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Environmental impacts during the operational phase of residential buildings

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Delft Centre for Sustainable Urban Areas

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Contents

1 Introduction

In the present day debate about the environment, copious use is made of the terms 'sustainable development' and 'sustainability'. Sustainable development generally focuses on three areas: social development, or reducing inequality; economic development, or securing prosperity now and in the future; and ecological development, or preserving and protecting the outdoor environment (Brundtland, 1987). In business strategy these three areas are also referred to as the Triple Bottom Line or the three P's: people, profit (or prosperity), and planet (Elkington, 1997). In this thesis the term sustainability is applied to ecological sustainability.

This chapter first presents the scientific and practical context for the research in Section 1.1, followed by a definition of the problem the research will help solve in Section 1.2. The objective of the research and the research questions are set out in Section 1.3. Sections 1.4 and 1.5 deal with the research approach and Section 1.6 provides an overview of the thesis.

1.1 Background

1.1.1 Quantifying ecological sustainability

The primary challenge posed by ecological sustainability is to ease the pressure on the environment amid a constantly rising world population and ever-increasing prosperity. This challenge calls for methods to formulate quantified targets for sustainable development and to measure and monitor progress.

The 'factor X' concept is a way to formulate quantified ecological sustainability targets. 'X' is the factor by which the environmental performance of products, economic sectors or national economies has to improve in order to reach a desired situation (Reijnders, 1998; von Weizsäcker *et al.*, 1998; Jansen and Vergragt, 1992; Ehrlich and Ehrlich, 1990; Speth, 1989). When a factor X goal is stated, four parameters need to be identified: the factor X, which is the quantified environmental performance; the unit of measurement, e.g. the amount of primary energy resources used; the point of reference, e.g. a specified economic activity in a specific geographical area and time frame; and the time frame in for reaching the goal. The unit of measurement should take account of contextual developments, such as increasing population and prosperity, since a reduction in the environmental impact per capita or per production unit need not necessarily imply a reduction in the total environmental impact if the population or production increases. Factor X originally assumed that the required reduction in environmental impact could be achieved via technological measures to bring about more efficient use of resources (Chertow, 2001; Reijnders, 1998). However, especially in the long run, factor X has to be very large to accommodate upward trends in population and prosperity in western and upcoming economies. Existing technology has its limits when it comes to increasing resource efficiency. Robèrt *et al.* (2000) therefore suggest that factor X thinking be applied to determine a desired level of sustainability in the long-term future. Instead of trying to reach a goal from what is considered realistic and possible at this point in time in the present (forecasting), one should think back from that point in time in the future and determine what needs to happen now (backcasting) (Jansen and Vergragt, 1992). The factor X approach is often used in international coordination of policymaking.

