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Espoo 2004 TKK-RTA-A2

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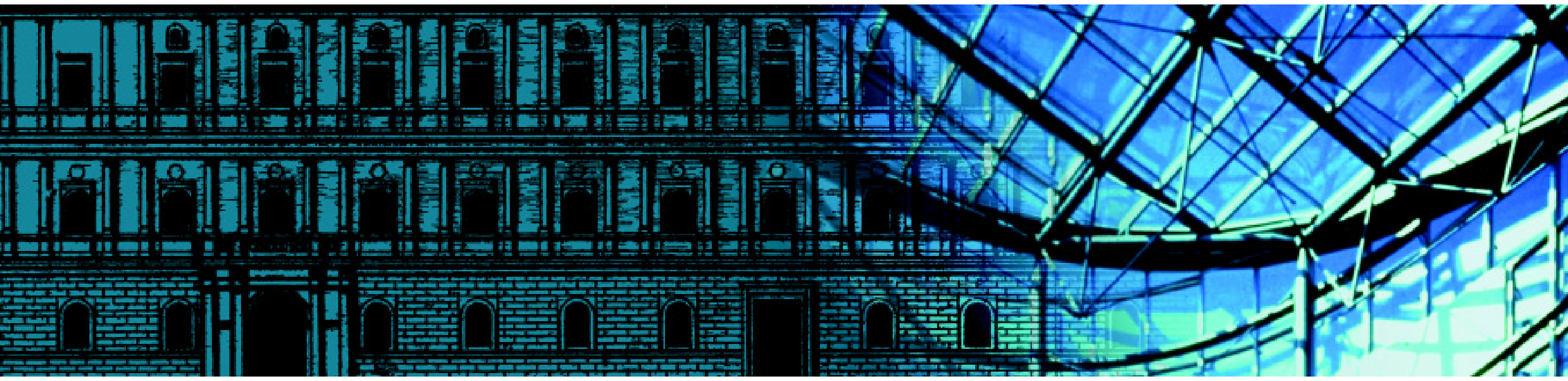

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ABSTRACT OF DOCTORAL DISSERTATION

Author	Seppo Junnila

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The environmental impact of an office building throughout its life cycle

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Supervisor	Prof. Jouko Kankainen (Helsinki University of Technology)
Instructor	Assistant Professor Arpad Horvath (University of California, Berkeley)

Abstract

This dissertation quantifies and compares the potential environmental impact caused by an office building during its life cycle, i.e. from the extraction of raw materials to disposal of waste. Using both a multiple-case study method and life-cycle assessment (LCA) the study determines the life-cycle phases and elements contributing most to a building's life-cycle impact. Furthermore, the study performed a sensitivity assessment to evaluate the effects of possible changes during the long service life, fifty years, of a building.

In the study, corresponding life-cycle phases were found to contribute similarly to the environmental impact of the office buildings studied, with building operations (electricity, heating and other services) dominating the climate change, acidification and eutrophication categories, while building material manufacturing (in construction and maintenance) dominated those of summer smog and heavy metals. The key environmental issues found for the buildings were: electricity use in the outlets, HVAC and lighting, heat in ventilation and conduction, materials used in internal surfaces and HVAC services, and the use of water and wastewater, which were quite dominant in that they, as 20% of all life-cycle elements, caused 45-75 % of the average life-cycle impact of the buildings studied and 60-75% of the cumulative range.

The sensitivity analysis indicated important issues. Firstly, it is ill-advised to use weight related cutoff criteria in the inventory analysis, because even very small flows of material can have a noticeable life-cycle effect. Secondly, although local conditions can have a clear influence on the degree of life-cycle impact, local conditions seemed to have less impact on the contribution made by different life-cycle phases. Finally, the traditional life-cycle phase approach in analyzing the result seems to produce a somewhat different conclusion than the system approach.

As a whole, the findings of the study would suggest that within the limitations of both the electricity mix used and the obsolescence (economic life cycle), the life-cycle impact of a typical contemporary office building would follow a similar pattern. Practical applications of the study could be in the conscious design and facilities management of office buildings based on the determined environmentally significant issues and the possibilities of influencing same.

Keywords
Office, building, life-cycle assessment, LCA, scenarios, environmental impact, management

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Tekijä Seppo Junnila

Väitöskirjan nimi
Toimistorakennuksen elinkaaren ympäristövaikutukset

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Työn valvoja	Prof. Jouko Kankainen (Teknillinen korkeakoulu)
Työn ohjaaja	Assistant Professor Arpad Horvath (University of California, Berkeley)

Tiivistelmä

Tutkimuksessa määritetään laskennallisesti toimistorakennuksen elinkaarensa aikana aiheuttamat ympäristövaikutukset. Tieteellisenä menetelmänä työssä on käytetty Multiple Case Study metodia sekä herkkyystarkastelussa skenaarioanalyysia. Ympäristövaikutukset työssä on laskettu Elinkaariarviointi (LCA) menetelmällä ja rakennuksen elinkaari on arvioitu perusskenaariossa 50 vuoden mittaiseksi.

Tutkimuksen tulos osoitti, että kaikissa tarkastelluissa toimistorakennuksissa pääsääntöisesti samat elinkaaren vaiheet aiheuttivat suhteellisesti eniten ympäristövaikutuksia: käyttövaihe ilmastonmuutosta, happamoitumista ja rehevöitymistä sekä rakennusmateriaalit alailmakehän otsonin muodostumista ja raskasmetallipäästöjä. Ympäristön kannalta keskeisimmiksi elinkaaren osa-alueiksi osoittautuivat käyttäjien sähkönkulutus, taloteknisten järjestelmien ja valaistuksen sähkönkulutus, lämpöhukka ilmastoinnin ja rakenteiden kautta, rakennusmateriaalit pintarakenteissa ja taloteknisissä järjestelmissä sekä vedenkulutus ja jätevedet. Keskeisiksi valitut osa-alueet olivat varsin hallitsevia, sillä viidesosalla kaikista elinkaaren osa-alueista ne aiheuttivat 45–75% ympäristövaikutuksista ja 60–75% yhteenlasketusta vaihteluvälistä.

Tutkimuksen herkkyystarkastelussa kävi lisäksi ilmi, että puhtaasti materiaalivirtojen massoihin perustuva rajaus elinkaarilaskennassa muuttaa lopputulosta merkittäväksi. Toiseksi, paikalliset olosuhteen näyttäisivät vaikuttavan vähemmän elinkaaren eri osa-alueiden suhteellisiin merkityksiin kuin niiden ympäristövaikutusten kokonaismääriin. Lopuksi, perinteinen rakennuksen elinkaaren vaiheisiin perustuva tarkastelu näyttäisi tuottavan erilaisen tulkinnan tutkimuksen tuloksista, kuin rakennusjärjestelmiin perustuva osittelu antaisi. Näiden seikkojen lisäksi rakennuksessa käytettävän sähkön tuotantotapa ja rakennuksen elinkaaren pituus vaikuttava merkittävästi laskennan lopputuloksiin.

Käytännössä tutkimuksen tuloksia voidaan hyödyntää sekä uusien toimistorakennusten ympäristötavoitteiden asettamisessa että olemassa olevien kiinteistöjen ympäristöominaisuuksien parannustoimenpiteitä suunniteltaessa.

Asiasanat
Toimistorakennus, elinkaariarviointi, LCA, ympäristövaikutus, herkkyystarkastelu

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The degree of one's emotions varies inversely
with one's knowledge of the facts
- the less you know the hotter you get.

- B. Russel

Acknowledgement

My dissertation is the result of fruitful collaboration between the University of California at Berkeley (UCBerkeley) and Helsinki University of Technology (HUT). The dissertation is a part of a larger research project at HUT concerning the environmental significance of buildings in society.

I am most thankful to my instructor Professor Arpad Horvath (UCBerkeley), who has not only taught me the modes of scientific thinking but also guided me to and gave me a good foundation in the world of academia. I owe much gratitude to my supervisor Professor Kankainen for creating the excellent circumstances in which I conducted my research, as well as, for the rich discussions and ongoing debate during my research. I am also grateful to the pre-examiners, Professor Lovio (HKKK) and Dr. Gadgil (Lawrence Berkeley National Laboratory), who have both provided me with valuable comments and suggestions for improvements. My fellow researchers, Dr. Guggemos and Mr. Rintala, provided me with invaluable assistance in respect of the technical aspects of building life cycle and the related data collection.

I am also indebted to all of the staff members at the Construction Economics and Management laboratory, who have helped to create an inspiring atmosphere that has served as a source of impetus and support as I worked on my dissertation. I owe special thanks to Mr. Puhto and Mr. Junnonen for their friendship and our many moments of brainstorming at the lab. I also have to pay tribute to my colleges and superiors at my industry-based organization of Jaakko Pöyry Building Engineering, who have all been sympathetic with my occasional lapses into periods of contemplation during the hard days of work and have challenged my theories in practice.

I have been extremely fortunate to have Tekes, Jaakko Pöyry Infra, Nordea, Kapiteeli and Nokia as my sponsors, who have not only provided me with financial support but also have made it possible to access the pertinent empirical data. I also would like to express my gratitude to the persons of the steering group of my research projects, who have encouraged me by showing the practical value of my work. The financial support from other institutes, Jenny ja Antti Wihurin rahasto, RIL- säätiö, TKK Tukisäätiö and Kiinteistöalan koulutussäätiö are also greatly acknowledged.

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On a clear fall afternoon in September 2004,

Seppo Junnila

List of appended papers

This dissertation of doctor of science in technology summarizes the following publications, which are being referred in the text with roman numerals:

I	Junnila, S. Estimating the environmental aspects of an office building's life cycle. In: Bontempi, F. (ed.) Proceedings of the second international conference on structural and construction engineering, ISEC-02. Rome, Italy. September 23-25, 2003. Lisse, the Netherlands. Balkema publisher. 2003. pp. 1685-1690.
II	Junnila, S. and Horvath, A. Life-cycle environmental effects of an office building. Journal of Infrastructure Systems, 2003. Vol. 9, Iss. 4, pp. 157-166. ASCE.
III	Junnila, S. Life-cycle assessment of environmentally significant aspects of an office building. Nordic Journal of Surveying and Real Estate Research (NJSR) Special Series, Vol. 2. *Accepted August 28, 2004.*
IV	Junnila, S. Identification of environmental impact of office buildings by building element and material groups. In: Sarja, A. (ed.) Proceedings of integrated lifetime engineering of buildings and civil infrastructures, ILCDES 2003. Kuopio, Finland. December 1-3, 2003. Association of Finnish Civil Engineers. 2003. pp. 433-438.
V	Junnila, S. Comparative life-cycle assessment of three office buildings. Saari, A. (ed.) Helsinki University of Technology, Construction Economics and Management, A Research Reports 1, TKK-RTA-A1. Espoo, Finland. 2004.
VI	Junnila, S., Horvath, A. and Guggemos, A. Life-cycle assessment of office buildings in Europe and the U.S. Journal of Infrastructure Systems. ASCE. *Accepted April 12, 2004.*
VII	Junnila, S. and Horvath, A. Environmental sensitivity analysis of the life cycle of an office building. In: Sarja (A.) ed. Proceedings of integrated lifetime engineering of buildings and civil infrastructures, ILCDES 2003. Kuopio, Finland. December 1-3, 2003. Association of Finnish Civil Engineers. 2003. pp. 215-220.
VIII	Junnila, S. and Rintala, T. Comprehensive LCA reveals new critical aspects in offices. In: Pettersen, T. D. (ed.) Proceedings of the CIB/iiSBE International Conference on Sustainable Building 2002. Oslo, Norway. September 23-25, 2002. EcoBuild. CD-rom.

Contribution of the author to Papers from I to VIII is as follows:

I	The author of this dissertation is fully responsible for writing this paper.
II	The author is responsible for writing the paper. Prof. Horvath provided comments on both the contents and the text of the paper.
III	The author is fully responsible for writing this paper.
IV	The author is fully responsible for writing this paper.
V	The author is fully responsible for writing this paper.
VI	The author is responsible for initiating this paper. The computations and written text was the result of collaboration of Prof. Horvath and Dr. Guggemos, and the author.
VII	The author is responsible for writing the paper. Prof. Horvath provided comments on both the contents and the text of the paper.
VIII	The author is responsible for writing the paper. The computations of the paper were done by Mr. Rintala, and the author.

Table of contents

1 Introduction

1.1 Background

In recent years, building-related environmental issues have become increasingly important. The building and construction sector has been found to be responsible for a large part of the environmental impact of human activities (UNEP 2003a, Worldwatch 1995). For example, in both the European Union and the U.S., the construction and building sector has been estimated to be responsible for roughly 40% of the overall environmental burden (U.S. DOE 2002, Sjöström 2000, UNEP 1999). Consequently, many articles have expressed the opinion that the environmental dimension should already be included in the design phase of the building (Arena & de Rosa 2003, Ball 2002, Pilvang & Sutherland 1998). Some governments have also introduced new policy instruments, such as the European Community's energy performance directive for buildings, in order to reduce the negative impact from the activities of building sector (Beerepoot 2002).

The environmental design of office buildings holds a particular interest for many companies, as well. As a matter of fact, at the moment, a large proportion of all companies with a certified environmental management system is already operating in the office intensive light and service industries (ISO14001 2001). As the transformation of the economies of the developed world towards service industries intensifies, it can be expected that the investments in office and other commercial buildings will grow correspondingly.

The potential of reducing the environmental impact of companies operating in the light and service industries is often substantial (Rosenblum et al. 2000). The majority of the companies' environmental impact is typically related to the use of offices. Some clear indications of the importance attached to office buildings are already appearing. For example, in the UK, some 25% of the new office buildings acquire an environmental assessment and label (Hasegawa 2002). Similarly, many international companies have stated that the major part of the environmental impact they generate are connected to the use of buildings (Swiss Re 2002, Kesko 2002, Royal & SunAllinace 2001).

The environmental design of buildings is essentially based on the body of knowledge about environmental issues of a building's life cycle (Gangemi et al. 2000, Bogenstätter 2000). This life-cycle knowledge also provides the basis for optimizing the requirements of both investor and end-user, in that both the environmental and user-friendly features are taken into account in the design from its very inception. This environmental knowledge enables the control of environmental aspects and therefore helps to minimize the degree of environmental impact (Roberts & Robinson 1998).

The term “environmental aspect” is used here as defined in the ISO 14001 (1996) environmental management standard: “Environmental aspect is an element of an organization’s activity, product or service that can interact with the environment.” Other important terms used in the study are life cycle, life-cycle phase, and life-cycle element. Life cycle consists of consecutive and interlinked stages of a studied product system (building), from raw material acquisition to the final disposal (ISO 14040). The life-cycle phases (building materials, construction, electrical service, heating service, other services, maintenance and demolition) are the main stages of the life cycle and act as the upper level of analysis of the studied system. Each life-cycle phase is further divided into life-cycle elements, which are the lower level of analysis. The life-cycle elements are constructed of unit processes, which are the smallest portion of the studied system for which data are collected when performing the life-cycle assessment.

From the perspective of environmental management, the areas of greatest interest are those where a small change can have a large impact on the environmental performance of a building. These areas, so called key issues, represent highly sensitive parameters in which a small deviation has a large influence that can be affected by alternative product and/or process designs (Heijungs 1996). The procedure of identifying key environmental issues entails focusing on elements that have either a high contribution or high variability. The key issues are those where both the contribution and the variability are high (Figure 1).

variability	*high*	perhaps a key issue	key issue
	low	not a key issue	perhaps a key issue
		low	*high*
		contribution	

Figure 1. The environmental key issues (reproduced according to Heijungs 1996).

1.2 Objective and scope of the dissertation

Despite several studies about the environmental impact of buildings, it is still very difficult to find comprehensive and detailed information about the life-cycle aspects of offices. As presented in this chapter, a large number of earlier studies are based on single building case studies. In addition, many of the studies suffer from some other limitations as well, such as a lack of life-cycle phases, comprehensive material inputs or extensive environmental data. Additionally, the range of environmental impact has sometimes been interpreted quite narrowly, studies having only one or two environmental impact indicators. Furthermore, the results in the literature have often been presented at a relatively high, life-cycle phase level and not by a life-cycle element level, which could be of more use in design management, for example.

The purpose of this study is to quantify and compare the potential environmental impact caused by an office building during its life cycle. The study aims at determining the life-cycle phases and elements that contribute most to the life-cycle impact and also to provide information about the connection between different life-cycle elements of the building and environmental aspects, as well as the degree of potential environmental impact. Furthermore, the study performs a sensitivity analysis of an environmental assessment of an office building in order to calculate the relative significance of possible alternative scenarios during the fifty years of use. The paper emphasizes the wide range of life-cycle elements in data collection so that an extensive picture of life-cycle impact could be obtained. The objectives, the structure of the study, and the corresponding articles are illustrated in Figure 2.

The study had two hypotheses. The first hypothesis was that a typical contemporary office building, different design teams, contractors and users notwithstanding, would have largely the same significant life-cycle phases and elements. The second hypothesis said that the inclusion of smaller flows of materials into the studied system (=office life cycle) would have a significant impact on the overall environmental impact of an office building.

Quantifying the environmental impact	Papers I, II, III, IV, V, VI, VII and VIII
Contribution of life-cycle phases and elements	Papers I, II, III, IV, V, VI, and VIII
Comparing the impact of offices	Papers IV, V, and VI
Sensitivity analyses	Paper IV, VI, VII and VIII

Figure 2. The main objectives and structure of the study. The roman numerals refer to the publications that deal with the objective in question.

The thesis consists of eight papers in addition to this summary. Papers I, II and III quantify the significant environmental aspects of a new office building over 50 years of service life. A comprehensive environmental life-cycle assessment (LCA) – including data quality assessment – has been conducted to provide detailed information for establishing the connection between the different life-cycle elements and potential environmental impacts.

Paper IV compares the components of three office buildings with the aim of determining those building elements and materials impacting the environment the most. This paper also studies in more detail the significance of the smaller flows of materials to the result of an office building LCA.

