Rolf André Bohne

Eco-efficiency and performance strategies in construction and demolition waste recycling systems

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Norwegian University of Science and Technology
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Department of Hydraulic and Environmental Engineering,
and Industrial Ecology Programme

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To Dad - in memory ...

Abstract

This thesis studies the Danish and Norwegian recycling systems for construction and demolition (C&D) waste. The Architectural, Engineering and Construction (AEC) industry is a major contributor to societies waste production; accounting for approximately 40% of the waste production. It is therefore important to manage the C&D waste effectively to move society towards sustainability.

This study applies the Industrial Ecology paradigm. This involved multidisciplinary approach, spanning the fields of Industrial Ecology, Systems Engineering and Organizational and Social Studies.

The scope of this thesis is threefold. The first scope is to get a better understanding of the processes that are taking place within the socio-technical sphere of a recycling system. Second, what is the nature of the C&D waste and what are the environmental impacts from the various waste fractions. Third, how can this information be used to improve recycling systems for C&D waste.

The study show that the suggestions in the National Action Plan and the corresponding policies are eco-effective, but that the environmental impact is very transport dependent. The study also shows that there is a great need to focus on future waste composition in the design of recycling systems for C&D waste. However, such waste projections are difficult to perform due to poor data availability.

There is a need for making more qualified decisions on environmental issues, with regard to long term management of such recycling systems. Long term models combined with environmental and economic information can make a powerful tool for such analysis.

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Chapter 1

Introduction

1.1 Background

After many years of attention on cleaner production and end-of-pipe solutions in the environmental field, the focus shifted towards the role of production and end-of-life treatment of products in the early 1990's. In order for the world to reach sustainability, society must reduce its use of non-renewable resources and its emissions of harmful substances. One of the strategies proposed is a factor X improvement in product systems [von Weizsäcker and Jesinghaus, 1992]. The field of Industrial Ecology (IE) is one of many ways of moving society towards sustainability. One of the challenges faced by Industrial Ecologists is to make sense of the diverse and complex connections between the society and the world around it. One of the key features of Industrial Ecology is to see human societies as part of the global ecosystem and to seek to understand the system as a whole.

This chapter briefly discusses the background behind this thesis, the chosen approach as well as the core goal and research questions.

Until recently, the focus was on consumer goods, transport and packaging. But as the ideas have matured, the focus has turned more towards how we as a society are using and distributing our resources. The Architectural, Engineering and Construction (AEC) industry uses roughly 40% of the energy, creates 40% of all waste, and uses 40% of the materials in industrialized countries

[GRIP/Økobygg, 2001]. In addition to this, the AEC industry makes use of a large portion of the transportation capacity (transportation consumes 30% of the energy in Norway [Rønningen, 2000]). It is therefore important to get more knowledge of how society deals with waste and resources within the AEC- and transport industry to move these industries towards sustainability.

This thesis studies one part of this system; i.e. the waste handling system for construction and demolition waste (C&D waste), to create knowledge of one piece of this picture. For this, I also need to understand how the society interacts with this subsystem and how this subsystem interacts with both the society and the environment.

In 2000 when this research work was started, there was little recycling of C&D waste in Norway, although some stand alone projects had been completed. The initial thought was to follow the recycling of approximately 100 000 tons of C&D waste from RiT2000 (Now Helsebygg Midt-Norge), the demolition, construction and running/management project of the regional hospital in Trondheim. Unfortunately, this project was temporarily stopped due to political processes. But, during the initial months of study, I was aware that the upcoming national action plan for C&D waste handling [GRIP/Økobygg, 2001] and the waste treatment scheme were being implemented in Oslo [Renholdsverket Oslo Kommune, 1997]. Further the Danish system, Copenhagen especially, had been a model for the upcoming Norwegian initiatives. It was therefore natural to select the recycling system of the municipality of Copenhagen as the first case study. Secondly, given the differences between Denmark and Norway, I wanted to see how the Danish experience was used in the construction of a recycling system for C&D waste in Norway. Therefore it was natural to study the Oslo system, before looking at the overall Norwegian system. These parts make the case study 2 and 3.

1.2 Research goal and questions

The concept Industrial Ecology emphasizes the *optimization of resource flows*, while other approaches to environmental science, management and policy stress the role of risk and purely technological trajectories. For example, pollution prevention (also referred to as Cleaner Production) emphasizes the reduction of risk primarily from toxic facilities and firm levels, particulary in the early phases of Cleaner Production during the 1980s and 1990s [Brattebø, 1997; Oldenburg and Geiser, 1997]. Similarly, Life Cycle Management focuses primarily on toxic substances in a specific value chain of a product or material [Lifset and Graedel, 2002]. Underlying this focus is an argument that when the use of these substances are eliminated or dramatically reduced the risk to humans and ecosystems are also reliably reduced [Lifset and Graedel, 2002]. In contrast, Industrial Ecology takes a systems view that draws the boundaries for analysis more broadly - around groups of firms, regions, sectors and so on - and asks how general resource use can be optimized. In this perspective resource use includes materials and energy (as inputs) as well as the ecosystems and biogeochemical cycles that provide crucial services to humanity [Ayres, 1993]. In practice, this means that Industrial Ecology often looks to recycling when Cleaner Production emphasizes prevention [Oldenburg and Geiser, 1997; Lifset and Graedel, 2002]. The concept of Industrial Ecology is built up around the ecological metaphor, assuming that industrial societies would become more ecologically and economically efficient if we accept the principles for resource utilization found in natural eco-systems. In natural systems we find for example a dynamic balance between resource take-out and consumption, implying that waste produced by one group of consumers is utilized as valuable resources for another.

Systems thinking is about the interrelated actions which provide a conceptual framework, or a body of knowledge, that makes the pattern clearer [Flood, 1999]. In order to meet the targeted objective successfully a number of policy sub-objectives must be met. This is when sub-objectives are understood to be outcomes that must be achieved before, and in order to, realize further outcomes [Mohr, 1995]. Ecosystems (and human systems) can be viewed upon as self-organizing holarctic open (SOHO) systems, whose dynamics are predominated by both positive and negative feedback processes operating over a range of spatial and temporal scales [Kay et al., 1999; Holling, 2001]. Self-organizing means that structure emerges spontaneously during the evolutionary process.