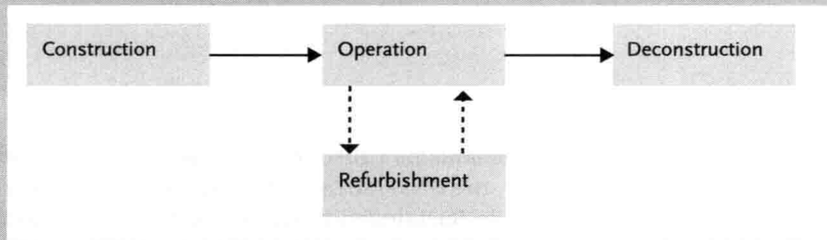
The challenge of ecological sustainability further calls for a quantified unit of measurement to monitor progress in ecological sustainability. Several approaches to measuring ecological sustainability have already been developed. The Ecological Footprint approach, inspired by the warning in the Brundtland Report (1987) concerning the limited availability of resources, compares the amount of ecologically productive land that is needed for the input and output flows of economic activity with the amount of available ecologically productive land (Wackernagel and Rees, 1996). The intention is to ensure that the use of environmental resources by economic systems does not exceed the carrying capacity of the environment. Another approach, Material Flow Analysis (MFA), analyses the energy and material input and output flows of economic activity and assesses the physical amount of material resources flowing into and out of a product system or economy (Brunner and Rechberger, 2004). In Material Flow and Stock Analysis (MFSA), which is intended for economies rather than product systems, the materials that remain in the system are also taken into account (Obernosterer *et al.*, 1998). Similarly, the energy resources needed to produce goods or services can be analysed by (Embodied) Energy Analysis (Brown and Herendeen, 1996). The Three Step Strategy approach to the use of energy and material resources states that in order to lower environmental damage it is necessary to first reduce the demand for energy and material resources, then to make greater use of more sustainable resources and, finally, using unsustainable resources more efficiently (Brouwers and Entrop, 2005; Lysen, 1996; Duijvestein, 1993). The Three Step Strategy has been updated by van den Dobbelsteen (2008) and Tillie *et al.* (2009) to the New Stepped Strategy, which includes the first step to reduce energy demand and material resources, then re-use material and energy waste flows and third to use sustainable resources. The New Stepped Strategy was inspired by the Cradle to Cradle theory by McDonough and Braungart (2002), which aims at closing material and energy cycles without producing waste. Straightforward analysis of material and energy flow follows the principle that the fewer resources are used the better, but it fails to provide any insight in the impact of individual materials and types of energy on the environment. The life cycle assessment (LCA) approach fills this void by analysing and quantifying the negative impact of material and energy flows on different environmental mechanisms called 'environmental impact categories' (Guinée, 2002). Currently, the UNEP/SETAC Life Cycle Initiative is working on guidelines for a Life Cycle Sustainability Assessment (LCSA) of products, in which LCA, Life Cycle Costing (LCC) and Social LCA (S-LCA) will be combined to form a Triple Bottom Line tool that includes all three aspects of sustainability (Life Cycle Initiative, 2010; Ugaya *et al.*, 2010). In this research LCA is used to quantify ecological sustainability. The results of an LCA show the contributions of products and processes to several environmental impact categories. The term 'environmental impacts' refers to the set of contributions to all impact categories that are assessed.

1.1.2 Current environmental policy

The United Nations (UN) deals with environmental problems at global level – global warming, depletion of the ozone layer and depletion of natural resources – which affect all people. The UN endeavours to initiate global action on sustainable development through international agreements. At the UN Conference on Environment and Development (Earth Summit) in Rio de Janeiro in 1992, an action agenda was set for international, national, regional and local actors in every area of the environment that is affected by human beings. This Agenda 21 was adopted by 178 governments (UN, 1993). Specific agreements have been reached on reducing global warming, protecting the ozone layer and preserving abiotic (non-living) natural resources. The Kyoto Protocol, the agreement on reducing greenhouse gas emissions, which cause global warming, had been signed by 84 signatories and ratified by 191 parties in June 2010 (UNFCCC, 1997, 2010). To protect the ozone layer, which is at risk mainly from CFCs, a UN agreement, the Montreal Protocol, on banning the use of CFCs has been signed and ratified by 191 nations (UNEP, 2000). Since the Montreal Protocol came into force, the depletion of the ozone layer appears to have come to a halt (McKenzie *et al.*, 2007; Weatherhead and Andersen, 2006). Lastly, the UN has developed activities in Africa to manage and protect reserves of natural resources.

The United Nations Environmental Programme (UNEP) and the European Commission (EC) have identified the building sector as a key factor in reaching the Kyoto Protocol targets (EC, 2006; UNEP, 2007). The building sector consumes an estimated 30-40% of energy worldwide and around 36% in the European Union (EU): the non-residential sector accounts for 8.7% and the residential sector for 27.5% of the total (UNEP, 2007). This thesis therefore focuses on residential buildings. EU governments have set minimum energy performance standards for new buildings, based on a common methodology to measure energy performance. The Energy Performance Building Directive (EPBD) applies from January 2006 to all new buildings and large old buildings undergoing major refurbishment. The Directive also requires sellers and

Figure 1.1 Schematic life cycle of a building



landlords to provide prospective buyers and tenants respectively with energy performance certificates. In 2008 the EC proposed a recast of the EPDB to include all buildings undergoing refurbishment and minimum performance requirements for building components. Furthermore, from 2020 all new buildings will have to comply with 'nearly zero' energy consumption standards. The definition of 'nearly zero' can be set by the individual Member States. The European Parliament approved the EPBD recast in May 2010 (Euractiv Network, 2009).

