rostfritt stål, *Onninen* http://www.onninen.com/sweden/tjanster/retailers/kampanjervillkor/Documents/Flik%2019_VVS-09.pdf (2012-05-08)

Persson-Engberg J., Sigfrid L. and Torring M. (1999) *Rivnings handboken*. Stockholm: Elanders Svenskt Tryck AB.

Palm D., Fredén J., Jensen C., & Ljunggren Söderman M.(2012) Avfallsförebyggande i praktiken, Avfallshandbok för kommuner, Swedish environmental research institute, IVL Swedish Environmental Research Institut, rapport B2052

SI metric (2011) SI metric http://www.simetric.co.uk/ (2012-05-07)

Sisab (2011) Kämpingeskolan, Sisabs fastighetsdatabas, http://www.sisab.se/Varafastigheter/Fastighetsdatabas/Kampingeskolan/ (2012-05-09)

SCB (2008), Var femte ny lägenhet i flerbostadshus tillkom genom ombyggnad, *Statistika central byrån*. http://www.scb.se/Pages/PressRelease____231508.aspx (2012-06-17)

SSAB, Så gör vi stål, http://www.ssab.com/sv/Produkter--Tjanster/Om-SSAB/Sa-gor-vi-stal/ (2012-05-19)

Stena Stål, Om Stena Stål. *Stena Stål* (2012-05-21) http://stenastal.se/Om-Stena-Stal/

Stockholm stad (2006) Materialsortering vid rivning, Förekomst – Hantering. Miljöförvaltningen, Stadsbyggnadskontoret and Stockholms SKAFAB in 2004 and updated in 2006 http://www.google.se/search?sourceid=chrome&ie=UTF-8&q=Materialsortering+vid+rivning%2C+F%C3%B6rekomst+%E2%80%93+Hantering (2012-02-06)

STR (2011)Antal registrerade fordon, Sveriges Trafikskolors Riksföbund i Sverige http://www.str.se/Korkort/Hem/Statistik/ (2012-06-16)

Sveriges riksdag (2009) http://www.riksdagen.se/sv/Dokument-Lagar/Forslag/Motioner/Beskattning-av-Europadiesel-so_GX02Sk310/?text=true (2012-05-25) Källa andv. Fastställa svavelinnehåll i diesel.

Svenska Fönster (2012) Välkommen till en av Sveriges ledande fönstertillverkare, http://www.svenskafonster.se/ (2012-05-18)

Tillman A. (2011) LCA in a Nutshell, lecture, Course *Life Cycle Assessment* at Chalmers spring 2011.

The Visegrad Group (2012) Energy and transport page http://www.centrel.org/energytransportation.html (2012-06-12)

Thormark C. (2001) Recycling Potential and Design for Disassembly in Buildings, Lund University, http://lup.lub.lu.se/luur/download?func=downloadFile&recordOId=41592&fileOId=1693314 (2012-08-30)

University Leiden (2012) Handbook of LCA, Institute of Environmental Science (CML), http://www.cml.leiden.edu/research/industrialecology/researchprojects/finished/new-dutch-lca-guide.html (2012-09-04)

Welty J., Wicks C. and Wilson R. (2001) *Fundamentals of momentum, heat and mass transfer*, 4th edition. Copyright by John Wiley & Sons, printed in the U.S.

Appendix A. Calculation of demolished buildings

In 2007 approximately 1500 apartments were demolished (SCB, 2008). An average apartment building has 14.55 apartments and there are a total of approximately 165 000 apartments in Sweden (Boverket, 2010a). Thus, one may assume that roughly 0.06 percent of apartment buildings are demolished per year in Sweden.

$$\frac{1500\ \frac{aparmetns\ demolished}{year}}{14.55\ \frac{apartments}{apartment\ buildings}} \Big/ 165000\ apartment\ buildings\ in\ Sweden \approx 0.06\ \%$$

The assumption is made that public and other buildings in Sweden are demolished at the same rate, 0.06 percent, as the apartment buildings. The total amount of buildings in Sweden is 2.1 million (Boverket, 2010a). Thus, the amount of demolished buildings is estimated to 1300 buildings per year.