In order to place the work in a broader perspective both the agenda setting phase and policy evaluation is included in what is referred to as, “the policy implementation analysis”. This rather broad focus – from the pre decision phase to impact evaluation – is based on the assumption that crucial conducts for the policy outputs can be identified throughout that process.

Until recently, “all” recycling has been looked upon as sustainable, and the common indicator on the success of recycling was the percentage of materials collected and recycled. In this thesis, the purpose is to study how to make use of and adapt existing theory and methodology from different fields of science and social science in order to develop a generic design criteria for sustainable recycling systems for C&D waste based on eco-efficiency. In order to do so, existing systems must be understood, how they function, and what structures support them. Environmental impacts of each process within the system will have to be analyzed and quantified. Learning processes and mechanisms for technology transfer and implementation must be investigated. From these finding I can then make the first steps towards developing some generic design criteria for sustainable recycling systems for C&D waste based on eco-efficiency.

1.2.1 The core goal of this Ph.D. thesis

My core goal with this research work was:

"To determine the performance of recycling systems for C&D waste in quantitative environmental, economical and societal units and the alignment of treatment, policy, legislation and end-of-life systems to make the foundation for generic design criteria and the improvement of the overall eco-efficiency of the recycling system."

In order to reach this core goal, this thesis has to answer the following research questions;

Research question 1

"What are the main factors and stakeholders involved in recycling of C&D waste, what are their roles, what structures define their action space, what environmental issues are relevant and how are these issues evaluated to date?"

The answer of the first question will identify all important actors, stakeholders, structures and processes involved in such recycling systems. By using system theory I can now turn towards how these structures, organizations and actors influence the overall eco-efficiency of the system. This leads to research question 2;

Research question 2

"How can we measure effectiveness in recycling systems, what indicators should be used and where should system boundaries be placed in evaluations?"

By defining the system boundaries and investigate how the different variables influence system behavior, system eco-efficiency is determined. By studying and understanding how the interrelations between system elements (structure) and organizations in the system work, research questions 3 can be answered;

Research question 3

"What are the technological and/or structural "behavior" in the recycling system, and how can policy, legislation and the system owners facilitate to improve the behavior of the system?"

1.3 Multidisciplinary approach

A broad multidisciplinary approach is chosen for this thesis. In order to answer the research questions, it is needed to connect several areas of expertise. The work has tried to determine the relationship between all relevant areas of expertise, juxtaposing different knowledge into a new model capable of supporting a deeper and better understanding of the system studied. This has led me to explore both qualitative and quantitative methods from engineering, science and social-science.

One of the first things that becomes evident when working with socio-technical systems, is that it does not matter how well an engineering solution can handle the problem. If people do not use it - it does not "work". Thus, to study such systems requires a systematic framework that is capable of including both qualitative and quantitative methods, of various origins.

As a backbone to my research I have used Systems Engineering [Olivier et al., 1997]. This has given me a valuable and systematic tool for data gathering, calculations, modeling and analysis.

In order to understand the social dynamics of existing systems, I have used

Actor Network Theory [Latour, 1987, 1997] and Systems Thinking [Senge, 1990]. Through this I have been able to shed some light on policy, organizational learning and the sociology of the system.

I have then used Industrial Ecology methodology [Lifset and Graedel, 2002] to assess and evaluate the environmental impacts from the various waste handling alternatives, and eco-efficiency [Keffer et al., 1999] for trade-off analysis.

Thus a multiple set of methods from different academic fields are needed in order to study complex socio-technological systems. I have therefore cooperated with colleges with different fields of expertise during this work in order to achieve this. In addition to my supervisors Helge Brattebø and Morten Levin, I have worked together with Håvard Bergsdal on waste projection, see Bergsdal et al. [2004]; Bohne, Brattebø and Bergsdal [2004*a*,*b*]; Bohne, Bergsdal and Brattebø [2004] and Hilde Nøsen Opoku on policy analysis, see Bohne and Opoku [2003]; Bohne, Opoku and Brattebø [2004]

1.4 Scope and positioning

The scope of this thesis is threefold. The first scope is to get a better understanding of the processes that are taking place within the socio-technical sphere of a recycling system. What are the processes behind the making of the system, what controls the system, what kind of powers drive the system, are there lock-ins in the system and so forth.

Second, what are the nature of C&D waste, and what are the environmental impacts from the various waste fractions. Will the composition of the waste change in the future, and how much waste is expected? Are there geographical differences to consider?

Third, how can we use all this information to improve recycling systems for C&D waste? Consequently, what policies and infrastructure are needed to do this?

Thus the position of this work is to study these processes and systems from the system owner's (read the authorities) viewpoint. That is, the system is studied and optimized with a focus on overall environmental impact, to improve the overall environmental-economic performance. By saying this, I also imply that some stakeholder may loose profit if my suggestions are implemented, others may increase profits.

I am here referring to the authorities as the “system owner”, since the authorities are the only ones with the power to make policies, create new structures and enforce sanctions in the system. Thus it is the authorities that design and control the system, through policies and sanctions.

1.5 Structure of this thesis

Chapter 2 presents the theoretical foundation of the thesis, discussing: Industrial Ecology, systems engineering, environmental impact, the C&D waste handling system, and organization, technology and change.

Chapter 3 deals with the methodology used in my research work, and how these methods are used together.

Chapter 4 presents the results, and Chapter 5 analyzes the results. Chapter 6 draws conclusions and gives recommendations. Finally, Chapter 7 provides some ideas for further research.