EU and national policies also contain regulations on building materials. The use of certain materials such as asbestos is prohibited for health and safety reasons and there are regulations for the collection and treatment of building waste. Between 1998 and 2001 the construction and demolition sector was responsible for about 31% of the total waste in western Europe (the 15 EU countries, plus Norway, Iceland and Switzerland) (EU, 2003). The EU has also developed an Integrated Product Policy (IPP) approach which seeks to improve the environmental performance in each phase of the life cycle of products (European Commission, 2001). Rather than one simple policy measure, the IPP consists of a whole arsenal of tools and measures – including Environmental Product Declarations (EPDs) – to cater for the many different products and actors who need different means to achieve the policy goal. An EPD contains environmental information about a product, according to the guidelines in the international ISO 14025 standard (ISO, 2010), which allows manufacturers to provide aggregated environmental information without releasing any confidential data. An additional international standard, ISO 12930 (ISO, 2007), is being developed for building products. The IPP concludes that LCA is the best available instrument for assessing the environmental impacts of products (European Commission, 2003). LCA has also been adopted in the ISO 14025 / ISO 12930 international standards.

1.2 Problem definition

LCA can also be applied to buildings. The life cycle of a building consists of three clearly distinguishable main phases: construction, operation and deconstruction (Figure 1.1). The construction phase includes all processes from the extraction of material resources to constructing the building on-site, while the deconstruction phase includes all processes from the deconstruction of building components to recycling and the final waste processing. The operational phase includes all processes between construction and deconstruction. In practice, a building might be refurbished or be given a new designation – e.g. an office building may become a residential building – which adds phases to the life cycle and starts a new operational phase after the changes have been made.

In the construction phase the environmental impacts of the building are directly related to the building and design decisions on, for example, the materials and building components or the energy needed for a specific type of construction. The environmental impacts in the deconstruction phase are similarly related to design decisions. The construction method and building components used in the construction phase, as well as any changes made during the operational phase, determine the parts of the building that can be re-used or recycled. The environmental impacts of the final waste processing depend on the materials used. Hence, design decisions made today will have environmental implications for decades or even centuries to come. Furthermore, the building design determines the possibilities and limitations for management and use in the operational phase.

In the operational phase the environmental impacts of the building are influenced by its characteristics and other – external – factors. For example, the thermal characteristics of a building determine how much energy is needed to establish and maintain a comfortable indoor climate, but it is the occupants who determine what a sufficiently comfortable climate is. The calculated energy consumption of a building is therefore valid only for the standardised comfort level and user behaviour which are assumed in the calculations. UNEP does recognise the influence of occupants on the energy consumption of buildings, as this may counteract efforts to improve energy efficiency (UNEP, 2007). Similarly, the building design and the local climate at the building site co-determine the speed at which a building deteriorates. This, in turn, influences levels of maintenance and the need to replace components. It is, however, the owner of the building who decides, on the basis of economic and functional rather than technical considerations, when actual maintenance and replacements are carried out. These decisions may then influence the total service life of the building.

The operational phase of a building spans multiple decades, which is why reducing the environmental impacts of buildings might be more effectively achieved by changing the way buildings are used and managed rather than by changing the building itself. This has been suggested by several authors (Fay *et al.*, 2000; Itard and Klunder, 2007; Klunder, 2002, 2005; Treloar *et al.*, 2000), but no comprehensive and detailed research has been published on this theme so far. International policy and research has focused up till now on energy consumption for climate control in buildings and the environmental impacts of specific building products, but little is known about the environmental impacts of processes and activities in the operational phase of a building, such as maintenance and renovation (Itard and Klunder, 2007). Klunder (2005) points out that little research has been conducted on the influence of occupant and management behaviour on the total environmental burden imposed by buildings. Borg (2001) and Paulsen (2001) do consider the operational phase of a number of separate building products and their influence on energy consumption, but not the use of a building as a whole.

Concluding, there is a lack of knowledge regarding the environmental impacts of regularly occurring activities in the operational phase of dwellings and the relationship between building-related and user-related impacts is unclear.