Appendix B. Calculation of demolition work

The calculation to find that the amount of diesel, 6838 kg/school, used to demolish the building is based on the following: An excavator operates for 8 hours per day during 6 weeks, 5 days per week, resulting in a total of 240 operation hours. This estimation is made with the help of demolition employee, Börje Åbinger. One may assume the demolition proceeds faster if more exactors and other demolition equipment are used. The diesel consumption of an average excavator is 35 l/h (Heavy equipment, 2008) (Hitachi, 2012). The density of diesel is 814 kg/m^3 (SI metric, 2011). This gives:

$$240\ h * 35 * 10^{-3}\ \frac{m^3}{h} * 814 \frac{kg}{m^3} = 6837{,}6\ kg \approx 6838\ kg$$

The net calorific value of diesel is 41.6 MJ/kg (Mörstedt & Hellsten, 2005). 1 MJ diesel accounts for 1.1656 MJ primary energy, according to the process in Gabi (German diesel produced from crude oil). This gives the primary energy of diesel fuel to: $41.6 * 1.1656 = 48.48896 \approx 48\ \text{MJ/kg}$

The total energy consumption for demolition is then:

$$48.48896 * 6837{,}6 = 331548{,}1129\ \approx 331548\ \text{MJ/school}$$

Which is: $\frac{331548}{9000} = 36.8387 \approx 37 MJ/m^2$ to demolish the school. This figure, 37 MJ/m^2 corresponds to study by Gustavsson L. et al. (2010) that proposes 36 MJ/m^2.

The estimated demolition work to demolish the building has a global warming potential of 2.5 tonnes carbon dioxide equivalents per building. This result is obtained from the Gabi model.

Appendix C. Analysis of the cement based mortar

Mulder et al. (2007) conducts an experiment with cement based mortar. The masonry debris is heated to 540 °C. At this temperature the cement based mortar is mechanically and chemically separated from the bricks.

To estimate the energy required, Q, to heat bricks to 540 °C the following heat equation is used. It is assumed the bricks initial temperature is 20 °C. Heat capacity, Cp_{bricks} , for bricks is $8.5 * 10^2 J/kgK$ (Welty J. et al., 2001). Equation 5 in *5.8.5 Bricks* determines the total mass of the bricks in the building to $m_{bricks} = 604560.7\ kg$

$$Q = m_{bricks} Cp_{bricks} \Delta T$$
$$Q = 604560.7 * 8.5 * 10^2 * (540 - 20)$$
$$Q = 2.672 * 10^5\ MJ$$

Assume the energy required to heat the bricks is obtained from coal. Approximately the carbon emission factor for coal is 25 gC/MJ (Azar, 2010). This results in the carbon emission, $m_C = 6680\ kg\ C$.

To find the carbon dioxide emissions the following equation is used. M_{CO2} is the molecular mass of carbon dioxide and M_C is the molecular mass of carbon.

$$\frac{M_{CO2}}{M_C} = \frac{m_{CO2}}{m_C}$$
$$\frac{44}{12} = \frac{m_{CO2}}{6680}$$
$$m_{CO2} = 24494\ kg\ CO_2 \approx 24\ ton\ CO_2$$

In *Table 7.3* in *Reasonability check* the difference between conventional and selective demolition for bricks is presented. The following, *Table C*, shows the difference of the two demolition alternatives if the removal of cement mortar is considered.

Table C. Global warming potential of bricks

	Conventional (kg carbon dioxide equivalents)	Selective (kg carbon dioxide equivalents)	Difference (kg carbon dioxide equivalents)
Removal of cement mortar not considered	$-1.49*10^3$	$-8.89*10^4$	$-8.7*10^4$
Removal of cement mortar considered	$-1.49*10^3$	$-6.4*10^4$	$-6.2*10^4$ kg

If one adds the amounts of emitted carbon dioxide, $m_{CO2} = 24494\ kg\ CO_2$, to $-8.89*10^4$ kg carbon dioxide equivalents, then the selective demolition only avoids $-6.4*10^4$ kg carbon dioxide equivalents. The difference between conventional and selective demolition is then $-6.2 *10^4$ kg carbon dioxide equivalents.