The two papers V and VI compare the life-cycle impact of different office buildings. Paper V compares the impact of three Finnish office buildings and determines the life-cycle phases and elements that contribute most to the impact, and also the elements that have the highest range of variation in impact values. Paper VI, in turn, compares the contribution of life cycle-phases of a Finnish and a U.S. office building.

The paper VII performs a sensitivity analysis of the material manufacturing, construction, use, maintenance, renovation/retrofit, and end-of-life phases of an office building in Finland. The paper puts in perspective the alternative scenarios with the base case scenario, and calculates the relative significance of the alternative scenarios. The sensitivity analysis concentrates on significant issues of the building's life cycle and uses eighteen different outside condition, model, input, and obsolescence scenarios to test the sensitivity of the result.

Paper VIII compares the results of an office building case study to the results of those presented in other LCA studies. In addition, the paper broadens the interpretation of the LCA result by assessing the effects of the possible exclusion of the smaller flows of materials from the studied system.

2 Life-cycle assessment of buildings

2.1 Environmental analysis of buildings

A majority of environmental studies on the impact of buildings describe the issue in relatively broad terms giving qualitative, though sometimes extensive descriptions. For example, Finnveden and Palm (2002) state that the use phase accounts for the major part of the environmental impact of buildings. Klunder (2001) gives a description of the environmental issues of dwellings, noting that assessments should focus primarily on components that involve large quantities of materials (e.g., foundation, floors, and walls), but some materials should be avoided regardless of quantity (e.g., lead). Energy consumption in space heating, hot water, lighting, and ventilation should be studied along with the energy carrier (electricity or gas). Interestingly, the environmental impact of water consumption is regarded as negligible compared to those of materials used and energy consumption.

In addition to descriptive guidelines, several methods and tools have been presented in the literature to assess the environmental effects related to buildings and construction. Generic environmental assessment methods that have been applied to the building and construction sector are, for example, life-cycle assessment (LCA), environmental-impact assessment (EIA), embodied-energy analysis, and material input per service method (MIPS) (Wallbaum & Buerking 2003, Borg 2001, Treloar et al. 1999, Horvath & Hendrickson 1998, EC 1997). An even wider range of tools designed for environmental assessment of buildings and construction specifically has been presented in the literature, such as NABERS, Miljöstatus, Ecoprofile, Green Globes, HQE, CASBEE, BREEAM, Eco-Quantum, BEAT, ATHENA, BEES, Build-It, LCA-House, PromisE and LEED (Boonstra & Pettersen 2003, Edwards & Bennet 2003, Nousiainen et al. 2003, Borg 2001).

The method, often mentioned as the most appropriate for environmental life-cycle studies of buildings and construction, is the life-cycle assessment (Kohler & Moffat 2003, Chevalier et al. 2002). Life-cycle assessment has been used on many occasions for assessing the environmental impact of building materials, components, systems, and building life cycles. This study concentrates on the use of life-cycle assessment as a method assessing the environmental impact of buildings.

2.2 Life-cycle assessment studies with few impact indicators

One group of life-cycle assessment (LCA) studies presents data about the whole life cycle of a building but utilize only one or two indicators, often primary energy and sometimes CO_2 emission, to assess the environmental impact of buildings. Seo and Hwang (2001), for example, have evaluated both the life-cycle primary energy usage and the CO_2 emissions of residential buildings in Korea using a combination of economic input-output and process-based LCA. Their results show that the energy consumed in building operation is the most significant life-cycle stage, amounting to a surprisingly high 88-97% of the environmental impact of a residential building during its 22,4 years of use. In addition, they stated that between the studied building there was a wide range of variation in CO_2 emissions from the operation.

Thormark (2000) has collected data from several studies and concluded that the use of energy often accounts roughly for 85% of the primary energy consumption of new "general" buildings with an assumed life cycle of 50 years. However, in another study she also points out that examples can be found, e.g. of low energy buildings, where the impact of building materials is much more significant factor, equivalent to that of one-half of a building's primary energy usage (Thormark 2002).

Treloar et al. (2001a) have used a hybrid input-output model to estimate the primary energy consumption and the relative importance of the life-cycle phases of commercial buildings. They have stated that the "embodied energy represents 20 to 50 times the annual operational energy of most Australian commercial buildings". Comparing embodied energy to operational energy, however, can be misguided since the amount of operational energy is always less than the actual primary energy (equaling the embodied energy) needed to produce the operational energy. In the case of Finnish energy production, for example, the ratio of primary and operational energy is on average around 2,3 but is dependent heavily on the actual energy production methods used in any given place. In another study, Yohanis and Norton (2002) assessed the primary energy of materials in an office building to be equal to 67% of the use-phase-energy over a 25-year period. Additionally, Cole and Kernan (1996) have found the operation energy to be the largest life-cycle contributor of an office building. The building structure also has been indicated as another significant component of embodied energy (Treloar et al. 2001a, Treloar et al. 2001b, Cole & Kernan 1996).

2.3 Building systems and components

Another group of building LCA studies have used a wider set of environmental impact indicators in their analyses, but have concentrated on limited number of life-cycle phases or building components in their calculations. Junnila and Saari (1997) have conducted a life-cycle inventory analysis to estimate the primary energy consumption, emissions of CO_2, CO, NO_X, SO_2, VOC, and particulates of some specific building components, such as ground floor slab, load bearing walls and slabs, external walls, roofs, and windows. They have concluded that in a three-story residential building, one of the lightest element groups, the windows, causes the greatest environmental emissions during 40 years of use, most of which is caused by the increased energy consumption due to heat loss.

Trusty and Meil (2000) have assessed the environmental impact of two alternative designs for an office building, including the structural and envelope elements, and compared them against the annual HVAC operating energy. They reported that in less energy efficient design options, the initial embodied energy of the structures and that of the envelope are roughly equal to the primary energy consumption during four years of operation of the HVAC system. However, in more energy efficient designs, the initial embodied energy of the structures and the envelope, which was roughly the same in both cases (4% more in energy efficient design), is equivalent to the primary energy consumption for approximately 10 years of operation.

There are numerous other examples, where LCA has been used to study individual building components. Gorgolewski (1999) for example, has conducted a full life-cycle assessment of steel pilings, including the construction process, energy use, recycling, and reuse of the piles. Björklund et al. (1996) have used LCA to compare the environmental impact of concrete and steel structural building frames. Börjesson and Gustavsson, (2000), in turn, have used LCA to compare the climate change emissions of wooden and concrete structures of a multi-story building. Yet another LCA compared wood, steel, and concrete structural frames for an office building in Canada, but did not include the impact from the end-of-life phase (Canadian Wood 1997). LCAs of various types of German windows and curtain walls were performed as part of an overall assessment of construction materials (IKP 1998).

2.4 Extensive studies

A third, much smaller group of building LCA studies included all the life-cycle phases of a building and used a wider set of environmental impact indicators. Most of the articles in the third group were studies of residential buildings, which indicate that the energy in building-operations impact the primary energy and climate change the most, roughly 75-95% of such impact (Ochoa et al. 2002, Saari 2000, Meil & Trusty 2000 , Norris et al. 2000, VTT 2000, Junnila & Saari 1998). Material manufacturing was also mentioned as having a significant impact, especially with regard to summer smog potential and toxic releases (Ochoa et al. 2002, VTT 2000, Junnila & Saari 1998).

Environmental studies of office or other commercial buildings have been published less. However, in the available studies, the office buildings have been estimated to produce similar results to those of residential buildings. Sheuer et al. (2003) have conducted a comprehensive and well-reported LCA study for a new commercial building on the University of Michigan campus. They concluded that with 75 years of use the operation phase (heat and electricity) accounts for a major part of the impact in all assessed categories. They reported that 93% of the global warming, 83% of the ozone depletion, 90% of the acidification and 90% of the nutrification occurred in the operation phase. The second greatest factor impacting during the life cycle was materials production and placement, accounting for 3-14% of impact values. Although the LCA study by Sheuer et al. (2003) is extensive, there are two assumptions that might emphasize the significance of operating energy. In the actual case, the operating energy is mentioned to be produced mostly with a combined heat and power plant, but in the LCA calculation the energy production model was simplified by separating electricity and heat production. The second assumption concerns the fuel used in the energy production, namely instead of of solely natural gas the energy is produced with the combination of gas, oil and coal. Both of the above-mentioned assumptions should increase the impact of operational energy, especially in the acidification and nutrification categories.

In some other office building studies, operating energy is also mentioned as factor having highest individual impact. Kommonen and Svan (1998) assessed climate change, acidification and summer smog impact on a government office building and concluded that during fifty year use phase both climate change and acidification had a dominating impact, their proportion being 94%, and that of summer smog 90%. Raiko et al. (1998) and Hara-Lindström (2001) have used the same impact categories in their studies of new office buildings and also concluded that the operating energy during fifty years of use dominates the result. All of the previous studies have used a cutoff criterion based on the weight or some other single parameter of building materials and have thus, for example, excluded the paints from the inventory, which could reduce considerably the impact of summer smog caused by the building's materials.

2.5 Multiple case studies

Precious few articles have based their conclusions of the environmental impact of buildings on a multiple-building case studies. The few articles found in this area have analyzed the results at a relatively coarse life-cycle phase level. Adalberth et al. (2001) have used a screening LCA method with 50 years of service life to compare the environmental impact of four multi-family houses in Sweden. The environmental impact categories included in the study were the global warming potential, acidification, eutrophication, photochemical ozone creation potentials, and human toxicity. They have reported that occupation is the life-cycle phase contributing the most, 70-90%, in all impact categories and the building materials manufacturing was second at 10-20% . Some of the building materials that could have significant ozone creation potential, i.e. paints, have been omitted from the inventory analysis. In addition, the result showed that the widest range of variation between the buildings was found in the occupation phase i.e. equal to 40% of the overall life-cycle impact. The corresponding difference in material manufacturing was roughly 10 % of the life-cycle impact.

Suzuki and Oka (1998) performed economic input-output LCA and compared the primary energy and CO_2 emissions of ten office buildings with 40 years of service life in Japan. They reported that the energy-use in the operation phase causes most of the impact in all ten cases, the average proportion being 80%. The second most impact was caused by construction (including materials) with its share being 15-18%. The variation between the buildings seem to be highest in the use of electricity, around 45% of the maximum life-cycle impact. Interestingly, the second highest variation was reported to be in finishing elements equaling 10% of the buildings' average life-cycle impact. The structural system had only a variation of 2% between the buildings.

2.6 Sensitivity analyses

In life-cycle analysis, the reference service life chosen for the buildings is often around 50 years or more (Doppelsteen et al. 2003, Herwijnen & Blok 2003, Balaras et al. 2003, UNEP 2003a). In life-cycle cost analysis, the end part of the life cycle has typically only a minor significance due to discounting. However, in environmental life-cycle assessments (LCA), the future is typically valued the same as the present, and as a result, the end part of the life cycle can have a significant influence on the overall result. Thus, the long life span of the buildings may cause the result to be unduly influenced and thus sensitive to various factors due to possible system changes in the future.

Although sensitivity analysis is a recommended part of an LCA study, it is still not a standard practice (Ross et al. 2002). However, the sensitivity has been assessed in some building LCA studies. For example, Adalberth et al. (2001) have assessed the effects of three alternative scenarios for a multi-family building in Sweden. They found that the energy mix used could have a considerable influence on the result (25-45%), but only a minor influence by the material data and the amount of operational energy, around 15%. In another study, Peuportier (2001) performed a sensitivity analysis for a single-family house in France. He tested four alternative scenarios and found that the type of heating energy used has a major influence on the result (around 40%); alternative building materials used having a minor one (18%).

Two Finnish studies have estimated the effects of numerous alternative scenarios during a building's life cycle. Junnila (1998) assessed the influence of 23 alternative scenarios of a multi-family building and found that the result is most sensitive to the assumptions made about the service life of the building (-40%-+80%) and the energy mix used (around 40%). Vaahterus and Saari (2001) tested the sensitivity of an ice-skating facility life-cycle assessment using fifteen different scenarios. They reported that the result is most sensitive to the operating hours, the indoor temperature, and the possible installation of heat recovery equipment.

Obsolescence is a special feature of a building's life cycle that has not yet been included in most sensitivity analyses. Typically, the technical life span of buildings is very long, and it can even be extended with proper maintenance. In LCAs, the life span typically used for buildings, around 50 years or more, is in technical terms quite feasible or even a cautious estimate. However, the situation may change dramatically, if obsolescence is included in the model. Lemer (1996) argues quite strongly that the impact of obsolescence has been largely neglected. In his opinion design service life is set typically based on a very limited rationale, and the assumptions of service life should in many cases be shorter than is currently common practice. Another study noticed that buildings undergo significantly more renovations to all systems (structure, enclosure, services, interior finishes) than is commonly assumed (Slaughter 2001).

The articles discussing obsolescence of buildings have indeed presented considerably shorter building life spans than are typically used in LCAs. For example, Barras & Clark (1996) in their extensive study of the obsolescence of office buildings in Central London found that over a 12 year period the net acquisition of newer properties at the expense of older ones has rejuvenated the post-war portfolio to the extent that its average age has remained fairly constant at around 15 years. In addition, they estimate that obsolescence will accelerate over the next 10-15 years. Additionally, other studies indicate that a realistic service life of a building is around 15-30 years (UNEP 2003a, Seo & Hwang 2001, Wong 2000, Iselin & Lemer 1993).

3 Methods

3.1 Research design

The research has a multiple-case design with embedded units of analysis and a positivistic orientation (Remenyi et al. 1998). The uncertainty of the result is assessed both quantitatively with the sensitivity analysis, and qualitatively according to the multiple-case methodology. A case study method was chosen because the article investigates an open system (Robson 2002); the studied phenomenon (building life cycle) is in its real life context, and the boundaries between the phenomenon and the context are not clearly evident (Yin 1989). The suitability of the case study design was also supported by the fact that multiple sources of evidence (drawings and specifications of a building, company documents, environmental statistics, interviews and observation) had to be used to collect the data needed. The chosen method also supports the goal of the study to gain in-depth knowledge of the cases; it helped to understand how and why certain life-cycle phases and elements contribute more to environmental impact than others.

A multiple- case design was used because the study *compares* the environmental characteristics of office buildings in different contexts, and also because the findings of a multiple case study are often considered more compelling than those of a single case study (Yin 2003, Green & David 1984). All the cases used in the study had embedded units of analysis: materials and energy flows that were analyzed quantitatively with the LCA method (ISO 14040). Remenyi et al. (1998) calls this kind of approach a positivistic case study, because it includes a collection of numerical evidence and the application of a mathematical analysis.

The research procedure follows mainly the guideline presented by Yin (1989). The contribution analysis of embedded units (life-cycle phases and elements) is first conducted within each case. The result is then interpreted at a single case level and is treated as a factor in a pattern-matching analysis at a single case level. The patterns or explanations for each single case is then compared between the cases, which is done following the replication mode of multiple cases. Finally, the multiple-case conclusions are drawn, which are in essence the conclusions for the overall study. In addition, some lower level cross-case analyses are conducted in order to find a range of variation for life-cycle phases and elements.

The impact of uncertainty is assessed both quantitatively, through sensitivity analysis (ISO 14040), and qualitatively with a data quality framework developed by Weidema and Wesnæs (1996) and Lindfors et al. (1995). Technically, sensitivity is the influence of one parameter (the independent variable) on the value of another (the dependent variable) (Björklund 2002). The independent variables in this study are both continuous and discrete. The system inputs are typically continuous parameters (i.e. energy consumption) and the system boundaries, allocation, model choices and process choices are discrete parameters.

The type of sensitivity analysis that is used here is scenario analysis. The scenario refers to the different choices of any model used, input parameters, and outside conditions of any system studied (Pesonen et al. 2000, Lindfors et al. 1995). Pesonen et al. (2000) separate two kinds of scenario development for LCA purposes, *What if ...* and *Cornerstone* scenarios. The *What if...* scenarios are used to compare quantitatively different alternatives in the system or to test some specific changes within the system. The *Cornerstone* scenarios are more fundamental and comparable to scenarios in future studies. The *What if...* approach was used here because specific changes in any given system with a relatively large number of scenarios needed to be tested.

The scenario analysis was performed for the processes contributing the most to the result as recommended by Heijungs and Kleijn (2000). The ranges of variation used in sensitivity analysis were determined based on empirical data, but not on statistical uncertainties (Björklund 2002). The reasoning for selecting the scenarios studied and the ranges used are presented in the chapter "description of the scenarios used".

The qualitative data quality framework used has been presented in LCA literature by Lindfors et al. (1995). The quality of data is assessed in the framework with six data quality indicators and on five quality level. A score of 1 means the best quality and that of 5 the lowest quality. The original data quality framework with a description of the performance demanded at each quality level is presented in the appended paper II.

Weidema (1998) conducted a multi-user test to investigate the repeatability of a similar data quality framework that has been used here. He concluded that the deviation of scores between different users were surprisingly low and could be kept at an acceptable level. In addition, all test persons in his study had confirmed their satisfaction with the usefulness of the qualitative-data-estimation framework.

3.2 Selection of cases

The multiple case design in this article consist of three office building cases in Finland and one in the U.S.A. The number of cases is congruent with Yin's (1989) suggestion that a multiple case study should involve approximately three cases for literal replication. The cases were chosen based on a replication logic so that all the cases having significant differences in their characteristics would still produce the same result. Remenyi (1998) calls this kind of sample, collected with a specific purpose in mind, a judgment or a purposive sample.

Both Yin (1989) and Eisenhart (1989) emphasize the significance of theoretical categories as factors guiding the choice of cases. In the study, the following principal criteria were used: office buildings should be new, and they should be designed, constructed, and used by different organizations in order to avoid the risk of having similar results due to the workings of an individual organization. The Finnish offices were, in addition, expected to be situated in Southern Finland because the majority of new office buildings are constructed there (Heinimäki & Puhto 1998). The building case in the U.S. was selected for its location comparable climate condition. Additional issues affecting the case selection were the interest of the owners to participate in the study and the amount of data available from these cases. The selected building cases are presented later in the chapter entitled "Presenting the Cases".