1.3 Objective and research questions

The objective of this research is to provide insight into the factors that cause the greatest environmental impacts in the operational phase of residential buildings and awareness of the long-term ecological consequences of decisions made in the design, construction and operational phases. The research further aims to contribute to the modelling of the operational phase of residential buildings in LCA by indicating if it is possible to assess the ecological sustainability of residential buildings with reasonable accuracy according to a limited number of contributing factors. The acquired knowledge may help policymakers to develop effective policies and can steer further developments in research and building practice towards areas that have the most potential for improving the environmental performance of residential buildings. The research includes a sensitivity analysis for variations in standard operational behaviour patterns, since those variations may have great influence on the results. The aim of this research is to establish how great the influence of operational behaviour and assumed variations thereof are compared to other factors. Further research may include behavioural science to determine how and why people behave like they do and how to effectively promote 'good' behaviour.

The main research questions are:

1. *What are the environmental impacts related to the operational phase of residential buildings?*
2. *Which factors significantly contribute to the various environmental impact categories?*
3. *To what extent do changes in the variable parameters of the assessment affect the environmental impacts?*
4. *How can the environmental impacts in the operational phase be most effectively reduced?*

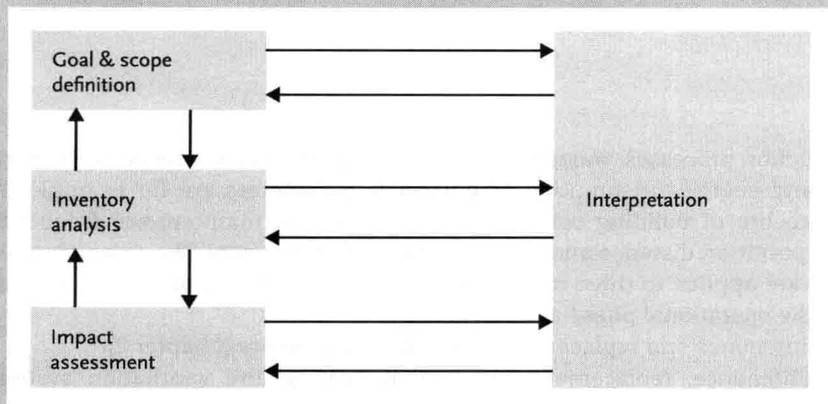
The factors that are taken into account are the use of material resources and production processes; waste processing; transportation of maintenance workers; and energy consumption. The variable parameters are for example the service life of building components and systems; maintenance frequency, transportation distance and energy consumption by users. The research questions are applied to three main aspects of the operational phase of dwellings and the operational phase as a whole:

- maintenance and replacement of façade components (Chapter 2);
- maintenance, replacement and use of heating and ventilation systems (Chapter 3);
- building-related and user-related gas and electricity consumption (Chapter 4);
- operational phase of dwellings, including the replacement of bathroom, toilet and kitchen (Chapters 5 and 6).

Since the research was completed in phases, the above research questions were sharpened over time and are therefore not literally repeated in all the chapters. However, all aspects of the main research questions are covered in the chapters. For example, question 3 is not mentioned specifically, but is addressed in the assessment of different use scenarios. Question 4 is part of the discussion and conclusion in the chapters. The research questions as formulated above will be reflected on in the final Chapter 6.

The main aspects of the operational phase have been selected on the basis of the probability of high environmental impacts, given the high frequency of activities and the amount of energy, materials and waste. The assessment of the operational phase is not exhaustive: it may exclude activities with low frequency and/or a relatively low flow of energy, materials or waste which have a high environmental impacts. Similarly, low volume elements of the façade components, climate systems and bathroom, toilet and kitchen that are omitted in the research may deliver high environmental impacts. Materials with known high environmental impacts have been included as far as possible. The research does not include extensive refurbishment of the dwelling, for example changing the floor plan, since that would change the functional performance of the building and produce a new product in terms of LCA. Maintenance and replacement of the roof has not been considered in this research, since roof maintenance has a low frequency and the roof of apartments in gallery flat buildings is shared by many dwellings, which reduces the material and waste flow per dwelling. Finishing of rooms has been limited to finishing provided by the building owner, therewith excluding all floor, wall and ceiling finishing except tiling in bathroom, toilet and kitchen.