Chapter 2

Theory

This thesis applies the new field of Industrial Ecology. This means three things; first, the goal of this thesis is to improve and maintain environmental quality. Second, Industrial Ecology takes a systemic view that typically draws the boundaries for analysis more broadly - around groups of firms, regions, sectors and so on. Industrial Ecology asks how resource use might be optimized to reduce the environmental impact, where resource use includes both materials and energy (as inputs) as well as the ecosystems and biogeochemical cycles that provide crucial services to humanity [Ayres, 1993]. Third, Industrial Ecology seeks to offer advice of the sort: *"if the goal is x, then the appropriate choice is y"* [Lifset and Graedel, 2002].

Theory from three fields is applied: Industrial Ecology, Systems Engineering, and Organizational and Social Studies. The work done therefore is of a cross disciplinary nature. Industrial Ecology provides the framework for this work, and the environmental impact describes the problem. Systems Engineering gives an approach to collect and analyze the information to solve the problem of interest. Eco-efficiency is an analytic tool to compare different approaches and waste handling solutions against each other according to the given criteria for system optimization. Finally, the organizational and societal studies provide the tools for the describing and identifying measures that ought to be taken in order to facilitate change toward the desired goal of action.

2.1 The Industrial Ecology foundation for this work

The concept Industrial Ecology is built around the ecological metaphor. The central paradigm is that industrial societies would become more ecological and economic efficient if we accept the principles for resource utilization found in natural eco-systems. In natural systems we find a dynamic balance between resource extraction and consumption, implying that waste produced by one group of consumers is utilized as valuable resources for another. Ultimately the conceptualization of resources is a rejection of waste [Frosh and Gallopoulos, 1989; Allenby and Cooper, 1994; Ehrenfeld and Gertler, 1997; Opoku, 2002].

An often used definition of the field of Industrial Ecology is: *"Industrial Ecology is the study of the flows of materials and energy in industrial and consumer activities, of the effect of these flows on the environment, and of the influence of economic, political, regulatory and social factors on the flow, use and transformation of resources"* [White, 1994].

White's description of Industrial Ecology is three fold. First, he speaks of the pressure on the environment when referring to the studies of *"the flows of materials and energy in industrial consumer activities"*. These studies are based on systems analysis techniques such as Material Flow Analysis (MFA) [Bringezu and Moriguchi, 2002]. Second, Industrial Ecology can deliver information on the state of the environment by studying *"the effects of these flows on the environment"*. This part requires additional quantitative and qualitative impact analysis of the industrial metabolism, based on methods such as Life Cycle Assessment (LCA) [de Haes, 2002]. Based on the information derived from the two first focus areas Industrial Ecology may, finally, by studying *"the influences of economic, political, regulatory, and social factors"*, contribute to define adequate response to problems identified [Opoku, 2002].

This means that Industrial Ecology is ecological in at least two senses [Lifset and Graedel, 2002]. One, following Frosh and Gallopoulos [1989], where Industrial Ecology looks to non-human *natural* ecosystem as models for industrial activity. This is what has been dubbed the *biological analogy* [Allenby and Cooper, 1994], and is often exemplified through the industrial symbiosis in Kalundborg, Denmark [Ehrenfeld and Gertler, 1997; Ehrenfeld and Chertow, 2002]. The second approach, *the ecological constraints approach*, places human technological activity in the context of ecosystem that supports it, examining the sources of resources used and the sinks that may absorb and detoxify wastes. This approach follows the *limit to growth* [Meadows et al., 1972] tradition, where we should use our knowledge of ecosystems to limit our actives so that our activities do not violate the carrying capacity of the earth.

These two approaches are now considered in turn:

The biological analogy

Industrial Ecology is based on the metaphor of an industrial system mimicking the natural ecosystem in a way that in the end eliminates wastes [Ehrenfeld and Chertow, 2002], that is, a circular material flow within the system. To achieve this, we must move industrial production and consumption from a type I and II system, to a type III system, Figure 2.1.

Figure 2.1 shows three different types of ecosystems. The Type I system describes a system not unlike the early earth, where resources and energy was unlimited, so also the sinks. Through time and evolution, most ecosystems have evolved to a Type II system. That is, the system still needs to get the energy and some resources from outside the system, and has a limited amount of waste leaving the system, but has a high degree of internal cycling of materials. A Type III system is a representation of the planet Earth, with energy received from the sun powering the ecosystem with internal material cycling, and process heat leaving the system back into space.

Ecosystems are built up of communities. Communities are defined as: *"a collection of organisms interacting directly and indirectly"* [Wallace et al., 1986]. Communities have properties that are derived from the sum of the properties of the individual organisms plus all of their interactions. The interactions produce system properties that are more than the simple sum of those of the individual organisms. We say that such properties emerge from the system ("emergence"). Emergence is important and difficult to understand, since it springs from a non-linear relationship among species and organisms. The questions within Industrial Ecology are how are such complex systems organized, and how can we use our knowledge about system behavior to reach sustainable development.

For the analogy to be true, several requirements must be in place (many of which are outside the scope of this thesis). First is the source of energy. Nature receives energy from the sun, and emits heat back to space. That is nature

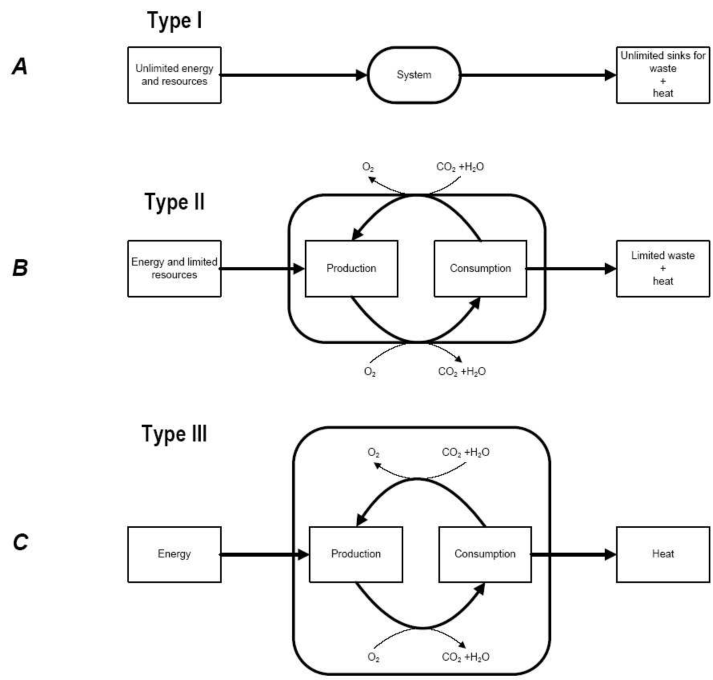


Figure 2.1: System models, adapted and modified from Graedel and Allenby [1995]