3.3 Assessing the environmental impact

3.3.1 Life-cycle assessment

A life-cycle-assessment framework (ISO14040 1997) was selected to assess the environmental impact of office buildings. The ISO 14040 (1997) standard defines the life-cycle assessment (LCA) as a framework for the identification, quantification, and evaluation of the inputs, outputs, and the potential environmental impact of a product, process or service throughout its life cycle, from cradle to grave, i.e., from raw material acquisition, through production, use, and to disposal. LCA is often mentioned as the most appropriate method for a holistic environmental assessment (Kohler & Moffat 2003, Curran 1996).

The start of the LCA studies is often situated in the 70's, but it was only in the 90's when the Society of Environmental Toxicology and Chemistry (SETAC) started the work to develop broad consensus on the conduct of LCA and to promote scientifically sound LCA (Consoli et al. 1993). SETAC defined the LCA as

> "a process to evaluate the environmental burdens associated with product, processes or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and materials used and released to the environmental; and to identify and evaluate opportunities to affect environmental improvements. The assessment include the entire life cycle of the product, process or activity, encompassing extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use, maintenance; recycling and final disposal."

The LCA models are based on system thinking, which states that any product or service can be described as a system (Consoli et al. 1993). The system is defined as a collection of materially and energetically connected operations (processes), which perform a defined function. The system is defined from its surrounding by a system boundary. The whole region outside the system in known as a system environment. The inventory of the system is a quantitative description of all material and energy flows across the system boundary.

A system is represented in LCA with unit processes and flows (ISO14040 1997). Unit processes are the smallest portion of the product system for which data are collected, and flows are material and energy inputs and outputs to and from the unit process. In order to compile the whole system, the unit processes are interlinked, each of which will be taking, as input, the output from an "upstream" operation and processing it into an output, which is then the input for the next operation "downstream" (Consoli et al. 1993).

Often the systems in LCA are described with using linear models, as in this study (UNEP 2003b). A linear model is a mathematical statement of the system in which the system is described via a set of linear functions. Linear functions are often simplified assumptions, but still desirable, since linear models are "well behaved", i.e. a feasible and optimum solution can be calculated (Ossenbruggen 1994). In Figure 3, an example of linear functions describing a building system in a linear model is presented.

The LCA is widely used in industry to analyze environmental issues and it could be held to be a "central tenet in industrial ecology" (Graedel & Allenby 2003). LCA is considered a systematic and most objective process for studying the life cycle (materials manufacturing, construction/manufacturing processes, use, maintenance, and end-of-life treatment) and supply-chain environmental effects of products, processes, and services. The LCA process identifies and quantifies energy and material usage and environmental releases of a given studied system, and evaluates the corresponding impact on the environment.

The LCA process consists of four main component: a goal and scope definition, an inventory analysis, an impact assessment, and an interpretation (ISO 14040). The goal and scope definition determines why the LCA is being conducted and also describes the system to be studied. The inventory analysis involves the collection and calculation procedures for quantifying relevant inputs and outputs of the system. The impact assessment evaluates the potential environmental impact in selected impact categories using the results of inventory analysis, and finally, in the interpretation, the findings of the study are combined together to reach conclusions and recommendations.

Although LCA is widely used, it is important to recognize its limitations while interpreting the results of an LCA study. All the components of the LCA still have uncertainties. Typically, the inventory stage of the LCA is thought to have the least uncertainty, and the most of the weaknesses are related to the scoping, impact assessment, and interpretation stages of the LCA (Consoli et al. 1993).

ISO 14040 (1997) has listed the following limitations to the LCA framework: subjective choices are included (e.g., system boundaries, selection of data sources and impact categories), models used in inventory and impact assessment are limited (e.g., linear instead of non-linear), local conditions may not be adequately represented by regional or global conditions, the accuracy of the study may be limited by restricted accessibility to relevant available data, and a lack of spatial and temporal dimensions introduces uncer-

```
Equations:
<Building life cycle>
BUILDING LC=1
Building GFA=1.56E+004*BUILDING LC
Building RFA=1.33E+004*BUILDING LC
Building space=6.17E+004*BUILDING LC
<Energy>
hydro, e=1.18E+004*BUILDING LC
natural gas, e=3.36E+005*BUILDING LC
nuclear, e=1.23E+003*BUILDING LC
oil, e=8.8E+003*BUILDING LC
other fuel, e=98.8*BUILDING LC
peat, e=0*BUILDING LC
petrol, e=8.82*BUILDING LC
solar, e=478*BUILDING LC
wind, e=80.4*BUILDING LC
bio fuel energy=601*BUILDING LC
coal, e=1.78E+005*BUILDING LC
diesel oil, e=2.21E+003*BUILDING LC
etc.

<Emissions to air>
aromatic HC, air=0.648*BUILDING LC
As, air=0.634*BUILDING LC
bezene, air=8.43*BUILDING LC
Cd, air=0.0846*BUILDING LC
CFC/HCFC=0.157*BUILDING LC
CH4=3.77E+005*BUILDING LC
Cl2, air=0.00102*BUILDING LC
CO=1.03E+005*BUILDING LC
CO2=1.07E+007*BUILDING LC
CO2, biogenic=4.94E+006*BUILDING LC
CO2, fossil=3.32E+007*BUILDING LC
Cr, air=1.64*BUILDING LC
Cu, air=1.07*BUILDING LC
dust=1.17E+004*BUILDING LC
F, air=0.00182*BUILDING LC
flue gas, tot=1.06E+005*BUILDING LC
H2S=0.0681*BUILDING LC
HC, air=1.82E+004*BUILDING LC
etc.
```

Figure 3. An example of linear equations describing a system (office building) in an LCA software.

tainty in the impact assessment. Some other comments made about the weaknesses of an LCA are its complexity, difficulty of obtaining usable results, risk of biased use, and the amount of required data being too large (Chevalier et al. 2002).

The limitations of the LCA inventory stage are often related to the assumptions and simplification made in relation to boundary setting, cutoffs, allocation, data sources and gaps, and also to the functional unit definition of the LCA (TemaNord 1995a). All the above-mentioned issues can have a significant influence (order of magnitude) on the result of the LCA and should thus always be stated with full transparency. Suh et al. (2003) have collected some special difficulties related to the defining of the system boundaries of the traditional process-based LCAs. They have presented the following weaknesses: there is no theoretical or empirical basis that small mass or energy flows will result in negligible environmental impacts, there are input flows that bypass the product system and do not contribute mass or energy content to the final product, inputs from the service sector cannot be properly judged on the basis of mass and energy, and the sum of all minor cutoffs may change the result considerably.

In the impact assessment stage (UNEP 2003b), the linear modeling “takes the effects of the substance into account, but not their background concentrations and the geographical dependency on fate, and aggregates the environmental consequences over time, locations and chemicals to potential impacts”. All this only allows the calculating of potential impact values, not actual damage.

The limitations related to above-described impact assessment approach of the LCA has been discussed in numerous papers. Often the limitation have been grouped under three headings: non-linearities and thresholds, temporal limitation, and spatial limitation (Seppälä 2003, Graedel 1998, TemaNord 1995b). Firstly, many of the emissions have a non-linear correlation regarding impact instead of a linear one. In addition, although the emissions are assumed to cause impact without any thresholds (sometimes called the “less is better” approach), in practice, the approach is suitable for emissions causing global problems, e.g. climate change and ozone depletion, whereas with other emissions the impact occurs only above certain threshold values (Seppälä 2003). Secondly, the environmental impacts are aggregated over a temporal scale, although the environmental effect can vary within. Typical examples are VOCs that need sunlight to cause summer smog and the emissions that cause climate change, the latter having a different relative potential causing climate change depending on the time horizon studied, e.g. 20 to 500 years. Finally, emissions can have spatial differences, i.e. emissions have different effects on different regions depending on the local characteristics of the environment. The spatially driven characterization factors (acidification, tropospheric ozone formation, terrestial eutrophication) can sometimes differ by order of magnitude in the context of regional impact categories (Seppälä 2003).

Emphasis should be made to the point that in the LCA the characterization of emissions to potential impacts, increases the uncertainty of the result, especially when comparing two different systems (Steen 1997). However, the value of the characterization is that it allows radically to condense the amount of variables under discussion (from over 100 to 5 in this study), and, in addition, it helps to address the environmental impact values under the same themes as typically used for environmental policy objectives. As a whole, the use of characterization significantly facilitates the interpretation of the result (Graedel & Allenby 2003, Lindfors et al. 1995).

Erlandsson and Borg (2003) have studied, in addition, the building and construction sector-specific problems related to the use of the LCA method. They have concluded that the problems are mainly due to the special characteristics of the sector, such as the fact that the functional output is a service rather than a product, the system behind the services is dynamic, and the functional service has a defined service life that differs from the service life of the products used.

3.3.2 Scope of the life-cycle assessment

A detailed description of the scope of the individual LCAs, included in this summary, can be found in the appended papers, especially in papers I, II, III, VI. Only a broad description of the scope is provided here.

The scope of the LCA covers the life cycle of three new office buildings in Southern Finland and one in the Midwest region of the U.S.A. Fifty years of use was assumed to be the basic service life of the buildings. In the comparison, the results are presented per gross floor area of the buildings. The LCA included all the life-cycle stages of an office building: extracting and processing raw materials, building materials manufacturing, construction processes, building operations (electricity, heating and other services), maintenance, and demolition. All the phases included transportations. The quality of the data was targeted at the level of “good”, which corresponds to the second highest level (two of five) in the selected framework (Weidema & Wesnæs 1996, Lindfors et al. 1995).

The electricity use of the buildings included also the electricity used by the office equipment (through the outlets). The effects of excluding outlet-electricity from the system studied was tested later in the sensitivity analysis. The basic service life of a building was not assumed to include any major refurbishment activities. Minor refurbishment activities, up to renewal of windows, are included in the maintenance activities. The effects of major refurbishment based on obsolescence were discussed in the scenario analysis.

All the ancillary inputs anticipated to be significant for the goal of the study were included in the study and traced back to extraction and landfill, e.g. fuels for the machinery and equipment, spillage and packaging, water used for courtyard care and gardening. Minor ancillary inputs, though, were excluded from the system e.g. capital equipment, materials used in cleaning, ancillary inputs from design and other similar services, and the transportation of and the food for employees. In the wood biomass formulation, the natural ecosystem was assumed to be included in the system i.e. the CO_2 emissions from the burning of renewable fuels were not assumed to have an impact on climate change. In the U.S. case study that was used in the sensitivity analysis also the minor ancillary inputs were included in the system due to the use of an EIO-LCA in the inventory phase (Hendrickson et al. 1998).

The primary data in the inventory stage, i.e. the data directly obtained from the projects studied (Consoli et al. 1993), were collected during the design and construction of the office buildings. The buildings are owned, designed, constructed, and operated by different companies, and they were constructed during the years 1998 - 2001. The data for the buildings were compiled mainly from the plans and specifications for each of them. Other data sources used included interviews, archival records and direct observations.

The amounts of materials in the buildings were collected according to the Finnish building classification system (Kiiras & Tiula 1999). The following building elements were included in the study: construction site (e.g., excavation and fillings for pavements, pipelines), substructure, foundation, structural frame, external envelope, roof, internal complementaries (e.g., doors, partition walls, suspended ceilings, railings), internal surfaces, elevators, mechanical services, and electrical services. The only category of the classification not included in the study was the materials used in the internal equipment (e.g., refrigerators and furniture). Building case B had no actual foundation, because it was constructed on top of an underground parking structure. The main source of data was the bill of quantities (quantity take-off), the architectural and engineering drawings, and the architect's specifications.

The construction phase of the building included all the materials and energy used in the on-site activities. Data were collected for the use of electricity, heat and steam on site, use of equipment, transportation of building materials to the site, materials used on site (needed in the construction processes, but not permanently attached to the building such as formwork, temporary structures, etc.), waste management, and water use. The data were mainly collected from the contractors' bookkeeping, and were further ascertained by interviews. Transportation of materials was included in each life-cycle phase and was divided by the following principle between the building materials and construction phases: the building materials phase included the transportation of materials to the producer's or wholesaler's warehouse, and in the construction phase from the warehouse to the site.

The operation phase of the building was divided into heating service, electricity service, and other services (water use, wastewater generation, courtyard care/landscaping, and office waste generation). The energy consumption calculations of the building were performed by a HVAC and electrical designer using the IDA indoor climate and energy simulation program (IDA 2002) or the WinEtana (VTT 2003) energy simulation program. The estimated heat and electricity consumption values were drawn from their calculations. For case A, the energy consumption estimation was later double-checked against actual consumption data. Material and energy use in the other services were estimated using relevant regional and Finnish averages for offices. The figures for water consumption and wastewater generation were taken from the facility manager's handbook (HUT 1992) and from annual consumption data (Case A), courtyard care/landscaping from another building case study (Junnila & Saari 1998), and the amount of office waste from a manual (YTV 1996) or annual waste data (Case A).

The maintenance phase included all the life-cycle elements needed during the 50 years of maintenance: use of building materials, construction activities, and waste management of discarded building materials. An estimated 73% of building materials, based on Finnish averages, was assumed to be landfilled and 27% recovered for other purposes such as in the recycling to new products (SYKE 1999). Maintenance did not include any modernization or other similarly fundamental improvement measures. The building materials required in maintenance were derived from the drawings and specifications of the building, and the service life of each material was estimated based on appropriate guidelines (Building Information 1998a, Building Information 1998b, HUT 1993).

The demolition phase included all demolition activities on site, transportation of discarded building materials (73% of total) to a landfill, and that of the recovered building materials to a recycling site (SYKE 1999). The entire building was assumed to be demolished. The energy needed for demolition was estimated based on another case study (Junnila & Saari 1998).

The secondary data of the inventory (data obtained from published sources) were mainly collected from the actual building material, component, and energy producers in Finland. The data for building materials were typically of a "cradle-to-gate", less than 5 years old, and it had been verified by an independent third party organization. (Neuvonen 2002). Energy production data were collected from the actual energy providers in Finland (Helsingin Energia 2000, Vantaa Energy 2000, Ahonen 2000), and the up-stream emissions, i.e. the emissions from the life-cycle stages before the energy production, were taken from a Finnish LCA database for energy (Virtanen et al. 1996). Water treatment data were taken from the actual company providing water and wastewater services (Helsingin vesi 1999), and the transportation data from the LIPASTO database (Mäkelä 2002) with an up-stream complementation from LCA databases (SimaPro

2002, KCL-ECO 1999, Boustead 1997). Additionally the emissions related to some minor material flows were taken from the above mentioned databases. The benefits (reduced emissions) gained by combined heat and power production, typical in Finland, were allocated to the products (electricity and district heating) in proportion to the fuel consumption needed by the alternative non-CHP production plants in order to produce separately the same products, electricity and district heating (Liikanen 1999).

In the impact assessment, the following impact categories were studied: climate change, acidification, eutrophication, and dispersion of harmful substances, which included summer smog and heavy metals. The impact categories were chosen according to those designated by the Finnish Environmental Institute, with the exception of ozone layer depletion (Rosenström & Palosaari 2002), and they were calculated using the Kcl-Eco software with Eco-Indicator 95 equivalency factors in characterization (KCL-ECO 1999). The impact assessment was conducted only until the end of the mandatory step of impact assessment, where the emissions from the inventory are classified and characterized but not valuated (UNEP 2003b). In the Finnish-U.S. comparison, the emissions of the buildings were compared instead of impacts because of the limitation of the European scale used in impact assessment characterization (Goedkoop 1995).

The result of the impact assessment has been presented both by quantifying the overall environmental impact of specific buildings and by comparing the contribution of each life-cycle phase and element of the buildings studied aiming at identifying possible characteristic “patterns” which would allow one to generalize according to the replication logic used in case studies (Yin 1989). The variability among the three buildings has been discussed by stating the range of such variation (the difference between the highest and lowest value) at both the life-cycle phase and element level. The range of variation has been calculated as the ratio (percentage unit) of the range and the highest impact value.

In the interpretation phase of the LCA, the results of the environmental key issues identification, sensitivity analysis, and data quality assessment are presented. The key issues are defined according to Heijung (1996) as the elements of a life cycle that have a high contribution and variability. The sensitivity analysis includes a scenario analysis, but also some specific inquires dealing with the influence of the smaller flows of materials, local conditions, and service instead of the product life-cycle phase approach in analysing the result. Finally, the data quality issues and optional impact assessment practices are also discussed in the interpretation chapter.

For the U.S. building used in he sensitivity analysis, the identification and quantification of material and energy flows were performed based on the plans, specifications, and estimates of a theoretical building. Process-based emissions data were used for all life-cycle phases, except for the materials manufacturing phase, and the material and electricity components of the other phases. Material emissions data include the manufacturing process (direct) as well as the supply-chain (indirect) emissions. This is achieved by quantifying the life-cycle impact of the materials using the economic input-output analysis-based LCA (EIO-LCA 2003, Hendrickson et al. 1998) that utilizes data from the U.S. Department of Commerce's commodity-by-commodity input-output matrix augmented by various resource use, waste, and emissions factors. Only the relative contribution of different life-cycle phases, not the absolute values, were compared between the Finnish and U.S. office buildings because of both the wider inclusion of the ancillary flows (indirect) through the EIO-LCA of the U.S. case (Suh et al. 2003, Hendrickson et al. 1998) and the above mentioned limitation of the European scale used in impact assessment characterization (Goedkoop 1995).

4 Presenting the cases

4.1 Characteristics of the case buildings

Case A is a new top-end office building occupied by administrative employees [III, IV, V]. The building has 24000 m^2 of gross floor area, and a volume of 110000 m^3. The building consists of a single office tower with nine floors and it has a prefabricated reinforced concrete framework with pre-stressed slabs. The exterior wall has a double glass facade system. The inner facade is made of painted concrete sandwich or mineral wool insulated steel panels. The building has two major partition wall types, one made of calcium-silicate bricks, and the other of gypsum board with glue-laminated studs and mineral wool sounding boards. The calculated heating energy consumption of the building is 15 kWh/m^3/yr, which is some 55% below the average heat consumption of new office buildings in Finland, and electricity consumption is 39 kWh/m^3/yr, which is some 37% above the average in Finland (Suomi 2003). Almost 130 different building parts and fifty different building material groups were identified in the inventory phase.