Figure 1.2 Schematic overview of the four steps of life cycle assessment



1.4 Research approach: LCA methodology

1.4.1 General description

LCA is a method that can be used to quantify the negative impact of a product on the environment during production, use and disposal. As shown in Subsection 1.1.1, it is necessary to quantify environmental impacts in order to monitor and set specific goals for sustainable development. LCA methodology is widely accepted and applied in scientific research to assess the environmental impacts of products. An LCA consists of four steps, the requirements and guidelines for which are described in the ISO 14044 standard (2006) (Figure 1.2).

The first step is to define the goal and scope of the assessment. These serve as a description of the type of study – e.g. a comparative analysis of products or a study to improve a production process – and determine the questions that the assessment is required to answer. The scope of the study determines the processes to be included in the next step, the inventory phase, which involves the compilation of an inventory of the flow of all substances to and from the environment during the period of interest. In the third step, impact assessment, the potential contribution made by each substance to predefined environmental impact categories is calculated. This is done by comparing the impact of a particular substance flow with that of a reference substance for each category. Once the environmental impacts have been determined, the last step in the assessment is to interpret the results of the calculations by, for example, comparing the calculated environmental impacts with the results of similar research in the literature or with the overall environmental impacts in a region (normalisation), and by determining the sensitivity of the results to changes in the input variables. The process is iterative: the interpretation phase of the assessment may highlight unanswered questions or inconsistencies in the study which need to be addressed.

In LCA several methods can be used to assess the impact of the substance flows collected in the inventory phase. The SimaPro 7.2 software provides 20 different methods to choose from, each with its own calculation methods and (set of) indicators to quantify environmental performance. Two frequently used methods in scientific LCA research are the CML 2000 baseline method and the Eco-indicator 99 method. The CML method uses multiple indicators at midpoint level (Guinée, 2002), while the Eco-indicator includes multiple endpoint indicators that can be combined in a single endpoint indicator (Goedkoop and Spriensma, 2001). Endpoint indicators represent the ultimate consequences of the environmental impacts for humans and ecosystems. They reveal the 'endpoint' of a possible chain of causes and effects. As more environmental mechanisms are involved, one of the weaknesses of these indicators is a higher level of uncertainty in the results (Goedkoop *et al.*, 2009). Midpoint indicators, in contrast, show the potential direct negative impact on the environment, which can be situated anywhere along the chain of cause and effect. Both types of indicator are problem-oriented: the higher the score, the worse the environmental performance. The CML and Eco-indicator methods have recently been combined in a new method named ReCiPe, which allows the user to display results at different levels along the chain of effects (Goedkoop *et al.*, 2009). In this research the CML 2000 LCA midpoint method was used to determine the environmental impacts of building components and processes because the level of uncertainty is lower. Since CML is widely used and will probably go on being developed and used due to its inclusion in the new ReCiPe method, the results can be compared with other past and future scientific research.

The environmental impacts are quantified by LCA methodology. The LCA is performed with the SimaPro software package (Goedkoop *et al.*, 2007). The input data for the calculations of the environmental impacts come from the commercially available ecoinvent 2.0 database (ecoinvent, 2007). The data in the database were gathered from different literature sources and manufacturers and are kept up to date by the Swiss Centre for Life Cycle Inventories. More information about non-confidential data is available in extensive background reports by ecoinvent. All ecoinvent data entries have been reviewed by experts.

The environmental impact categories assessed in the CML 2000 method are selected from the most commonly used indicators in LCA studies. The impact categories used in this research are listed in Table 1.1 and further explained in Appendix 1. The full set of environmental impact categories is known as the 'environmental profile'. The impact category 'Marine aquatic ecotoxicity', one of the mandatory impact categories in the CML method, is not taken into account because significant problems are associated with the calculation of the contribution to that category using the CML method (Sim *et al.*, 2007). The problems in question are related to the time a substance is present in the marine ecosystem and to the absence of data for normalisation. The characterisation models for the influence of metals on ecotoxicity contain flaws in