is solar driven. Ultimately industry is not! Second, nature uses this energy to build structures (plants) which stores energy, and is capable to capture and store more energy. This energy is then used as both fuel and structural components for other organisms. Then, at the end, all the stored energy is transformed and dissipated back into the surroundings as heat, and all structures are broken down into their initial elements. Industrial systems on the other hand, are not solar powered, and we are in general not able to retrieve the initial components after use.

But the analogy has some shortcomings. If we for example look at Type II and Type III systems, most ecosystems at a local scale follow a type II system, it is only at the global scale the carbon cycle is closed. Also, nature is full of waste (when seen from the producers perspective), but waste that is free of pollutants, and therefore may serve as input to other systems.

The ecological constraints approach

Harte [2001], Bohne [2003] and Korhonen [2004] argue that Industrial Ecology should follow the ecological constraints approach, not the ecological analogy approach. That is, we will not be able to learn from ecosystem models what to do (the analogy approach). But ecosystem models provide us with enough information about limits and boundaries, for us to know what we should not do. This knowledge derived from ecology and natural science should be used to insert a 'do not' menu for our activities. There are limits to nature's capacity to produce services; the source and the sink functions essential for human societies are limited. The resource flows from economic activity and the ability of nature to assimilate wastes and emissions is limited. Thus, "it is the *ecology as constraint* approach that industrial actors and policy makers must listen to in order to reduce the ecological footprint to a sustainable level" [Harte, 2001].

My position within Industrial Ecology

The great extent and dynamic nature of the interrelationships and spontaneous self-organization in ecosystems means that it is only possible for us to develop a good understanding of some processes in nature, and only those that are local to us in space and time. With *"local in space and time"* I refer respectively to *"things that we are immediately involved in"* (it is not a geographical concept) and *"not very far into the future"*. Thus we have a restricted understanding about what is going on around us, and a limited capability to know what will happen next [Flood, 1999].

Given these constraints, Industrial Ecology has an important role in shaping the future towards sustainability, first in its ecological constraint mode, later in the analogy mode.

This thesis is about contributing to the progress towards a type II system, but a type II system where the waste is in such a form that it can be useful as input for other industrial processes; free of toxic contaminants. Such recycling must however be carried out within limited geographical regions to be sustainable. I believe that the best way of achieving a type II system, is by using our knowledge on ecosystems to restrict development of more land, and to reduce extraction of virgin materials and production of waste from our society. If we manage this, then the sum of local type II systems may approach a type III system globally. The AEC-industry is a significant contributor to our society's material use, energy spending and waste production. In the western industrialized countries, the AEC-industry is referred to as the "40% industry", and the industry is important since it builds the infrastructure in which most societal activities take place, and thus are determining the future energy use within the technosphere.

Waste handling, recycling and reuse of C&D waste was common practise a century ago, but was forgotten in the post WWII era, as new construction techniques and materials were introduced. The shift in costs, from material to labor, contributed to this change in practise. But in the last decade, recycling and reuse has attained renewed attention. I believe that to change current development, it is necessary, first to reduce our resource extraction, especially new development of virgin soil, or industrialization of agricultural land. And second, to reduce output flows, so that we reduce pressure on the detoxification services of nature.

2.1.1 Human impact on natural ecosystems

Human activity influences the natural ecosystems in numerous ways. We harvest plants, fish and game, we develop land areas, and we pollute. All these activities somehow alter the fundamental resource base on which we depend. And due to our use of technology and non-renewable fuels, we are in may ways bypassing the natural feedback mechanism of the natural ecosystems, since the source of energy is "unlimited". An example of such bypass of the natural feedback mechanisms, is the way we have managed many of our marine fish resources. In earlier times, where fishermen were sailing or rowing their boats, their area of fishing were limited. They needed the energy from their catch to survive. If their catch was limited, starvation would occur. Starvation led to reduced reproduction, thus less fishermen. This again would allow the fish population to recover and multiply. More fish then would allow for an increase in fishermen and so on. By the introduction of fossil fuel driven engines, the earlier energetic feedback mechanism was bypassed, with the result that humans in many cases have driven the fish resources to extinction. Even today, as I write this thesis, there is warning from researchers that we should ban fishing of several species in the Barents Sea to avoid "permanent" damage to the resources. On top of that we add pollution.

All this is altering the world around us in ways we are not yet capable of understanding. The basic problem with our impact on natural systems, is that we can not tell when or how nature will respond to our actions. That is, there is no precise answer to the questions we might want to be answered, "as how much CO_2 can we emit?", "how much Nitrogen can we use as fertilizers?" and so on. The only thing we know, is that we have altered these cycles significantly, and that at some point there will be a response from nature. We are also starting to gain knowledge on how nature reacts when pushed to far out of equilibrium, it "flips" [Kay et al., 1999]. Unfortunately, we can not predict towards where or what if flips. Moreover, we can assume that it will take a lot of effort to recreate the old equilibrium after such an event.

Global warming is an example of the fact that human activity is pushing the eco-system away from equilibrium [Spiegelman, 2003]. Although we know that nature will respond to this, we are not capable to predict when and how, we can only make qualified guesses. Thus, we can predict that we are moving towards a system "flip", but we can not tell towards where or what end state.

2.1.2 System dynamics

Classical ecological science is about natural eco-systems, and its behavior at a near equilibrium state, that is, at "steady-state". Such systems are regulated by feedback mechanisms, that often follow cyclic patterns. These cyclic patterns are again a product of positive and negative feedback systems. The Lokta-Volterra model of predator-prey interaction is well known example [Wallace et al., 1986], Figure 2.2.