Case B is a new high-end office building [II, IV, V, VII and VIII]. The users of the building are medium-sized high-tech organizations. The building has 15600 m^2 of gross floor area, and a volume of 61700 m^3. The building consists of three 5-story office towers. The structural frame is made of in situ cast concrete. The most common exterior wall structure is a masonry wall made of clay bricks having a steel-profile support and mineral wool insulation. The building has two major partition wall types, one made of calcium-silicate bricks, and the other of particleboard with glue-laminated studs and mineral wool sounding board. The calculated heating energy consumption of the building is 18 kWh/m^3/yr, which is some 46% below the average heat consumption of new office buildings in Finland, and electricity consumption is 25 kWh/m^3/yr, which is some 11% below the average in Finland (Suomi 2003). More than 120 different building parts consisting of over fifty different building material groups were identified in the inventory.

Case C is a new intermediate office building [I, IV, V and VI]. The users of the building are medium-sized public and private organizations. The building has 4400 m^2 of gross floor area, and a volume of 17300 m^3. The building has one office tower with four floors. The structural frame is a beam-and-column system with pre-fabricated concrete elements. The exterior wall is made of concrete sandwich-panels, and the partition walls of gypsum board with steel-profile studding and mineral wool sounding boards. The calculated heat energy consumption of the building is 36 $kWh/m^3/yr$, which is 8% above the average heat consumption of new office buildings in Finland, and the estimated electricity consumption is 18 $kWh/m^3/yr$, which is some 36% below the average in Finland (Suomi 2003). More than fifty different building parts and fifty material groups were identified in the inventory phase.

The U.S. building chosen for the sensitivity analysis is a typical office building in the Midwest region [VI]. The location and size was selected to match more closely the climate conditions in the Finnish case building study C. The five-story building has 4400 m^2 of gross floor area, and a volume of 16400 m^3. The structural frame is a steel-reinforced concrete beam-and-column system with shear walls at the core. The exterior envelope of the building consists of an aluminum curtain wall. For the Midwest office building, yearly electricity use is estimated at 49 kWh/m^3 and natural gas use at 4,7 m^3/m^3 (EIA 1998). The annual energy consumption for lighting is assumed to be 15 kWh/m^3 (Vorsatz 1997).

4.2 Description of scenarios used

Building case B was chosen for the scenario analysis, presented above. The alternative scenarios used in the scenario analysis are described shortly below and also presented in Table 1. A more detailed description of the scenario analysis is presented in the appended paper VII.

The alternative scenarios for the electricity mix and heating energy mix are based on data from the actual energy companies providing electricity and/or heating energy in Finland. The emissions of electricity and/or heating energy generation were taken from the environmental reports of the selected companies. In the case of combined heat and power production (CHP), the emissions were allocated to the products (electricity and district heating) in proportion to the fuel consumption needed by the alternative non-CHP production plants in order to produce separately the same products, electricity and district heating (Liikanen 1999). The up-stream life-cycle stages before the energy production were taken from the SEEP (Virtanen et al. 1996) database.

The scenario for wastewater treatment was tested with one theoretical and one actual treatment plant. Instead of the current plant, a theoretical that fulfills the requirements of the new urban wastewater treatment directive (Council Directive 2003) was used (mostly the current plant already performs better than the new requirements, in which case the current performance has been maintained). The pessimistic scenario was based on a low-performance, but still operating treatment plant in Finland (Finnish Environment Institute 2003).

In the case of the manufacturing of building materials, the pessimistic scenario was based on older production data (10-15 years old) within a wider geographical area (US, OECD) resulting in an average 31% increase in major emissions (Boustead 1997). The optimistic scenario was based on a theoretical 30% reduction value in all emissions.

Table 1. The scenarios used in the sensitivity analysis.

Outside condition and model assumptions	**Optimistic**	**Expected**	**Pessimistic**
Electricity mix		CHP	CHP
- hydro	42 %	-	-
- gas	-	50 %	-
- coal	-	17 %	95 %
- nuclear	58 %	11 %	-
- other	-	21 %	5 %
Heating energy mix	CHP	CHP	CHP
- bio (wood, peat)	71 %	-	-
- recycled paper	19 %	-	-
- natural gas	-	63 %	-
- coal	-	35 %	95 %
- others	10 %	7 %	5 %
Water treatment			
- P, w	90 %	90 %	74 %
- N, w	80 %	60 %	15 %
Materials manufacturing	-30 %	Finland	30 %
Recycling metals	50-90%	no allocation	no allocation
Recycling all	40-90%	no allocation	no allocation
Inputs	**Optimistic**	**Expected**	**Pessimistic**
Operating electricity	-50 %	25 kWh/m^3	50 %
Operating heat	-35 %	18 kWh/m^3	35 %
Maintenance cycles			
Steel profile			
-external envelope	-15 %	40 yrs	15 %
-roof	-20 %	30 yrs	20 %
-ventilation plant	-10 %	25 yrs	10 %
Paints			
-external surfaces	-15 %	15 yrs	15 %
-internal surfaces	-60 %	10 yrs	60 %
Obsolescence	**Optimistic**	**Expected**	**Pessimistic**
Rebuilding	>50 yrs	>50 yrs	30 yrs
Refurbishment	>50 yrs	>50 yrs	15 yrs

In the base case scenario no allocation of emissions was assumed for the future products that are made of the recycled building materials from the case buildings. The first alternative scenario assumed a 90% recycling ratio and endless recycling for the metals used in the building equaling a 50-90% allocation to the future (Building Information 2003). The second scenario assumed the same for metals, but in addition, a 90% recycling ratio with one time recycling for all other building materials equaling a theoretical 40% allocation to future products.

The scenarios for the operational electricity consumption were created based on statistical data of energy-audited private sector offices in Finland (Suomi 2003). The operational energy of the office was assumed to vary by the amount of the standard deviation of the metered offices, which equals ±50%. The scenarios for the operational heat consumption were created based on the same data source having a range of ±35% for heating.

The building material maintenance scenario was based on a Finnish maintenance guideline (Building Information 1998a). The variations in maintenance cycles for building materials or elements were typically 10-20% of the reported maintenance cycle, with the exception of painted surfaces where a variation of 50-60% was reported.

The effects of obsolescence were tested with two scenarios. The first scenario assumed a total rebuilding of the office once during the life cycle of fifty years. The second scenario assumed a major refurbishment of the building every fifteen years (Barras & Clark 1996). The major refurbishment included the renewal of the following building components: internal complementaries, building services, and all the internal surfaces.

5 Results

5.1 Environmental impact of case buildings

The results of the impact assessment of the three office buildings are presented in Figure 4 and in more detail in papers I, II, III, V. The result shows that there are some differences between the buildings studied. Case A has the highest impact in almost all categories and B the lowest. The impact values of case B are around 30-45 % less than the corresponding values in case C, with the exception of the heavy metals category in which the impact value is 55% less.

For the purpose of the comparison, the results have been normalized per gross floor area of the buildings, which is often used for normalizations in the construction business in Finland (Kiiras & Tiula 1999). Before examining in some detail the influence of the selected normalizing factor, it should be emphasized that although the selection of any given normalizing factor affects the results in absolute values (comparison of the environmental impact of building cases), it does not affect the results in relative values (comparison of the environmental contribution of the building life-cycle phases), which is the main purpose of the study. One building specific feature affecting all the reported (absolute) impact values is the height of spaces. Because case A has a higher cubic content per gross floor area (m^3/m^2 = 4,6) than cases B (4,0) and C (3,9), the result of case A per m^2 are roughly 15% higher than they would be per m^3.

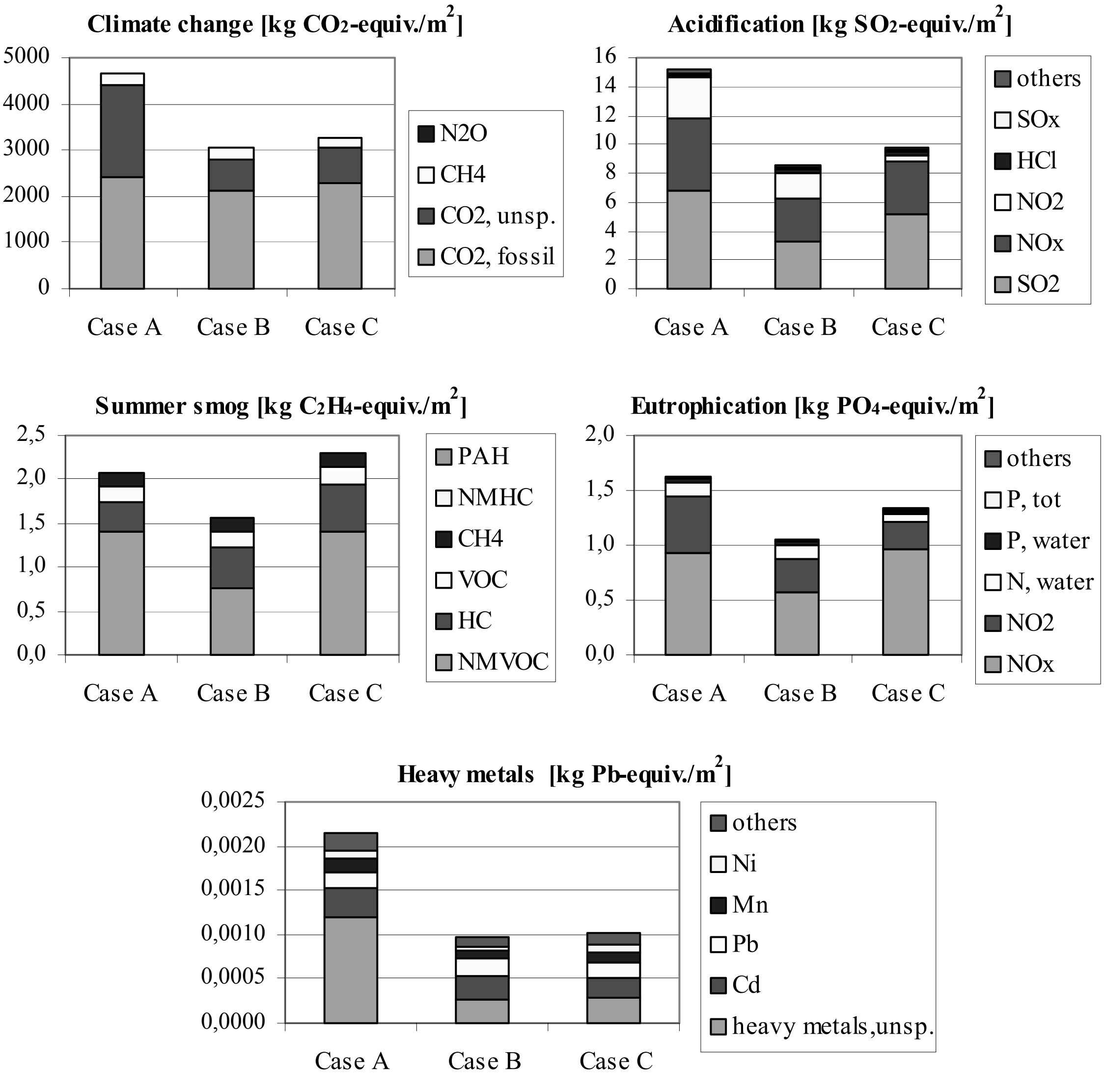


Figure 4. Environmental impact of three office buildings (V).

Another alternative, besides the building size, for normalizing the environmental impact values of the buildings studied could be the function or service that the building delivers. For this purpose, at least two different normalization factors could be used, namely the number of occupants in the building or the usable floor area. An accurate number of occupants for the cases studied were not available, but a rough estimates would suggest that, if the estimated number of occupants were used, it would not reduce the difference between case A and the others since A has fewer expected occupants per m^2. However, the influence of the actual number of occupants (dependent on both design and underutilization) could be significant. In another study, Junnila & Nousiainen (2004) have found that in six case organizations the actual number of occupants per net floor area of an office building ranged from 21 to 33 net-m^2/occupant with a median of 29 net-m^2/occupant. Such a wide variation in the number of occupants would, of course, have a considerable influence on the results.

The other and more traditional indicator for estimating the functional value of a building is that of the usable floor area i.e. the net floor area of the building (net-m^2). In the cases studied, the ratio of net and gross floor area (net-m^2 / gross-m^2) was 0,72 for case A, 0,86 for case B and 0,75 for case C. Thus, using the net floor area as the normalizing factor would further increase the difference between case B and the others by around 20%. To put the space efficiency of building cases in a wider perspective, their efficiency is compared to the efficiency of a "typical" cost-effective office building (Haahtela & Kiiras 1999). The ratio of net and gross floor area in the "typical" cost-effective office building is 0,88, which is, as can be seen, very close to that of building case B.

Figure 4 also shows that quite a low number of emissions (1-3) in each impact category are responsible for most of the impact. In the climate change category, the significant emissions are non-renewable CO_2 and unspecified CO_2; in acidification SO_2 and NO_X, in eutrophication NO_X and NO_2, in summer smog non-methane VOC and unspecified hydrocarbons, and in heavy metals cadmium, lead, and a group of unspecified heavy metals.

5.2 Contribution of life-cycle phases and elements

5.2.1 Life-cycle phases

The environmental impact of the office buildings studied is presented in Figure 5 by life-cycle phases [I, II, III, V, VIII]. The contribution of phases in different cases seems to follow a similar pattern: the use of a given building with its consumption of electricity, heating and other services dominates the impact in the climate change, acidification, and eutrophication categories with its proportion being 70-85%, whereas the impact of summer smog and heavy metals are mainly caused by the phases of building material manufacturing in construction and maintenance with their proportion being 40-80%. In the heavy metals category, the consumption of electricity is also significant. The order of magnitude between the life-cycle phases is mainly the same for each building. The only clear exceptions are the statuses of electricity and heating services. In case C, the heating service has a higher impact, whereas in cases A and B the electricity service contributes more.

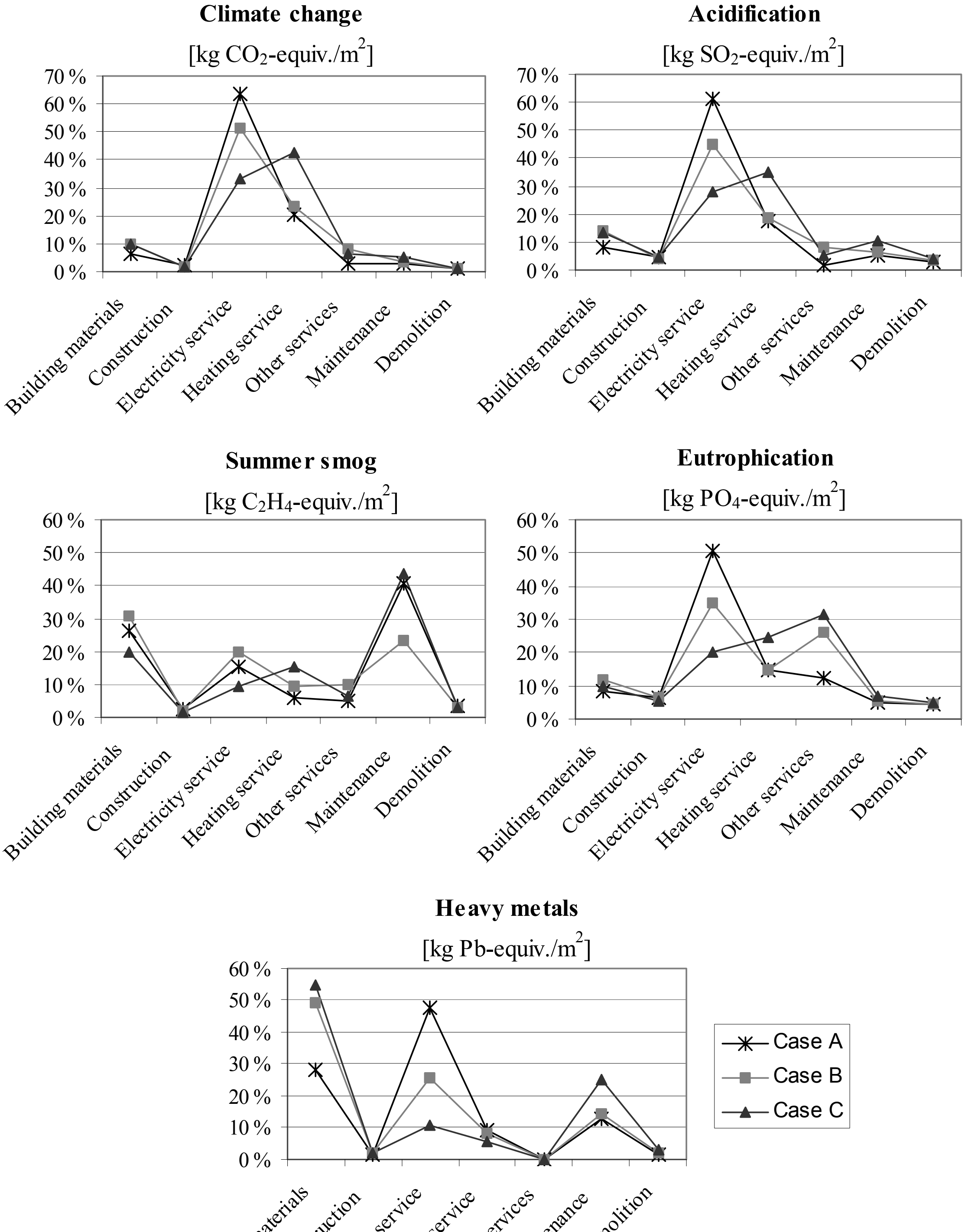


Figure 5. Environmental contribution of three office buildings by life-cycle phases.

The differences in results of the buildings studied are clearly widest in the electricity service where the range is often around 30%-units. In other life-cycle phases, the range between the buildings remains mostly under 15%-units.

5.2.2 Life-cycle elements

The life-cycle impact of the three office building case studies is here presented in more detail; each life-cycle phase studied (building materials, construction, electricity, heating and other services, maintenance, and demolition) is further divided into life-cycle elements. A wider description of the environmental impact of life-cycle element is provided in papers I, II, III, and V. The contribution of the elements studied and the elements having the widest range are presented in compact form in Table 2.

Here as well, the buildings seem to follow a similar pattern; the same life-cycle elements tend to stand out as significant. The elements contributing most to the environmental impact are the electricity in outlets, HVAC, and lighting, causing constantly high contributions (often 10% to 30% of the overall contribution). The heat in conduction and ventilation, internal surfaces in maintenance, and structural frame and building services in building materials cause the second greatest impact, having occasionally high contributions.

When examining the differences between the buildings, two of the elements studied stand out clearly, namely the electricity in outlets and the surfaces in maintenance both have a range of more than 20%-units in some impact category. Additionally, the heat in ventilation, the electricity in lightning, the electricity in HVAC, and the use of water and wastewater all have a notable range in some impact categories, 10-20%-units. The table shows also that the elements contributing the most are almost the same as the ones having the widest range. However, building materials and heat in conduction are exceptions. In those life-cycle elements a high contribution does not indicate a wide range.

Table 2. Environmental impact of three office buildings by life-cycle elements. The elements contributing the most are in bold type and the ones with widest range underlined. The (-) indicates no data was available (V).

	Climate change [CO$_2$ eq./m^2]			Acidification [SO$_2$ eq./m^2]			Summer smog [C$_2$H$_4$ eq./m^2]			Eutrophication [PO$_4$ eq./m^2]			Heavy metals [Pb eq./m^2]		
Case A	4700 kg			15,1 kg			2,1 kg			1,6 kg			0,0021 kg		
Case B	3100 kg			8,5 kg			1,6 kg			1,0 kg			0,0010 kg		
Case C	3300 kg			9,8 kg			2,3 kg			1,3 kg			0,0010 kg		
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Building materials	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
Structural frame	2	3	3	2	3	2	5	5	3	2	4	2	7	**12**	9
External envelope	1	2	2	2	3	2	2	7	2	1	2	2	3	7	3
Complementaries	1	1	1	1	2	2	4	6	2	1	2	1	2	4	3
HVAC services	1	1	1	1	1	1	4	3	4	0	0	1	6	7	**14**
Foundations	0	0	1	1	1	1	0	1	0	1	1	1	1	1	3
Roof elements	0	1	1	0	1	2	1	5	4	1	1	1	1	3	6
Substructure	0	0	0	0	0	1	0	0	0	0	0	1	1	0	2
Electrical services	0	0	0	0	1	1	1	1	1	0	1	0	5	**12**	**12**
Surfaces (int.)	0	0	0	0	1	1	9	2	3	1	1	0	1	1	1
Constructions on plot	0	0	0	0	1	0	0	0	0	0	1	0	0	1	1
Lifts, escalators	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Construction															
Equipment	1	1	1	2	2	2	2	1	1	3	3	2	-	-	-
Energy	1	1	1	1	1	1	0	0	0	1	0	0	1	1	1
Materials in construction	0	0	0	1	1	1	0	1	0	1	1	1	1	2	1
Transportation	0	0	0	1	0	1	0	0	0	1	0	1	0	0	0
Others	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0
Use of building															
Electricity, outlet	**28**	**19**	**11**	**26**	**17**	9	7	8	3	**22**	**12**	7	**21**	9	4
Electricity, HVAC	**18**	**17**	**12**	**17**	**14**	**10**	4	6	3	**14**	**11**	7	**14**	8	4
Electricity, lighting	**18**	**16**	10	**17**	**14**	8	4	6	3	**14**	**11**	6	**14**	8	3
Heat, conduction	**10**	**14**	**17**	9	**11**	**14**	3	6	6	7	8	9	5	5	2
Heat, hot water	6	1	3	5	1	2	2	1	1	5	1	2	3	0	0
Office waste mgnt	3	7	5	1	5	3	4	9	5	2	5	4	0	0	0
Heat, ventilation	2	6	**22**	2	5	**17**	1	2	8	1	4	**12**	1	2	3
Heat, loss in air leakage	1	3	2	1	2	1	0	1	1	1	2	1	1	1	0
Courtyard care	0	1	0	1	3	1	0	1	0	1	4	2	0	0	0
Water and wastewater	0	0	0	0	0	1	1	1	1	10	**14**	**25**	-	-	-
Maintenance															
HVAC services	1	1	0	1	1	0	4	2	0	0	1	0	6	2	1
Complementaries	1	1	1	1	2	2	4	9	3	1	1	1	2	4	3
Surfaces (int.)	0	0	1	1	1	3	**28**	6	**33**	1	1	2	2	2	8
Maintenace works	0	0	0	1	1	1	1	0	1	2	1	1	0	0	0
External envelope	0	1	1	1	1	2	2	3	4	1	1	1	1	3	3
Roof elements	0	0	1	0	0	2	1	3	4	0	0	1	0	2	6
Constructions on plot	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lifts, escalators	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Structural frame	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Electrical services	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Substructure	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Foundations	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Demolition															
Waste management	1	1	1	2	2	3	3	2	2	4	3	4	2	2	3
Demolition equipment	0	0	0	1	1	1	0	1	0	1	1	1	-	-	-

6 Interpretation of the results

6.1 Environmental key issues

In Figure 6, the so called environmental key issues are presented, the key issues being defined according to Heijung (1996) as an element having a high contribution and variability. The key issues in the Figure 6 have been selected primarily to have a wide range of variation and secondly to contribute significantly to the result. The selected environmental key issues based on the three Finnish office building case studies are electricity in outlets, lighting and HVAC, heat in ventilation and conduction, materials in internal surfaces and HVAC services, and the use of water and wastewater. The defined eight elements (20% of all elements) together caused 45-75% of the average life-cycle impact of the buildings and 60-75% of the cumulative range.

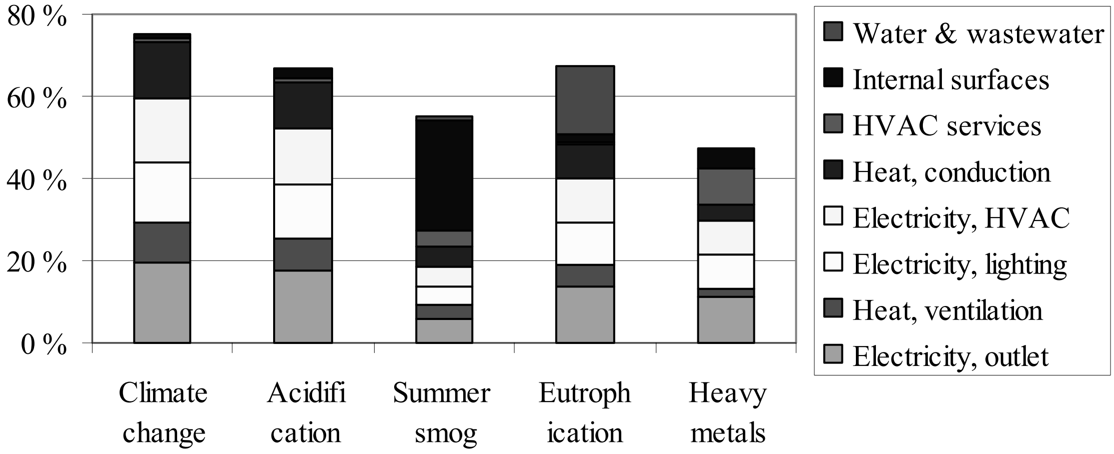


Figure 6. The life-cycle contribution of environmentally key issues of an office building based on the three case study offices (V).

6.2 Sensitivity analysis

6.2.1 Scenario Analysis

The result of the scenario analysis, which was used to assess the effects of changes in the outside conditions, model used and input parameters are presented in Table 3 [VII]. As the Table 3 shows, the alternative scenarios can have a significant influence on the results of the study. The scenarios with the highest influence were related to outside conditions and model assumptions; the electricity mix (pessimistic and optimistic), rebuilding (pessimistic), heating energy mix (pessimistic), and refurbishment (pessimistic) all caused a variation of 50% or more in at least one impact category (electricity mix

Table 3. Results of scenario analysis of an office building life-cycle assessment (VII). The scenarios having an impact of more than 50% are in bold type and underlined. The scenarios having an impact of more than 25% are in bold type.

Sensitivity Analysis Scenarios	Climate change [CO_2 eq.]	Acidification [SO_2 eq.]	Summer smog [H_2C_4 eq.]	Eutrophication [PO_4 eq.]	Heavy metals [Pb eq.]
Base Case	48 000 ton	130 000 kg	24 000 kg	16 000 kg	15 kg
Electricity mix, optimistic	**-52 %**	**-43 %**	-17 %	**-31 %**	**-27 %**
Electricity mix, pessimistic	**60 %**	**119 %**	-6 %	**58 %**	2 %
Heating energy mix, optimistic	-19 %	18 %	-3 %	1 %	-3 %
Heating energy mix, pessimistic	21 %	**42 %**	-3 %	21 %	**52 %**
Water treatment, optimistic	0 %	0 %	0 %	-6 %	0 %
Water treatment, pessimistic	0 %	0 %	0 %	19 %	0 %
Materials manufact., optimistic	-4 %	-8 %	-17 %	-6 %	-20 %
Materials manufact., pessimistic	4 %	8 %	21 %	6 %	20 %
Recycling, metals	-3 %	2 %	-21 %	2 %	3 %
Recycling, all	-8 %	-8 %	**-38 %**	-6 %	-20 %
Operational electricity, optimistic	**-27 %**	-23 %	-8 %	-13 %	-13 %
Operational electricity, pessimistic	**27 %**	23 %	13 %	19 %	13 %
Operational heat, optimistic	-8 %	-8 %	0 %	-6 %	0 %
Operational heat, pessimistic	8 %	8 %	4 %	6 %	7 %
Maintenance, optimistic	0 %	0 %	-8 %	0 %	0 %
Maintenance, pessimistic	0 %	0 %	13 %	0 %	7 %
Rebuilding, pessimistic	13 %	23 %	**38 %**	**25 %**	**53 %**
Refurbishment, pessimistic	6 %	15 %	**33 %**	13 %	**60 %**

– pessimistic even in three). The input scenarios with greatest effect, over 25%, were operational electricity (pessimistic, optimistic) and recycling (all materials). Water treatment and maintenance scenarios seemed to have the least significant influence on the results.

6.2.2 Minor material flows

Here the sensitivity of the building LCAs to the inclusion and exclusion of the smaller flows of materials (by weight) of the system studied is investigated. The effect of the smaller flows of materials is an important issue, especially in the screening product life-cycle assessments were different kind of cutoff criteria are often used (Graedel & Allenby 2003, Wenzel 1998, TemaNord 1995a). The significance of the smaller flows of materials is studied in more detail in papers IV and VIII.

Figure 7 compares the weight and environmental impact of building materials used in the structures of three office building cases. The structural elements included in the comparison were the foundations, structural frame, external envelope, roof, internal complementaries, internal surfaces, elevators, and mechanical and electrical services.

Figure 7 shows that the result is dominated by two major material groups, namely reinforced concrete and steel. They are responsible for 80-90% of the material flows for the building and 40 to 80% of the environmental impact. On the other hand, the figure also shows that the smaller flows of materials (by weight) have a significant influence on the result. For example, the lower 5 percentile of the material flows produce 15-40% of the

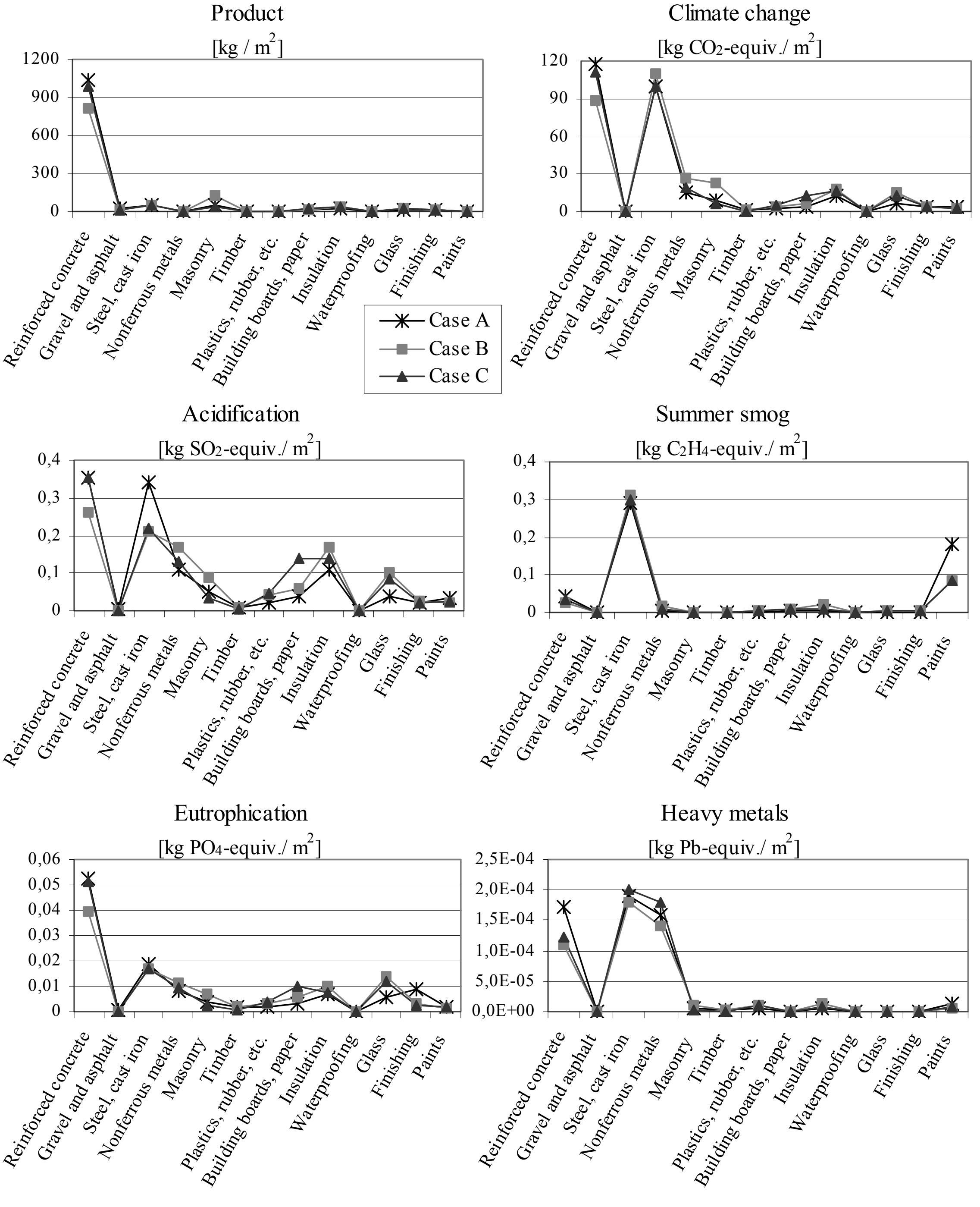


Figure 7. Environmental impact of the structures of three office buildings by building materials. The graphs compare the weight of building materials with their environmental impact (IV).

environmental impact. Respectively, 2 percentile of the material flows produce 10-35% of the environmental impact, and even the least 0,5 percentile produce 1-35% of the overall impact. The effect of the smaller flows of materials is especially strong in the summer smog category and weakest in the climate change category. The strong effect in the summer smog category is mainly due to the paints used in the buildings. The paints having about 0,1% of the materials produce still 20-30% of summer smog impact in the specific buildings.

At the whole system level (all life-cycle phases are included as opposed to merely the building structures), the overall significance of the smaller flows of materials decreases considerably in some impact categories. For example, in the climate change category, the contribution of the least 5%, 2% and 0,5% of the material flows is 2-3%, 1-2% and c.1% respectively. Additionally, in the acidification and eutrophication categories the impact of the smaller flows of materials remains relatively low. However, in the summer smog category, even the least 0,5% of material flows account for between 20 and 40% of the environmental impact of the whole building life cycle. Also in the heavy metals category the effect of the least 0,5% of material flows is still quite considerable, between 5 and 15%.

6.2.3 Local conditions

The sensitivity of building LCA vis-a-vis the local conditions in different countries is discussed here. The life-cycle contribution of two office buildings, located in Finland and the other in the U.S. are compared here and in detail in paper VI. Both buildings were calculated based on local design and emission data.

Even though the buildings are on two different continents and the case studies include comparable construction technologies but dissimilar operating and maintenance schedules with different input energy mixes, the proportions of emissions associated with the different life-cycle phases of the buildings are similar. As we can see from the Figures 8 and 9, the use phase dominates most of the emissions studied. The average proportions of the life-cycle phases of the emissions studied of the Finnish building are 15% for the materials, 4% for construction, 71% for use, 10% for maintenance, and 1% for end-of-life. The equivalents for the U.S. building are 13%, 5%, 70%, 9%, and 3%. The difference in average proportions is 2%-units or less in all the life-cycle phases.

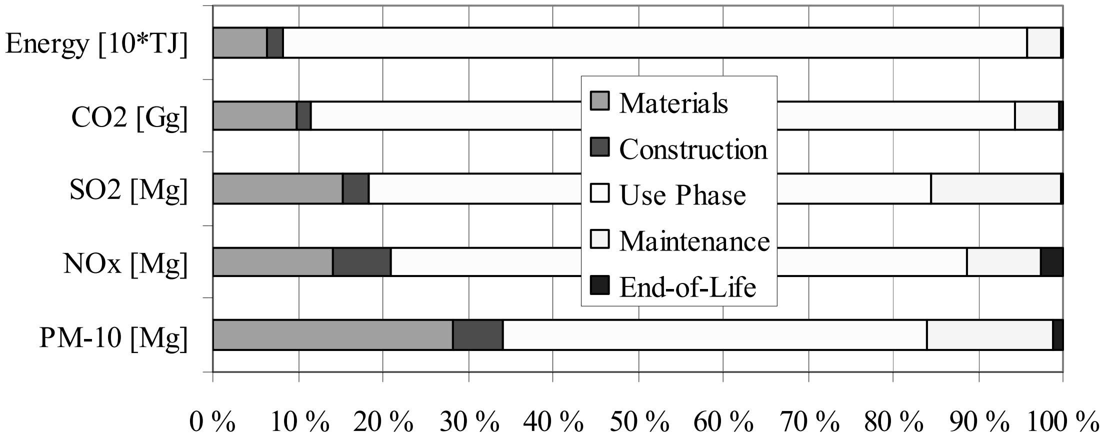


Figure 8. European case study proportions of emissions attributed to each life-cycle phase (VI).