Another way of looking at such dynamic system is by causal loop diagrams. Figure 2.3, shows the same predator-prey relationship as Figure 2.2, but now as a causal loop diagram. The causal loop diagram shows how the different parts of the system are influencing and interacting with each other in a dynamic system.

As we add complexity to such systems, we soon find them unmanageable, and incapable of dealing with situations some distance from equilibrium. A weather forecast is a good example of our limits to model complex dynamic systems. With a lot of data from weather stations around the globe, along with a good understanding of the atmospheric physics, we can predict the weather relatively accurate for the next few days, but not weeks in advance. Chaos theory has

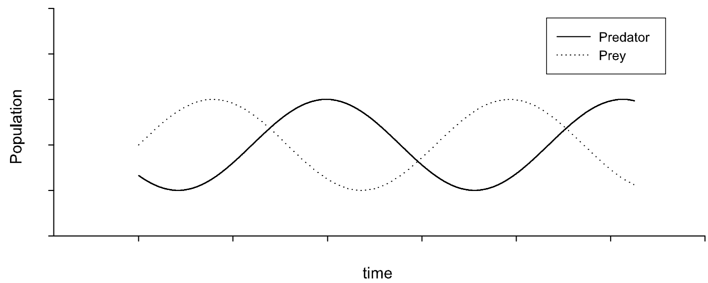


Figure 2.2: The Lokta-Voltrerra model of predator prey interaction

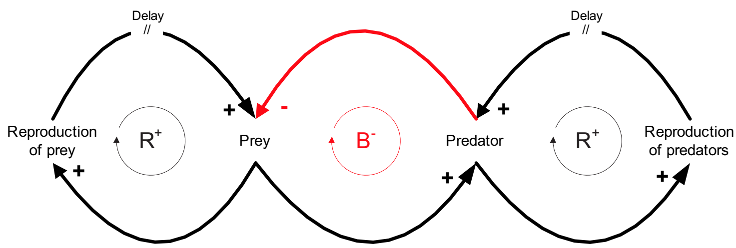


Figure 2.3: The causal loop diagram of the Lokta-Voltrerra model

given us a vague understanding of the system's emergent properties, and the picture of "a butterfly in Amazona starting a cascade of events that turns out to be a tornado in Texas" has a tremendous intellectual power [Lovelock, 1979].

From evolutionary biology, we now start to understand the dynamics of self organization and mechanisms of change, although we do not have the possibility to understand the outcome of evolutionary processes. Thus the more we understand of these mechanisms, the more we see the need of the precautionary principle and the conservation of biodiversity.

2.1.3 Self-organizing holarctic open (SOHO) systems

Ecosystems are built up of hierarchies and adaptive cycles, across different scales. Following the work of Kay et al. [Kay et al., 1999; Kay, 2002], ecosystems (and human systems) can be viewed upon as self-organizing holarctic open (SOHO) systems, whose dynamics are predominated by both positive and negative feedback processes operating over a range of spatial and temporal scales. Self-organizing means that structure emerges spontaneously during the evolutionary process. Open means that energy and materials can flow into and out of the system. Holarctic means the system can be considered to be made up of nested subsystems (holons), each of which is a complete self-organizing, open system itself. Holarctic has replaced the term hierarchic, which often carried a misleading top-down connotation.

We can interpret the behavior and structures of these system with reference to the language of non-equilibrium thermodynamics: holons, canons, information and attractors. A canon is the story of change in an ecosystem, that is, "the complex nested interplay and relationships of the processes and structures, and their propensities that give rise to coherent self-perpetuating behaviors, that define the attractor" [Kay et al., 1999]. The canon is qualitative and capable of going in multiple directions. Attractor is a term from non-linear mechanics that points to a topographic region of stable behavior. The way an observer often describes a SOHO system is by reference to its attractor. Eco-systems, often, have multiple operating states (attractors).

Holling [2001] describes SOHO systems through the notion of panarchy. The panarchy is described though the notions of linked adaptive cycles. The basic adaptive cycle can be described through a four-box cyclical model of terrestrial ecosystems (Figure 2.4).

In Figure 2.4 the first trajectory is the *exploitation* to *conservation* path that culminates in the *climax* or steady-state structured community. The biological attractor is the autotrophic system (the forest). The canon is expressed, for example, as the growth (energized by solar energy) of a forest to maturity. However, in the process of increasing the utilization of solar energy and hence building more structure, much energy is stored in the biomass. This has the effect of moving the system further and further away from thermodynamic equilibrium as it develops.

When, as Holling puts it, the inevitable accident (fire, windstorm or pest out-

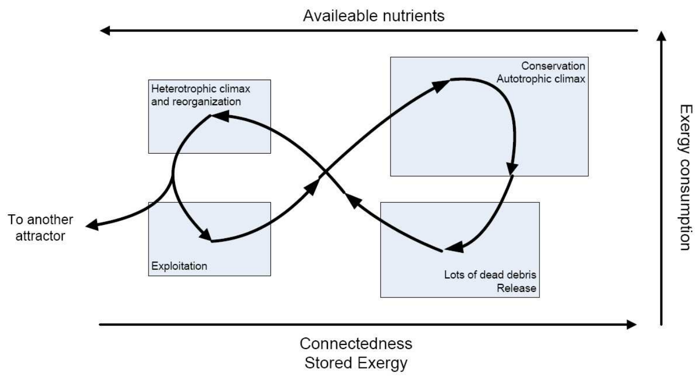


Figure 2.4: Hollings four-box model as a dual thermodynamic branch system, adapted from Holling [2001]; Kay et al. [1999]

break) happens, suddenly much exergy is available as dead biomass. This energizes a new biological attractor, the heterotrophic or decomposer system. This change moves the system along a new path that runs from *release* to *reorganization*. As the system progresses along this path it releases the stored nutrients while using the stored exergy. Eventually the stored exergy runs out and the heterotrophic system collapses. However, in the process it has released nutrients necessary for the reemergence of the solar energy-powered system. This interplay between two biological attractors, which are organized around different forms of exergy, material and information, is played out giving rise to the landscape we see.