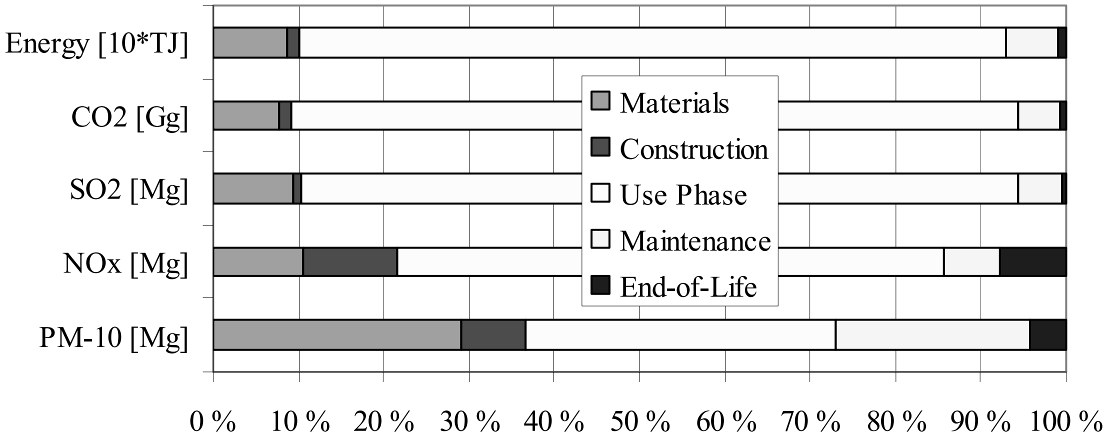


Figure 9. American case study proportions of emissions attributed to each life-cycle phase (VI).

6.2.4 Building systems vs. life-cycle phases

Above, the environmental impact of the buildings' life cycle were analyzed by chronological life-cycle phases from beginning of the building life cycle to the end. However, the functional output of a building could also be seen as a service rather than a product (Erlandsson & Borg 2003). In practice, the building design process also proceeds by building systems (equaling services), not by chronological life-cycle phases.

The life-cycle elements belonging to different building systems are grouped together here, and the life-cycle impact of each building system – structural, HVAC, electrical, site layout, construction processes, and user-focused systems – are calculated. The structural system includes building materials of structural elements, heat conduction through structures, maintenance of structures, and demolition and disposal of structural

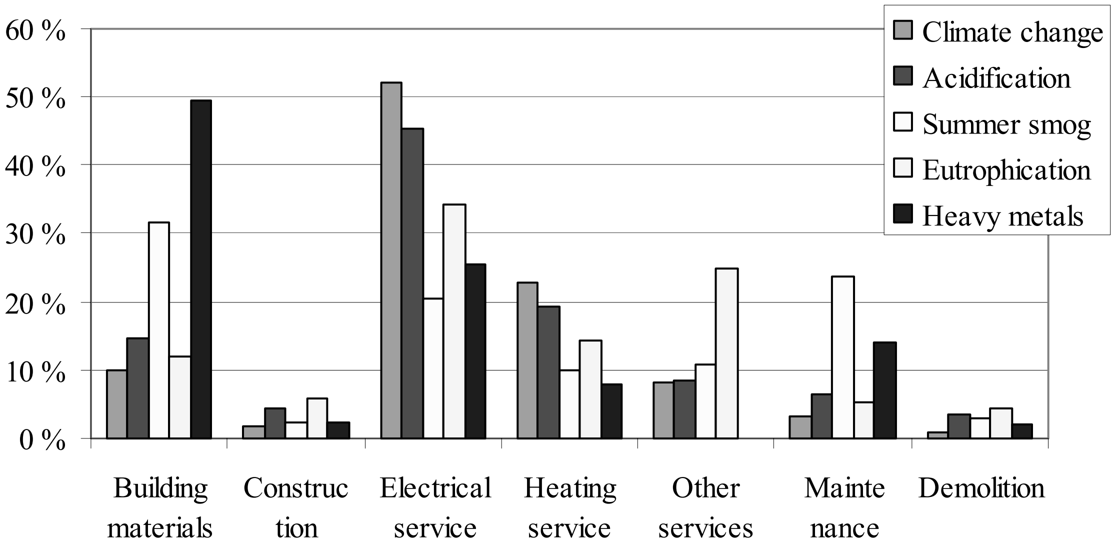


Figure 10. Environmental impact of an office building by building life-cycle phases over 50 years of service life (II).

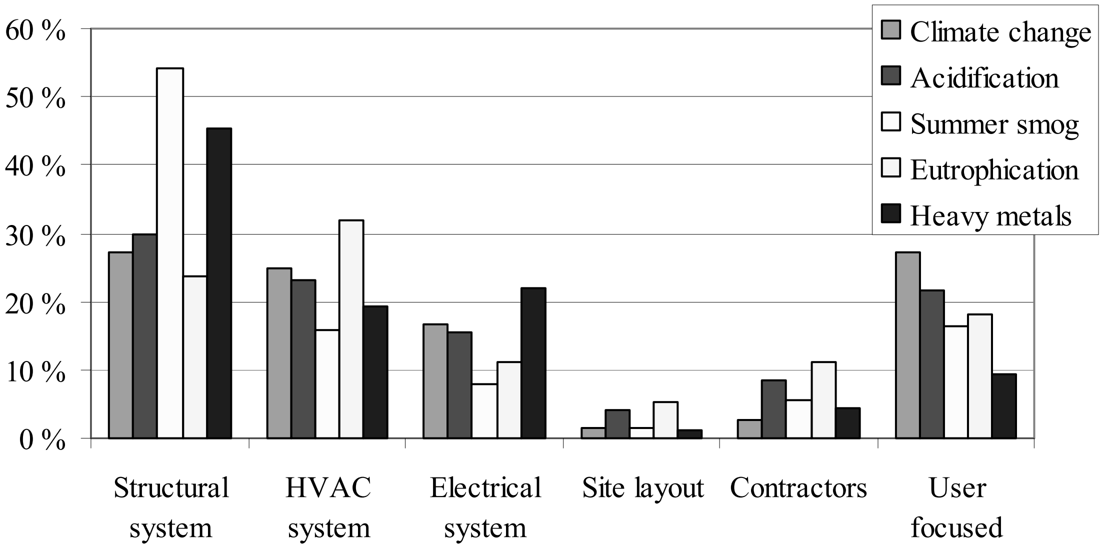


Figure 11. Environmental impact of an office building by building systems over 50 years of service life (II).

materials. The HVAC system includes the materials and the use of electricity in HVAC, heat loss through ventilation, maintenance, and demolition and disposal of HVAC materials. In the Finnish building classification system (Kiiras & Tiula 1999), HVAC systems also include water, hot water, and wastewater. The electrical system includes materials, use of electricity in lighting, and demolition and disposal of materials. Site layout includes materials used in landscaping and pavements, and energy and materials used in courtyard care. The contractors' processes include all the construction site operations needed during the life cycle of the building. The user-focused operation includes the life-cycle elements that are mainly related to the user operations, namely electricity drawn from the outlets (PC, printers, etc.) and used by special equipment (e.g., kitchen, sauna), and office waste management. The life-cycle impact of an office building (Case B) is presented in Figure 10 divided by life-cycle phases and in Figure 11 by service systems.

As we can see in Figure 11, the two systems that account for most of the impact are the structural and the HVAC systems. The result is somewhat surprising as in the previous section (also shown in Figure 10) the use of electricity was found to be the most significant impact contributor. The change in interpretation is due to two facts: first, in office buildings a considerable part of the heating energy is consumed in the heat conduction through structures; second, that the majority of operational electricity is used in operating both the HVAC system and the occupants' office equipments (PC, printers, etc.). The user-focused operations and the electrical system are the second greatest building systems' impact contributors. The impact of the contractors' activities during the life cycle of an office is relatively low, 3-11% of total impact.

6.3 Data quality assessment

The data quality of the life-cycle inventory has been evaluated here with a qualitative estimation framework (Weidema & Wesnæs 1996, Lindfors et al. 1995). The data quality assessment started by giving data quality scores for every unit process included in the study. The scores were then aggregated to life-cycle elements and finally to the life-cycle phase level. The results of the data quality assessment are presented in Table 4. The data quality scores in the table have been rounded to the nearest whole number. The more detailed data from the data quality assessment is presented in papers IV and V.

As can be seen from the table, the data quality scores are as targeted, two or better, with most of the used indicators. As life-cycle phases contributing the most (building materials, electricity service, heating service and maintenance) attained a score of two or better, the overall quality of the data used can be considered good. This supports the findings presented in the result section.

Table 4. Summary of the data quality assessment (V).

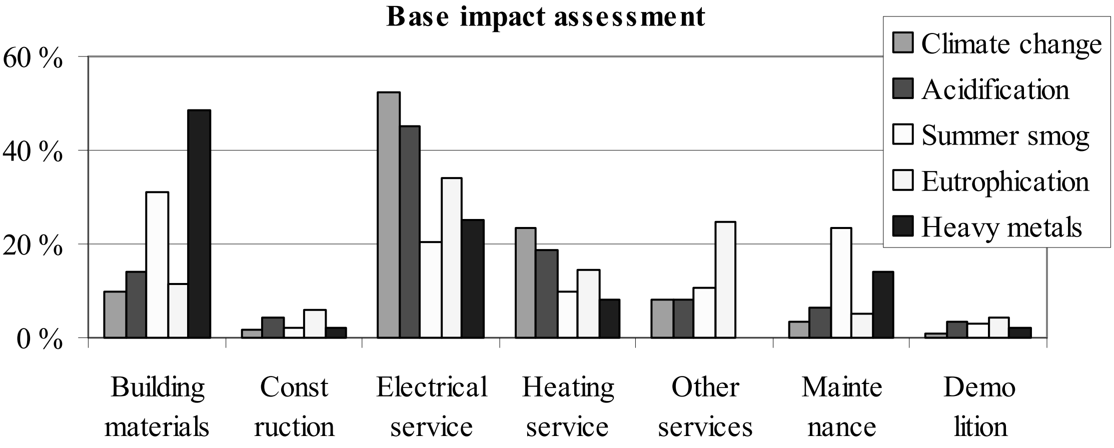
Data Quality* Table	Acquisition method	Independence of data supplier	Representa-tiveness	Data Age	Geographical correlation	Technological correlation
	A B C	A B C	A B C	A B C	A B C	A B C
Building materials	2 2 2	1 1 1	2 2 2	2 2 2	2 2 2	2 2 2
Construction	2 2 3	1 1 1	2 2 2	2 2 2	2 2 3	2 3 4
Heating service	2 2 2	2 2 2	1 1 1	1 1 1	1 1 1	1 1 1
Electrical service	2 2 2	2 2 2	1 1 1	1 1 1	1 1 1	1 1 1
Other services	2 2 2	2 2 2	1 2 1	1 1 1	2 2 3	4 4 4
Maintenance	2 2 2	1 1 1	2 2 2	2 2 2	2 2 2	2 2 2
Demolition	3 3 3	2 2 2	3 3 3	2 2 3	3 3 3	4 4 4

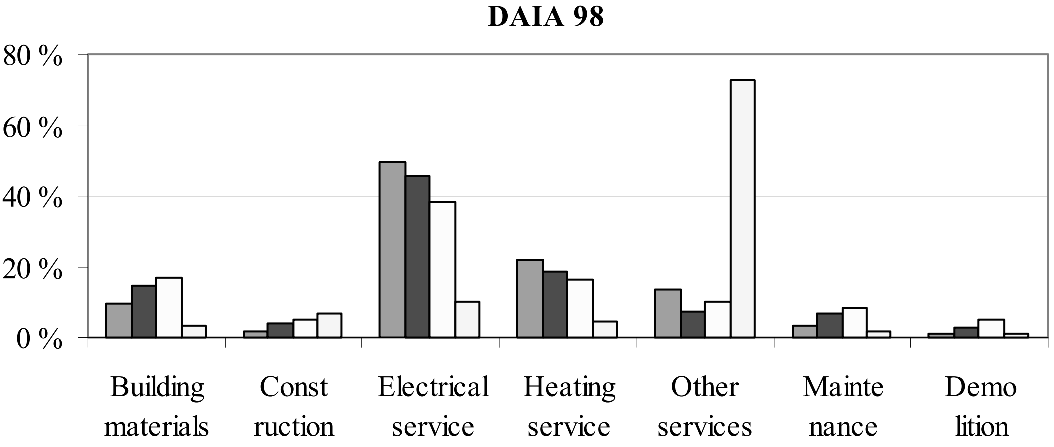
*Maximum quality = 1
*Minimum quality = 5

One life-cycle phase that may cause significant uncertainty is that of "other services". The data quality scores are worse than two and the contribution is high (10-30% of eutrophication impact). The quality of the data is also lower than that targeted in the construction and, especially, demolition phases, but since they only have a negligible contribution, they should not cause significant uncertainty in the results. The data quality differs only slightly throughout the cases, which should further support the findings presented in the results

The characterization of emissions to impact (equivalency factors used) has also a strong effect on the quality of the results (Björklund 2002, ISO14042 2000, TemaNord 1995b). However, since the important emissions that emerged are well-known and the same characterization method was used for all building case studies, the characterization would probably produce coherent results with other methods as well. Heavy metals could be an exception because it is a rather seldom characterized impact and the equivalency factors have a wide range of variation.

The characterization of emissions to impact were tested with two other sets of characterization factors, DAIA (1998) presented by Finnish Environmental Institute and EC App.3 (1997) presented by European Commission (Figure 12). The result was found to be similar with both alternative methods (almost identical in most of the impact categories). The only clear difference was to be found in the summer smog and eutrophication categories with the DAIA's set of characterization factors. The importance of energy use in summer smog increased due to the high valuation of NO_x emissions in the characterization, and similarly the importance of other services increased due to the higher valuation of N emissions to water. Some difference was also found in the climate change and heavy metals category due to the differences in the characterization factors. The DAIA did not have characterization factors for a heavy metals category.





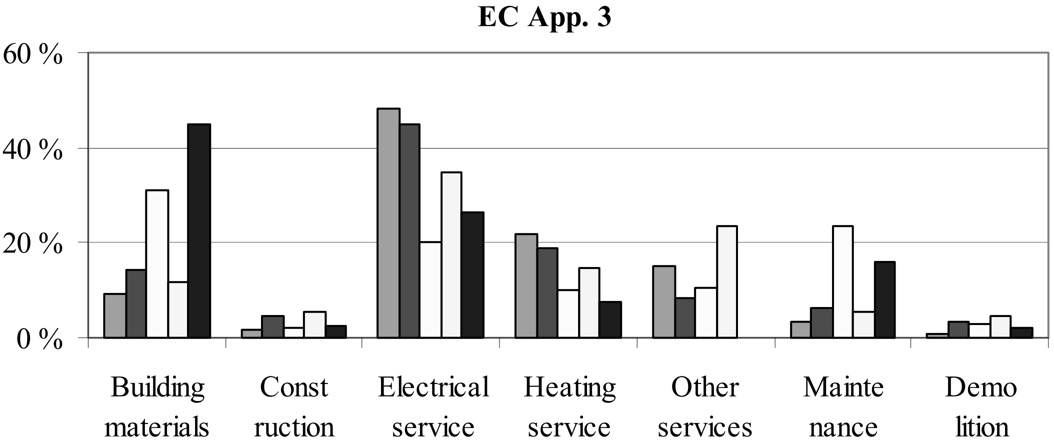


Figure 12. The characterization of emissions of building case B with the base characterization factors and two alternative set of factors.

7 Discussion and conclusion

The purpose of this study was to quantify and compare the potential environmental impact caused by an office building during its life time. The study determined the life-cycle phases and elements contributing most to a building's life cycle-impact. Furthermore, the study performed a sensitivity assessment to evaluate the effects of possible changes during the long service life, fifty years, of the building. The result of the study supported the original hypothesis, that a typical contemporary office building, different design teams, contractors and users notwithstanding, would have largely the same environmentally significant life-cycle phases and elements, and that the smaller flows of materials can have a noteworthy influence on the overall environmental impact of an office building.

The corresponding life-cycle phases were found to contribute similarly to the environmental impact of the office buildings studied; building operations (electricity, heating and other services) dominating the climate change, acidification and eutrophication categories, while building material manufacturing (in construction and maintenance) the categories of summer smog and heavy metals. Surprisingly though, the impact of the use of electricity was found to have a high variation across the cases in almost all the estimated impact categories. The maintenance phase was also found to have considerable variation, 28%, but only in the summer smog category. In contrast, the impact of building materials were found to vary significantly less, having a range of 5% or less. At the more detailed, life-cycle element level the electricity used through outlets and the surfaces in the maintenance phase were found to have the widest range of variation. In the interpretation of the result, the key environmental issues were determined to be: electricity use in the outlets, HVAC and lighting, heat in ventilation and conduction, materials in internal surfaces and HVAC services, and the use of water and wastewater were quite dominant because with 20% of all life-cycle elements they caused 45-75% of the average life-cycle impact of the buildings and 60-75% of the cumulative range.

The scenario analysis showed that building LCAs seem to be quite sensitive to assumptions made about the future. The most sensitive factors of the results seem to be those related to the outside condition and obsolescence assumptions (electricity mix, rebuilding, heating energy mix, and refurbishment scenarios), which were also quite sensitive to some input assumptions (energy consumption and recycling). Actually, several studies have already noted that the energy mix has a significant influence on the results. However, the effects of obsolescence have not yet been flagged as a significant cause of sensitivity in building LCAs.