Regier and Kay [1996] provide an example from Lake Erie, which processes a two-attractor catastrophe cusp model as a way of integrating much empirical information of how aquatic systems might transform under powerful, careless human intervention. Two different attractors for shallow lakes have been identified. In the oligotrophic/benthic state, a high clarity bottom vegetation ecosystem exists. As nutrient loading results in increasing density of planktonic turbidity in the water, the internal state of the adapting ecosystem eventually hits a catastrophic threshold and the ecosystem flips into a eutrophic/pelagic state. At least three different descriptions of such lakes are needed: one for the pelagic state, one for the benthic, and one for the intermediate stage as the system flips between attractors (Figure 2.5).

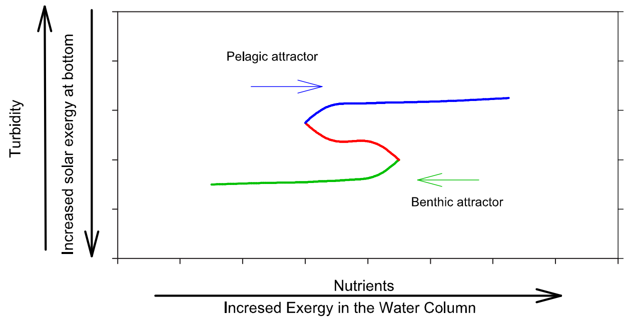


Figure 2.5: Benthic and Pelagic Attractors in shallow lakes, after Regier and Kay [1996].

The essence of the canon of the benthic system is that it is dependent on solar energy reaching the bottom, for the exergy necessary to energize the system. The solar exergy is captured by the green matter on the bottom and is transformed into forms appropriate to power the benthic processes. These include predation and grazing of the pelagic system, thus suppressing it. Various means emerge to the ecosystem to the benthic attractor. Notable among theses are the means for keeping the water clear so that solar energy will reach the bottom, which means the water column will be kept free of sufficient exergy which would empower the pelagic attractor.

The pelagic system depends on exergy in the water column to energize it. Solar energy may be in the water column, however, unless the materials necessary for the existence of dissipative processes, which can utilize solar energy, are present in the water column, nothing can be done with the solar energy, so it has no exergy. For example, in many lakes, available phosphorus in the water column limits the level of photosynthesis by phytoplankton. Beyond a critical level of available phosphorus in the water column, there is enough availability of solar energy (i.e. sunlight exergy) to support phytoplankton bloom necessary for the activation of the pelagic attractor. Once this occurs, the solar energy capture happens nearer to the water surface instead of at the bottom and means emerge for promoting and maintaining the pelagic attractor. Of course by its very presence the pelagic system shades the benthic from irradiation by the sun, thus decreasing exergy at the bottom

Of course, both attractors have feedback loops, which seek to buffer from changes in external influences. The benthic attractor has elaborate feedback schemes, operating at different spatial and temporal scales, for limiting the phosphorus in the water column. The pelagic attractor has elaborate schemes to accomplish just the opposite. Such buffer capacity is expressed as the system resistance towards change.

It is important that these processes do not follow a linear relationship. Thus a marginal decrease in anthropogenic impact on environments does not necessary result in marginal improvements in environmental quality. Or in the opposite direction, the nonlinearity of a incremental increase in anthropogenic impact does not necessary result in a marginal reduction of environmental quality, but can "flip" the system toward a new attractor.

Another related important feature to notice about self adaptive systems is resilience. Resilience is a measure of how quickly and completely a complex system recovers after being perturbed, and is a measure of system integrity. The diversity of species is important in maintaining high resilience, since high diversity leaves more candidates to explore the "new" opportunities in a reorganization of the system after a "catastrophe".

Applying these examples to industrial ecosystems, it is necessary to implement change in such a way that we do not initiate a system "flip" that can not be reversed. Careless management of C&D waste, can invoke serious damage to ecosystems, due to the huge volumes of waste. Our knowledge from ecology, natural science and waste management can be used to limit our impacts to a level within the limits of the ecosystem. Traditionally waste management has often been landfills, a method that generate emissions over long periods, often longer than a persons lifetime. The longest lasting emission is leachate, often containing unwanted organic components and heavy metals [Belevi and Baccini, 1989; Kylefors et al., 2003]. Thus, if the objective of a waste management policy is to ensure that future generations are not forced to deal with the wastes of their ancestors, then each generation must transform its wastes to *"final storage quality"* (FSQ). FSQ is defined as: *"a landfill whose leachate is compatible with the environment"*[Belevi and Baccini, 1989].

I believe that the Industrial Ecology paradigm is the key tool to moving society to a more sustainable system. It is therefore necessary to manage C&D waste in a better in the future, than what is currently done.

2.1.4 Industrial systems - the technosphere

The industrial system is a part of the total global ecosystem of the Earth, although not an necessary or integrated part. That is we are dependent of the natural ecosystem surrounding us for food and services, while nature will do without us.

Much of what we think of as the industrial system, or the technosphere, is mainly the built environment, but also the cultivated landscape - or agricultural areas. The built environment is then all our infrastructure; houses, roads, water lines, sewers, railways, airports, harbors etc.

In 1985 Whyte note that: *"Urbanization is a major ecological driving force which involves large transformations of land, air, water, energy resources and human populations"* [Whyte, 1985]. She adds, if we do not change the way we organize our cities, we will reach a substantial resource problem within a short period of time. Since 1981 the area used for agriculture is reduced by 7% due to urbanization and city development. Until recently, the increased productivity in agriculture has been able to compensate for this loss, but this may not longer be the case. In 1998 the worlds production of grain was reduced by 2% from the previous year, at the same time as the population grew by 1.4% [Thompson, 2000]. In addition to growing urbanization (land use), the pollution per capita from cities is increasing. In 1960, there were three cities with more than eight million citizens, in 2015 there will be 33; 27 of which will be in developing countries [Thompson, 2000]. Newmann [1992] has, by analyzing urban density, infrastructure and fossil fuel consumption, shown how pollution increases with recent development. The increase is mainly due to the modern infrastructure and the use of cars (especially in the USA). The same trend has been observed in the Nordic countries. Næss [2000] claims that *"A sustainable global development is not possible without an urban development in accordance with the criteria for sustainability... A counter-initiative which is natural to rise, is to increase the internal concentration instead of expanding the urban areas"*.