The specific areas studied in the sensitivity analysis brought forth some quite interesting discoveries. Firstly, it is risky to use any weight related cutoff criteria in the inventory analysis of building LCA, because even very small flows of material (less than 0,5% of overall weight) can have a noticeable life-cycle effect (10-40%) in a given impact category. Secondly, although the local condition on two continents can have a clear influence on the degree of life-cycle impact, it seemed to have less impact on the contribution of different life-cycle phases. Finally, the suggested (design oriented) service system approach for defining the functional unit, seems to alter somewhat the conclusion of the result. The traditional life-cycle phase approach would seem to suggests that the use of electricity is the most important issue during the life cycle of a building, but the service system approach, in turn, would seem suggest that the structural and HVAC systems are the most important issues.

The results of this study are generally in accord with the findings of previous studies. Almost all articles have emphasized the importance of energy-use as causing the climate change impact. The importance of building material manufacturing in the harmful substance category has also been mentioned in some articles. Individual life-cycle elements causing a given impact have not typically been identified, as in this study, but the significant elements found here constitute the life-cycle phases also found to be important in other studies.

Some interesting comparisons can be made between the findings of this study and other published studies. For example, Sheuer et al. (2003) seem to have got quite a different result in their extensive study. They have stated that almost all life-cycle impacts occur in the use phase of a building, for example 93% of the climate change, 90% of the acidification, 90% of the nutrification impact; here 80-85%, 60-70%, 45-65% respectively. However, when the two basic differences in the systems studied (one a model assumption and the other an input assumption) are removed from the comparison (50 years of use instead of 75, and 210 kWh/m^2/year of energy consumption instead of 420) the result of their study is already quite similar to the one presented here, further, if the two other assumptions discussed in chapter 2 are taken into account, the results would almost be identical. The impact categories, namely summer smog and heavy metals, where the building materials seem to be significant, where not included in their study.

Two studies that have estimated the range of variation in the environmental impact of life-cycle phases, though for different building types (Adalberth et al. 2001) or with partly a different method (Suzuki & Oka 1998), have presented a similar range of variation to that found in this study. Adalbert et al. (2001) have estimated the environmental impact of four residential buildings and concluded a range of 20-40% within the energy-use phase and 20-50% within the building materials and construction phase; respectively 25-50% (heavy metals 85%) and 15-20% in this study. The narrower range in energy-use could be explained partly by the lower relative electricity consumption of residential buildings and by the wider range of materials used, i.e. wood, in the bearing structures of residential buildings.

Suzuki and Oka (1998) have estimated the climate change impact of ten office buildings and have concluded a range of 50% within the operation phase, 40% within building materials, and 35% within maintenance; respectively 40%, 15% and 40% in this study. The wider range of the impact of building materials in Suzuki and Oka is mainly due to the variation in finishing elements, especially one building seemed to have a high CO_2 intensity in its finishing elements.

The results of the sensitivity analysis are, to an extent, comparable to other studies that have tested the sensitivity of a building LCA. Several studies, as is the case here, have reported the energy mix as having a significant influence on the results (Adalbert et al. 2001, Peuportier 2001, Junnila 1998). However, the effects of obsolescence have not yet been flagged as a significant cause of sensitivity in building LCAs. In this study, both obsolescence scenarios, rebuilding and refurbishment were found to be among the most significant ones to cause sensitivity. One reason may be that most of the other studies have estimated the sensitivity of multi-family buildings or homes where obsolescence is perhaps not as relevant as it is in the case of office buildings, as indicated in this study.

Although the study aimed at comprehensiveness, there are some limitations that might affect the validity and reliability of the result. The validity issues are discussed here under three sub-groups according to Kidder and Judd (1986): construct validity, internal validity and external validity (also called generalizability). To meet the test of construct validity attention has been paid to establishing the suitability of the measures used in the concepts (environmental impact) being studied. Multiple sources of evidence, which have been stated in previous chapters, have been used to double-check the exactness of the input data used in the calculations. The suitability and limitations of the LCA method for measuring the environmental impact of buildings has mainly been discussed in the chapter on method, but some other limitations specific to this study have been listed below. Firstly, the LCA covered neither all the impact areas of an LCA, i.e. resource depletion (Consoli et al. 1993) nor all environmental impact categories considered important, e.g. ozone depletion, particulate matter emissions, radioactive waste, biodiversity, and indoor air quality. Secondly, the scope of the study was to examine the life cycle of an office building. However, since an office life cycle is not a definite system that could be separated from its context, subjective choices had to be made about the allocation and elements to be included or excluded. For example, the use of electricity, water, and office waste management were included in the system studied, but some other elements such as office furniture, computers, commuting, business travel, construction of infrastructure, and manufacturing of construction equipment were excluded. Finally, the compilation and quantification of material and energy flows (inputs and outputs) were mostly based on the plans and specifications of the buildings in the study, whereby all the data used represent calculated and estimated values.

Internal validity, the causal relationship between unit processes and the environmental impact values, is inherently stated in this kind of flow sheet calculation as an LCA. The environmental impacts are calculated based on a set of equations, which are created from material and energy inputs (independent variables) and their known relations to emissions and, further, to environmental impact (dependent variables). The quality of data used, which is connected to the material and energy inputs, becomes crucial for the internal validity of the study. The quality of both emission and impact data used has been discussed earlier in the chapter called Data Quality Assessment.

External validity, the domain to which a study's findings can be generalized, rests on analytical generalization and replication logic in these kinds of multiple case studies (Yin 2003). The four cases do not allow statistical generalization. The findings of the study can be generalized (analytically) to new office cases based on replication logic, because each of the cases studied were found to produce similar results as predicted (literal replication). However, the findings are only to be generalized to a certain extent, which was defined in the sensitivity analysis (theoretical replication).

The performed sensitivity analysis had some limitations that could limit the external validity. First, the selected building cases were situated only in two countries, and, thus, a board generalization can not be justified concerning the external characteristics of the buildings used as being representative of those found in other countries as well. The result seems to be applicable, to some extent, to other industrialized countries where the external conditions tend to be similar, as could be seen in the literature review, but it would be highly probable that the buildings in developing countries would have a different environmental profile. Secondly, the sensitivity analysis investigated only some of the possible scenarios and focused on the life-cycle elements with a high contribution. This approach may leave some aspects with a low contribution but a high uncertainty undetected, which could have an influence on the overall sensitivity (Heijungs 1996). Additionally, the selection of ranges of uncertainty used in the scenarios were chosen subjectively based on empirical evidence, but not on statistical uncertainty. Furthermore, the scenario approach used a static model for evaluating sensitivity and it does not assess simultaneous effects of uncertainty as, for example, a Monte Carlo simulation would.

The reliability of the study was supported by conducting all the case studies in accordance with the same research protocol and by reporting both the protocol and the results at a detailed level in the appended papers and this summary. Unfortunately, not all the documents used to conduct the case studies could be included in the appended papers or the summary. For that reason an additional document database has been collected using the original documents, for the purpose of facilitating both the recollection of all the information as well as the replication of the chain of evidence.

The findings of the study would suggest that within the limitations of both the electricity mix and obsolescence the life-cycle impact of a typical contemporary office building would follow a similar pattern, the use phase dominating the climate change, acidification and eutrophication impact, and the building material manufacturing those of the summer smog and heavy metals impact. The use of electricity is the single issue that could be expected to be significant in all offices. Additionally, the choices made about the HVAC system and internal surfaces could be anticipated to play a central role.

All the buildings included in the study presented conventional design solutions, thus, in the future, it would be interesting to compare the environmental impact of unconventional design solutions to the ones presented here. Further research could also have a more action-oriented approach, so that the implementing of new knowledge in design processes with its potential beneficial effect on the environmental performance of buildings could be tested. Since a majority of the environmental burdens of a given building stock are caused by old buildings, it would also be interesting to conduct a similar study from a facility management perspective. Finally, as the user of an office building plays a central role in deciding the value of environmental performance, it would be interesting to compare the environmental impact of office buildings in a broader corporate and facilities management context. For example, how significant would the building-related impacts be compared to business travel, commuting, and the use of paper in the office studied?

Practical applications of the study’s results could be the conscious design and facilities management of office buildings based on environmentally friendly alternatives. Companies, owners, project and facility managers, and designers not yet familiar with environmental issues could use the list of key issues to help them focus their attention to the environmentally sensitive areas of design, construction, use, maintenance, and demolition. More experienced organizations could use the longer list of life-cycle elements and environmental impact as a check list with an eye to considering whether they have considered all the issues relevant to them, or to benchmark the environmental performance of their building against the impacts of the presented case study. Finally, because the LCA of a building, could be expected to be sensitive to some models and outside conditions, such as energy mix and obsolescence, these should be clearly stated when presenting the results of an LCA study. However, it is also true that a conscious will by managers to affect these conditions could result in an effective mode of influencing positively the environmental impacts of office buildings.

8 References

Adalberth, K., Almgren, A. and Petersen, E. H. (2001) Life cycle assessment of four multi-family buildings, International Journal of Low Energy and Sustainable Buildings, Vol. 2. Royal Institute of Technology, Stockholm, Sweden. pp. 1-21.

Ahonen, T. (2000) Environmental Report 2000. Espoo Electricity. http://www.esoy.fi/, Interviewed January 2, 2002.

Arena, A. P., de Rosa, C. (2003) Life-cycle assessment of energy and environmental implications of the implementation of conservation technologies in school buildings in Mendoza - Argentina. Building and Environment, Vol. 38, pp. 359-368.

Balaras, C.A., Droutsa, K., Dascalaki, E., Hansen, K. and Petersen, E.H. (2003) Environmental impact Assessment of residential buildings. In Sarja A. (ed.). Proceedings of the 2nd international symposium, ILCDES 2003, Integrated lifetime engineering of buildings and civil infrastructures, December 1-3, 2003, Association of Finnish Civil Engineers RIL, Kuopio, Finland. pp 439-445.

Ball, J. (2002) Can ISO 14000 and eco-labelling turn the construction industry green? Building and Environment, Vol. 37, pp. 421-428.

Barras, R. and Clark, P. (1996) Obsolescence and performance in the central London office market. Journal of property valuation and investment, Vol. 14, No. 4, pp. 63-78.

Beerepoot, M. (2002) EC Draft Directive on Energy Performance: Impact for the European Building Sector. In Pettersen T.D. (ed.) Proceedings of CIB/iiSBE International Conference on Sustainable Building, September 23-25, 2002, Oslo, Norway. EcoBuild, Norway.

Björklund, A. E. (2002) Survey of approaches to improve reliability in LCA. International Journal of Life Cycle Assessment, Vol. 7, No. 2, pp. 64-72.

Björklund, T., Jönsson, Å. and Tillman, A.-M. (1996) LCA of building frame structures: Environmental impact over the life-cycle of concrete and steel frames. Chalmers University of Technology, Technical Environmental Planning Report 1996:8. Göteborg. Sweden.

Bogenstätter, U. (2000). Prediction and optimization of life-cycle cost in early design. Building Research & Information, Vol. 28, No. 5, pp. 376-386.

Boonstra, C. and Pettersen, T. D. (2003) Tools for environmental assessment of existing buildings. Industry and environment, Vol. 26, No. 2-3. United Nations Environmental Programme, Division of Technology, Industry and Economics. Paris. France. pp. 80-84.

Borg, M. (2001) Environmental assessment of materials, components and buildings. Doctoral Thesis. Kungliga tekniska högskolan, Byggnadsmaterial, TRITA-BYMA 2001:4. Stockholm. Sweden.

Boustead, I. (1997) The Boustead Model 3 for Life Cycle Inventory Calculations.Boustead Consulting Ltd, UK.

Building Information (1998a) KH 90-00159 Maintenance File (KH- kortit) in Finnish Building Information Ltd, Finland.

Building Information (1998b) RT 18-10663 Construction File (RT- kortit) in Finnish Building Information Ltd, Finland.

Building Information (2003) Environmental declaration. Building Information Ltd. http://www.rts.fi/ymparistoselosteet/nro34.htm, accessed May 7, 2003.

Börjesson, P. and Gustavsson, L. (2000) Greenhouse gas balances in building construction: wood versus concrete from life-cycle and forest land-use perspectives. Energy Policy, Vol. 28, pp. 575-588.

Chevalier, J.-L., Krog, H. and Tarantini, M. (2002) Environmental performance assessment of glazing and windows: context, overview, main concerns. Task 27 Workshop Papers, Ottawa, Canada, October 2002, Solar heating and cooling programme, International Energy Agency. http://www.iea-shc-task27.org/download/workshop_ottawa/c1_Environmental_Performance_16.pdf, accessed 17.12.2003.

Cole R.J. and Kernan P.C. (1996) Life-cycle energy use in office buildings. Building and Environment, Vol. 31, No. 4, pp. 307-317.

Consoli, F., Allen, D., Boustead, I., Fava, J., Franklin, W., Jensen, A. A., de Oude, N., Parrish, R., Perriman ,R., Postlethwaite, D., Quay, B., Seguin, J. and Vigon, B. (1993) Guidelines for life-cycle assessment: A "code of practice", 1st ed. Society of Environmental Toxicology and Chemistry. Brussels, Belgium.

Council Directive 91/271/EEC of 21 May (1991) Concerning Urban Wastewater Treatment. http://europa.eu.int/smartapi/cgi/, accessed April 29, 2003.

Curran, M. (1996) Environmental Life-Cycle Assessment. McGraw-Hill, New York, U.S.A.

DAIA (1998) Life cycle impact assessment method. KCL-ECO 3.0. LCA software. Finnish Pulp and Paper Research Institute, Espoo, Finland.

EC App.3 (1997) European methodology for the evaluation of environmental impact of buildings, Application of life cycle analysis to buildings, Detailed description and review, Appendix 3: definition of LCA indicators. European Commission, Directorate general XII for science, Research and development, Programme Apas, Regener project, Final Reports.

EC (1997) European methodology for the evaluation of environmental impact of buildings, Application of life cycle analysis to buildings, Detailed description and review. European Commission, Directorate general XII for science, Research and development, Programme Apas, Regener project, Final Reports.

Edwards, S. and Bennet, P. (2003) Construction products and life cycle thinking. Industry and environment, Vol. 26, No. 2-3. United Nations Environmental Programme, Division of Technology, Industry and Economics. Paris. France. pp. 57-61.

EIO-LCA. (2003) Carnegie Mellon University Green Design Initiative (2003). “Economic Input-Output Life-cycle Assessment (EIO-LCA) Model,” http://www.eiolca.net; accessed May 15, 2003.

Eisenhardt, K.M. (1989) Building theories from case study research. Academy of Management Review. Vol. 14, No. 4, pp. 532-550.

Energy Information Administration (EIA) (1998) 1995 Commercial building survey, A look at commercial buildings in 1995: Characteristics, energy consumption and energy expenditures. U.S. Department of Energy, Office of Energy Markets and End Use, Report DOE/EIA-0625, October 1998.

Erlandsson, M. and Borg, M. (2003) Generic LCA-methodology applicable for buildings, constructions and operation services—today practice and development needs. Building and Environment, Vol. 38, No. 7, pp. 919-938.

Finnish Environment Institute (2003) Water treatment plants in Finland, http://www.vyh.fi/palvelut/julkaisu/elektro/sy542/sy542.htm, accessed May 7, 2003.

Finnveden, G. and Palm, V. (2002) Rethinking producer responsibility. International Journal of Life Cycle Assessment, Vol. 7, No. 2, pp. 61.

Gangemi, V., Manlanga, R. and Ranzo P. (2000) Environmental management of the design process. Managing multidisciplinary design: the role of environmental consultancy. Renewable Energy, Vol. 19, pp. 277-284.

Goedkoop, M. (1995) The Eco-indicator 95. Netherlands agency for energy and the environment. The Netherlands.

Gorgolewski, M. (1999) Environmental assessment of steel piling. The Steel Construction Institute. UK.

Graedel, T. E. (1998) Streamlined Life-Cycle Assessment. Prentice Hall. 310 p.

Graedel, T. E. and Allenby, B. R. (2003) Industrial ecology, 2nd ed. Prentice Hall, New Jersey, U.S.A.

Green, D. and David, J. L. (1984) Research design for generalizing from multiple case studies. Evaluation and Program Planning, Vol. 7, pp. 73-85.

Haahtela, Y and Kiiras, J. (1999) Building information system (Talonrakennuksen kustannustieto) in Finnish. Building Information Ltd. Tammerpaino Oy, Tampere.

Hara-Lindström, E. (2001) LCA of Sateliitti office building (Elinkaariarviointi: Leija-Ympäristöalan keskittymä) in Finnish. Technical Report 2001. Espoo - Vantaa Institute of Technology. Espoo. Finland.

Hasegawa, T. (2002) Policy Instruments for Environmentally Sustainable Buildings In Pettersen, T.D. (ed.) Proceedings of CIB/iiSBE International Conference on Sustainable Building, September 23-25, 2002, Oslo, Norway. EcoBuild, Norway.

Heijungs, R. (1996) Identification of key issues for further investigation in improving the reliability of life cycle assessments. Journal of Cleaner Production, Vol. 4, No. 3-4, pp. 159-166.

Heijungs, R. and Kleijn, R. (2000) Numerical approaches toward life cycle interpretation. International Journal of Life Cycle Assessment, Vol. 6, No. 3, pp. 141-148.

Heinimäki, S. and Puhto, J. (1998) Markets for property management services in Finland (Kiinteistöjohtamispalveluiden markkinat Suomessa) in Finnish. Helsinki University of Technology, Faculty of Civil and Environmental Engineering, Construction Economics and Management, Reports No. 35. Espoo, Finland.

Helsingin Energia (2000) Environmental Report. http://www.helsinginenergia.fi/ymparisto/ yr00/ymparistoraportti.html, accessed October 14, 2002

Helsingin vesi (1999) Environmental Report (Ympäristöraportti) in Finnish. Helsinki, Finland.

Hendrickson, C., A. Horvath, S. Joshi, and Lave, L.B. (1998) Economic Input-Output Models for Environmental Life Cycle Analysis. Environmental Science & Technology, Vol. 32, No. 7, pp. 184A-191A.

Horvath, A. and Hendrickson, C. (1998) Steel versus steel-reinforced concrete bridges: Environmental assessment. Journal of Infrastructure Systems, Vol. 4, No. 3, pp. 111-117.

HUT (1993) Target costs for facility managers. Report 119. Helsinki University of Technology, Faculty of Civil and Environmental Engineering, Construction Economics and Management. Espoo, Finland.

IDA (2002). Indoor Climate and Energy 3.0. The Royal Institute of Technology in Stockholm, Helsinki University of Technology. http://www.equa.se/ice/intro.html, accessed November 25, 2002.

IKP (Institute for Polymer Testing and Polymer Engineering) (1998) Integrated life cycle assessment (LCA) of windows and curtain walls. Verband der Fenster und Fassadenhersteller e.V., Frankfurt, Germany.

Iselin, D. G. and Lemer A. C. (1993) Fourth Dimension in Building: Strategies for Avoiding Obsolescence, National Academy Press, Washington, pp. 11-25.

ISO 14001 (1996) Environmental management systems, Specification with guidance for use. SFS-EN ISO 14001. Finnish Standards Association SFS. Finland.

ISO 14001 (2001) Types of US Companies Registered to ISO 14001. The ISO 14001 Information Center, http://www.iso14000.com/Community/cert_us_analysis.html#USTypes, accessed October 14, 2002.

ISO 14040 (1997) Environmental Management, Life Cycle Assessment, Principles and Framework. SFS-EN ISO 14040, Finnish Standards Association SFS, Finland.

ISO 14042 (2000) Environmental Management - Life cycle assessment - Life cycle impact assessment. SFS-EN ISO 14040, Finnish Standards Association SFS, Finland.

Junnila, S. (1998) Quantitative estimation of environmental burdens of a Finnish apartments building, Licentiate Theses. Helsinki University of Technology, Faculty of Civil and Environmental Engineering, Construction Economics and Management.

Junnila, S and Nousiainen, M. (2004) Environmental management of office premises (Toimitilojen ympäristöjohtaminen) in Finnish. Helsinki university of technology, faculty of civil and environmental engineering, construction economics and management, Report No 225. Espoo. Finland.

Junnila, S. and Saari, A. (1997) Material and energy flow estimation for building elements in the context of LCA (Rakennusosien aiheuttamien ympäristökuormien laskenta) in Finnish. Helsinki university of technology, faculty of civil and environmental engineering, construction economics and management, Report No 150. Espoo. Finland.

Junnila, S. and Saari, A. (1998) Environmental burdens of a Finnish apartment building by building elements in the context of LCA. Espoo: Helsinki University of Technology, Faculty of Civil and Environmental Engineering, Construction Economics and Management, Report 167. Espoo, Finland.

KCL-ECO 3.0. (1999) LCA software. Finnish Pulp and Paper Research Institute, Espoo, Finland.

Kesko (2002) Indicators of Environmental Responsibility. Report of Corporate Responsibility, Kesko. http://www.kesko.com/users/26/227.cfm, accessed October 10, 2002.

Kidder, L. and Judd, C. M. (1986) Research methods in social relations. In: Yin, R K. 2003. Case study research, Designs and method, 3rd edition. Applied social science method series, Vol. 5. Sage Publications, London.

Kiiras, J. and Tiula, M. (1999) Building 90 - The Finnish Building Classification System. The Finnish Building Centre Ltd., Helsinki, Finland.

Klunder, G. (2001) Environmental impact of Dutch dwellings: Priorities for reduction and benefits of sustainable construction. In: Maiellaro N. (ed.) Towards Sustainable Building. Kluwer, Dordrecht, The Netherlands. pp. 109-134.

Kohler, N. and Moffat, S. (2003) Life cycle analysis of the built environment. Industry and Environment, Vol. 26, No. 2-3. United Nations Environmental Programme, Division of Technology, Industry and Economics. Paris. France. pp. 17-21.

Kommonen, F. and Svan, T. (1998) The environmental aspects of Ambiotica (Ambiotican ympäristöominaisuudet) in Finnish. Technical report 1998. Senate Properties, Helsinki, Finland.

Lemer, A. C. (1996) Infrastructure obsolescence & design service life.Journal of Infrastructure Systems, Vol. 2, No. 4, pp. 153-156.

Liikanen, J. (1999) Allocation of emissions in combined heat and power production, Ministry of Trade and Industry, Reports 19. Finland.

Lindfors, L.-G., Christiansen, K., Hoffman, L., Virtanen, Y., Juntilla, V., Hanssen, O.-J., Rønning, A., Ekvall, T. and Finnveden, G. (1995) Nordic guidelines on life cycle assessment. Nord 1995:20. Nordic Council of Ministers, Copenhagen, Denmark.

Meil, J. K. and Trusty, W. B. (2000) Whole building life cycle assessment. In: Sarja A. (ed.), Proceedings of RILEM/CIB/ISO international symposium of integrated life-cycle design of materials and structures ILCDES, Helsinki, Finland, May 22-24, 2000. Proceedings 14. RILEM, Helsinki, Finland.pp. 345-349.

Mäkelä, K. (2002) LIPASTO calculation model, Unit emissions of traffic. VTT Technical Research Centre of Finland. Espoo, Finland. http://lipasto.vtt.fi/info.htm, Accessed February 22, 2002.

Neuvonen, P. (2002) Environmental declarations of building Products in Finland. In: In Pettersen T.D. (ed.) Proceedings of CIB/iiSBE International Conference on Sustainable Building, September 23-25, 2002, Oslo, Norway. EcoBuild, Norway.

Norris, G. A., Fisk, P. and McLennan, J. (2000) What are the key input categories and points of leverage for upstream environmental improvements of construction project -surprising results from application of baseline green. In: Boonstra C., Rovers R., Pauwels S. (eds.),Proceedings of CIB International Conference on Sustainable Building 2000, October 22-25, Maastricht, The Netherlands. Aeneas, Technical publisher. pp. 189-191.

Nousiainen, M., Junnila, S. and Puhto J. (2003) The facility management, a driver for improved environmental performance of premises (Kiinteistönhoidon vaikutusmahdollisuudet toimitilan ympäristöominaisuuksiin) in Finnish.. Helsinki university of technology, construction economics and management, Reports No. 220. Espoo. Finland.

Ochoa, L., Hendrickson, C. and Matthews H. S. (2002) Economic input-output life cycle assessment of U.S. residential buildings. Journal of Infrastructure Systems, Vol. 8, No. 4, pp. 421-428.

Ossenbruggen, P.J. (1994) Fundamental principles of systems analysis and decision-making. John Wiley & Sons, Inc., New York. U.S.A.

Pesonen, H.-L., Ekvall, T., Fleischer, G., Huppes, G., Jahn, C., Klos, Z., Rebitzer, G., Sonnemann, G., Tintinelli, A., Weidema, B. P. and Wenzel H. (2000) Framework for scenario development in LCA. International Journal of Life Cycle Assessment, Vol. 5, No. 1, pp. 21-30.

Peuportier, B. L. P. (2001) Life cycle assessment applied to the comparative evaluation of single family houses in the French context. Energy and Buildings, Vol. 33, No. 5, pp. 443-450.

Pilvang, C., Sutherland I. (1998) Environmental management in project design. Building Research & Information, Vol. 26, No. 2, pp. 113-117. E&FN Spon.

Raiko, E., Miettinen, A., Kopra, J. and Kommonen, F. (1998) The environmental aspects of Pöyry-House (Pöyrytalon laajennuksen ympäristöprofiili) in Finnish. Technical report 1998. JP-Building Engineering Ltd, Espoo, Finland.

Remenyi, D., Williams B., Money A. and Swartz E. (1998) Doing research in business and management. Sage Publications, London.

Roberts, H. and Robinson, G. (1998) ISO 14001 EMS Implementation Handbook. Butterworth-Heinemann Ltd., Oxford, UK.

Robson, C. (2002) Real world research, a resource for social scientists and practitioners - researchers, 2nd edition. Blackwell publishers. Oxford, UK.

Rosenblum, J., Horvath, A. and Hendrickson C. (2000) Environmental Implications of Service Industries. Environmental Science & Technology, Vol. 34, No. 4, pp. 4669-4676. American Chemical Society.

Rosenström, U. and Palosaari, M. (2002) Indicators for sustainable development in Finland. Finnish Environment 404. The Finnish Environment Institute, Helsinki, Finland.

Ross, S., Evans, D. and Webber, M. (2002) How LCA Studies Deal with Uncertainty.International Journal of Life Cycle Assessment, Vol. 7, No. 1. Ecomed publishers. pp. 47-52.

Royal & SunAllinace (2001) Carbon Dioxide Emission Equivalents, Benchmarking. Environmental Issue, http://www.royalsunalliance.com/pdfs/environment/environmentalissues.pdf, accessed October 10, 2002.

Saari, A. (2000) Management of life-cycle costs and environmental impacts in building construction. In: Sarja, A. (ed.), Proceedings of RILEM/CIB/ISO international symposium of integrated life-cycle design of materials and structures ILCDES, Helsinki, Finland, May 22-24, 2000. Proceedings 14. RILEM, Helsinki, Finland. pp. 117-122.

Seo, S. and Hwang, Y. (2001) Estimation of CO2 Emissions in Life Cycle of Residential Buildings. J. of Construction Engineering and Management, Vol. 127, No. 5, September/October, pp. 414-418.

Seppälä, J. (2003) Life cycle impact assessment based on decision analysis. Doctoral Dissertation. Helsinki University of Technology, Engineering Physics and Mathematics. August 2003.

Sheuer, C., Keoleian, G. A. and Reppe, P. (2003) Life cycle energy and environmental performance of a new university building: modelling challenges and design implications. Energy and Building 2003, Vol. 35, pp. 1049-1064.

SimaPro 5.1. (2002) LCA calculation programme. PRé Consultants, Amersfoort, The Netherlands.

Sjöström, C. (2000) Challenges of sustainable construction in the 21st century. In: Sarja A. (ed.), Proceedings of RILEM/CIB/ISO international symposium of integrated life-cycle design of materials and structures ILCDES, Helsinki, Finland, May 22-24, 2000. Proceedings 14. RILEM, Helsinki, Finland. pp. i-viii.

Slaughter, E. S. (2001) Design strategies to increase building flexibility. Building Research & Information, Vol. 29, No. 3, pp. 208-213.

Steen, B. (1997) On uncertainty and sensitivity of LCA-based priority setting. Journal of Cleaner Production, Vol. 5, No. 4, pp. 255-262.

Suh, S., Lenzen, M., Treloar, G. J., Hondo, H., Horvath, A., Huppes, G., Jolliet, O., Klann, U., Krewitt, W., Moriguchi, Y., Munksgaard, J. and Norris, G. (2003) System boundary selection in life-cycle inventories using hybrid approaches. Environmental Science & Technology. Web Release, Date: 18-Dec-2003.

Suomi, U. (2001) Energy auditing in buildings, years 2000-2002. Motiva Publication 1/2001. Information Centre for Energy Efficiency and Renewable Energy Sources. Interviewed April 23, 2003.

Suzuki, M. and Oka, T. (1998) Estimation of life cycle energy consumption and CO2 emission of office buildings in Japan. Energy and Buildings, Vol. 28, No. 1. Elsevier. pp. 33-41.

Swiss Re (2002) Internal Environmental Performance Indicators 2001 for Swiss Re Group. Internal Environmental Management, Swiss Re, http://www.swissre.com/, accessed October 13, 2002.

SYKE (1999) Finland's national waste plan in brief. Finland: Ministry of Environment and Finnish Environmental Institute. http://www.vyh.fi/eng/orginfo/publica/electro/waste/waste.pdf, accessed October 10, 2002.

TemaNord (1995a) LCA-Nordic, Technical Report No1-9. TemaNord1995:502. Rendan A/S, Söborg, Denmark.

TemaNord (1995b) LCA-Nordic, Technical Report No. 10. TemaNord1995:503. Rendan A/S, Söborg, Denmark.

Thormark, C. (2000) Inclusion of recycling in the assessment of buildings. In: Sarja A. (ed.), Proceedings of RILEM/CIB/ISO international symposium of integrated life-cycle design of materials and structures ILCDES, Helsinki, Finland, May 22-24, 2000. Proceedings 14. RILEM, Helsinki, Finland. pp. 179-184.

Thormark, C. (2002) A low energy building in a life cycle-its embodied energy, energy need for operation and recycling potential. Building and environment, Vol. 37, No. 4, pp. 429-435.

Treloar, G., Fay R., Ilozor, B. and Love P. (2001a) Building materials selection: greenhouse strategies for built facilities. Facilities, Vol. 19, No. 3/4. pp. 139 - 150.

Treloar, G., Fay, R., Ilozor, B. and Love P. (2001b) An Analysis of the embodied energy of office buildings by height. Facilities, Vol. 19, No. 5/6, pp. 204 - 214.

Treloar, G.J., McCoubrie, A., Love P.E.D. and Iyer-Ragina, U. (1999) Embodied energy analysis of fixtures, fittings and furniture in office buildings. Facilities, Vol. 17, No. 11, pp. 403-409.

Trusty, W. and Meil, J. (2000) The environmental implications of building new versus renovating an existing structure. In: Boonstra, C., Rovers, R. and Pauwels, S. (eds.),Proceedings of CIB International Conference on Sustainable Building 2000, October 22-25, Maastricht, The Netherlands. Aeneas, Technical publisher. pp. 104-106.

U.S. Department of Energy (2002) Why is Sustainable Building Important. Technical Report, Washington Department of Ecology, http://www.ecy.wa.gov/programs/swfa/cdl/Benefits.htm, accessed October 13, 2002.

UNEP (1999) Energy and Cities: Sustainable Building and Construction. United Nations Environmental Program, http://www.unep.or.jp/ietc/Focus/Sustainable_bldg1.asp, accessed October 14, 2002.

UNEP (2003a) Sustainable building and construction: facts and figures. Industry and environment 2003, Vol. 26, No. 2-3. United Nations Environmental Programme, Division of Technology, Industry and Economics. Paris. France. pp. 9-12.

UNEP (2003b) Evaluation of environmental impact in life cycle assessment. United Nations Environmental Programme, Division of Technology, Industry and Economics. Production and Consumption Branch. La Fenice Graphica, Rome, Italy.

Vaahterus, T. and Saari, A. (2001) Environmental loads of a Finnish indoor training ice-skating rink, Helsinki University of Technology, Construction Economics and Management, Report 194. Espoo, Finland.

Wallbaum, H. and Buerking, C. (2003) Concepts and instruments for sustainable construction sector. Industry and environment, Vol. 26,No. 2-3. United Nations Environmental Programme, Division of Technology, Industry and Economics. Paris. France. pp. 53-57.

van den Dobbelsteen, A., Arets, M. and van der Linden, K. (2003) The factor time in sustainability: integration of the building lifespan in environmental performance and decisions between demolition and re-use. In Sarja A. (ed.). Proceedings of the 2nd international symposium, ILCDES 2003, Integrated lifetime engineering of buildings and civil infrastructures, December 1-3, 2003, Association of Finnish Civil Engineers RIL, Kuopio, Finland. pp 457-463.

van Herwijnen, F. and Blok, R. (2003) LC(I)A comparison of two alternative building structures for XX office building in Delf, Netherlands, each as a result of different design approach. In Sarja A. (ed.). Proceedings of the 2nd international symposium, ILCDES 2003, Integrated lifetime engineering of buildings and civil infrastructures, December 1-3, 2003, Association of Finnish Civil Engineers RIL, Kuopio, Finland. pp 475-483.

Vantaa Energy (2000) Environmental Report. http://www.vantaanenergia.fi/, accessed October 14, 2002.

Weidema B.P. (1998) Multi-user test of the data quality matrix for product life cycle inventory data. International Journal of Life Cycle Assessment, Vol. 3, No. 5, pp. 259-265.

Weidema, B. P. and Wesnæs, M. (1996) Data quality management for life cycle inventories - An example for using data quality indicators. Journal of Cleaner Production, Vol. 4, No. 3-4, pp. 167-174.

Wenzel, H. (1998) Application dependency of LCA methodology: Key variables and their mode of influencing the method. International Journal of Life Cycle Assessment, Vol. 3, No. 5, pp. 281-288.

Virtanen, Y, Askola, R and Junttila, V. (1996) The life cycle data base of Finnish energy production parts I-VI (Kenttäsuuntautunut elinkaaritietojen hankintamenetelmä. Suomen energiantuotannon elinkaaritietokanta) in Finnish. VTT Technical Research Centre of Finland, VTT Research Notes 1996, No. 1782-1787. Espoo, Finland.

Wong, K. C. (2000) Valuing the refurbishment cycle. Property Management, Vol. 18, No. 1, pp. 16-24.

Wood Council (1997) A case study: Comparing the environmental effects of building systems. Report No. 4. Ottawa, Ontario, Canada.

Worldwatch (1995) A Building Revolution: How Ecology and Health Concerns are Transforming Construction. Worldwatch Paper 124. http://www.cityofseattle.net/sustainablebuilding/overview.htm, accessed August 10, 2002.

Vorsatz, D., Shown, L., Koomey, J., Moezzi, M., Denver, A. and Atkinson, B. (1997) Lighting market sourcebook for the U.S. Report LBNL-39102, Energy Analysis Program, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, Berkeley, CA, December 1997.

VTT (2000) Eco-efficiency, new direction in construction. Environmental Technology and Cosntruction 1994-1999. Tekes- National Technolgy Agency. Helsinki, Finland.

VTT (2003) WinEtana 1.0 LT. VTT, Technical Research Centre of Finland http://www.rte.vtt.fi/benchnet/ econbase/winetana/, accessed July 4, 2003.

Yin, R.K. (2003) Case study research, Designs and method, 3rd edition. Applied social science method series, Vol. 5. Sage Publications, London.

Yin, R.K. (1989) Case study research: Design and methods, Revised Edition. Applied Social Research Methods Series. Sage Publications, London.

Yohanis, Y.G. and Norton, B. (2002) Life-cycle operational and embodied energy for a generic single-story office building in the UK. Energy, Vol. 27, pp. 77-92.

YTV (1996) Office waste manual (Toimiston jäteopas) in Finnish. YTV Waste Management, Helsinki Metropolitan Area Council 1996). http://www.ytv.fi/jateh/oppaat/oppaat.html, accessed October 15, 2002.

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