It seems therefore logical, within an Industrial Ecology framework, to start working on reducing the output flow from the technosphere, improved waste management and resource recovery in the AEC-industry - the single most important waste producer in the technosphere. Hopefully, the work on recycling systems for C&D waste, will provide feedback to how we construct our cities, which in turn will influence energy demand from these cities. Both the construction and use phase of the built environments is of greater economic and environmental importance, since the input to, and and the the total volume of the stock is much larger than the output in form of C&D waste. But these things take time. Infrastructure has on average a very long service time, so that the changes we start implementing today, on the input side, will not be seen as waste for another 50-60 years. Material composition of the building stock has changed rapidly since WWII [Brunner and Stämpfli, 1993], at the same time as the functional life time of buildings are decreasing [Müller, 2005].

2.2 Systems engineering

Systems Engineering is a method designed and used to combine text descriptions and rigorous modeling to analyze and describe complex systems. *"Systems engineering begins with the needs of users, owners, and operators and with the realities of the marketplace. The system engineering work transforms these needs into a description of a system architecture and design that specifies the component to be designed, implemented and integrated. The fundamental process for the engineering of systems is an optimization process'* [Olivier et al., 1997].

This PhD thesis have used the systems engineering approach to organize the work, and to aid in designing and answering the research questions. The systems engineering process is: the ordered set of engineering steps that engineers use to go from user needs to specifications for all the components to be assigned or procured. Two parallel sub-processes are considered: a System Engineering Management Process and a Systems Engineering Technical Process, Figure 2.6 [Olivier et al., 1997].

As described above the purpose of thesis is to provide input to the Systems Engineering Management Process for a generic C&D waste system. This means that the focus of this thesis is in the Core Technical Process, and thus a part of the overall process as described in Figure 2.7.

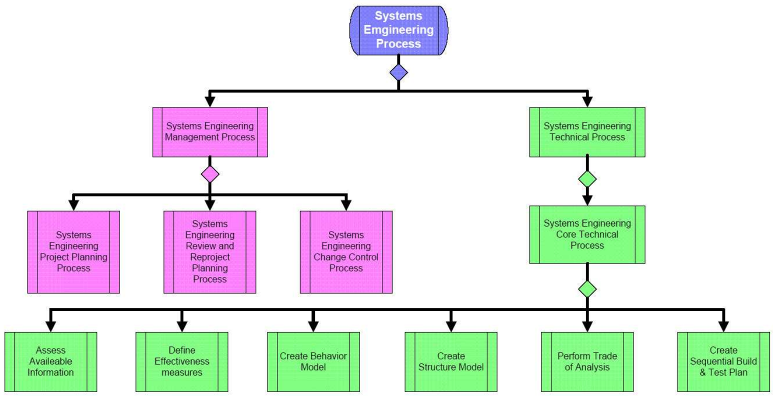


Figure 2.6: Extended part list for Systems Engineering process, after Olivier et al. [1997]

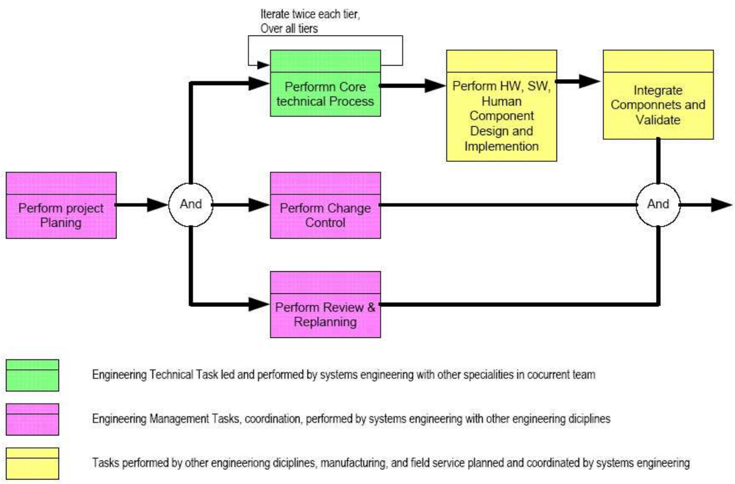


Figure 2.7: Model for the System Engineering Process, after Olivier et al. [1997]

2.2.1 Systems Engineering Management Process

As can be seen from Figure 2.6, the System Engineering Management Process is broken down into three pieces: project planning, review and replanning, and change control. The systems Engineering Technical Process serves as input to the System Engineering Management Process [Blanchard and Fabrycky, 1990; Olivier et al., 1997], Figure 2.7. Although this thesis aims to provide input to such processes, the System Engineering Management Process is outside the scope for this work, and are thus not covered in detail in this text.

2.2.2 Systems Engineering Technical Process

The work in this thesis is organized as a Systems Engineering Core Technical Process (although not all parts of this thesis are technical). The Systems Engineering Core Technical Process is split into six steps, see Table 2.1, but these are not followed in a linear manner. Steps 2, 3 and 4 are concurrent activities, and as understanding progresses in one part, it suggests changes in the other two. Also, the steps in the Core Technical Process are iterated until an feasible (optimal or near optimal) solution is found. A Functional Flow Block Diagram (FFBD) of the process is shown in Figure 2.8.

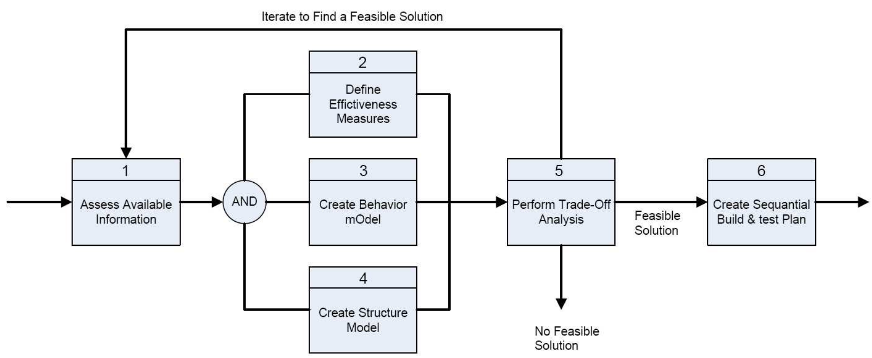


Figure 2.8: FFBD View for the Systems Engineering Core Technical Process, adapted after Olivier et al. [1997]

This work have been studying the processes of establishing a recycle system for C&D waste in Norway, based on Danish experience. By using the six steps of Systems Engineering, I started by assessing information about the two systems. Second, the study had to define what criteria to use for evaluation of the performance in my systems. Third, it was necessary to create a model of behavior from the information assessed, and fourth a structural model of the systems studied. Fifth, trade-off analyzes based on the information obtained in the previous steps could be performed. Sixth, based on the trade-off analysis, new feasible (improved) solutions for the handling of the waste fractions studied could be suggested. Table 2.1 explains the tasks in the six steps of the Core Technical Process, and links them to work done in this study.

Table 2.1: The Six Steps in the Systems Engineering Core Technical Process

Step		Task	Part of thesis
1	Assess available information	Evaluates and categorizes available information and obtains missing information	Chap 2, 3 and 4
2	Define Effectiveness Measures	Defines the criteria for optimization, the effectiveness measures	Chap 2
3	Create Behavior Model	Defines the behavior that is desired with an executable model	Chap 3 and 4
4	Create Structure Model	Defines model of the alternate sets of objects from which to build the system	Chap 3 and 4
5	Perform Trade-off Analysis	Trade-off, selects among the alternative design and architectures	Chap 3, 4 and 5
6	Create Sequential Build & Test Plan	Creates a feasible plan, and near optimal design or architecture	Chap 3, 4 and 5

No further details about the different steps will be made here, but a few remarks will be added.

Steps 2, 3 and 4 are the traditional process of engineering. The way Systems Engineering is used in this thesis, that is looking at a socio-technical system, makes it necessary to include also non-engineering theory and methods in these steps (indicated in Table 2.1). Another point to be mentioned here, is that the case study of the Recycling System for C&D waste in Copenhagen, which will be presented later, is in Systems Engineering terms actually a Re-engineering process of that system.

Re-engineering

Re-engineering of large complex system is often necessary in order to understand how such systems function. The main objective of re-engineering processes is to extract information about how the system works, and thus get the necessary knowledge for the construction of a new system (i.e. a re-construction) that includes or improves the functionality of the "old" system, at higher effectiveness measures.

2.3 Environmental impact

Data on environmental impact for the different alternatives for end-of-life treatment in the C&D waste system is calculated on the basis of data from many different sources, using Life Cycle Assessment methodology [PRé Consultants, 2002; Kotaji et al., 2003].

A problem with these kind of calculations for recycling systems is that we deal with a wide range of products, of different age and from many different producers. Hence, it is a challenge to make use of appropriate system boundaries, cut-off rules and allocation rules when doing the analysis.

2.3.1 Life Cycle Assessment, LCA

The concept of life cycle assessment (LCA) originated in the late 1960s when it became clear that the only sensible way to examine industrial systems was to examine their performance, starting with the extraction of raw materials from the Earth and tracing all operations until the final disposal of these materials as wastes back into the Earth (cradle to grave).

"The environmental life cycle of a product consists of all the stages from raw material extraction to its waste management. Life cycle assessment, then, is the assessment of the environmental impact of a product across its lifecycle" [Baumann and Tillmann, 2004].

There are two reasons for this approach. First, individual component operations could apparently be made cleaner and more efficient by simply displacing the pollution elsewhere, thus the benefits occurring in one location were offset by the problems generated elsewhere, so that there was no overall real improvement. A current example is the proposal to introduce electric cars into towns: this reduces the pollution in the towns but displaces it to the pollution arising elsewhere from the power stations needed to provide the fuel (electricity). The second reason was that traditionally engineers had concentrated their efforts into making individual unit operations more efficient, but nobody was looking at the way in which these unit operations were put together to form an overall production and use sequence. Sometimes, by rearranging the building blocks, overall systems can be made more efficient [Baumann, 2004].

In the early 1970s, LCAs concentrated mainly on energy and raw materials but later air emissions, water emissions and solid waste were included in the calculations. The 1990 SETAC conference in Vermont was the first to analyze LCAs in three main stages as shown in Figure 2.9;

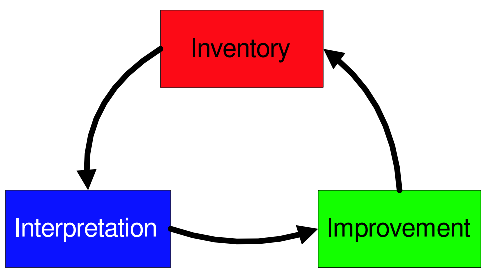


Figure 2.9: The three main stages of a life-cycle assessment.

1. **Inventory** in which the data describing the system are collected and converted to a standard format to provide a description of the physical characteristics of the system of interest.

2. **Interpretation** in which the physical data from the inventory are related to observable environmental problems.

3. **Improvement** in which the system is modified in some way to reduce or improve the observed environmental impacts.

Once improvements have been suggested then the inventory stage is repeated to see if the expected improvements do in fact occur and also to identify any adverse side-effects resulting from the changes. By cycling through the three phases shown in Figure 2.9, it is hoped to optimize the environmental characteristics of the system.

The fundamental idea underlying the calculation of environmental inventories (LCI) is simple. Any group of industrial operations can be regarded as a system by enclosing them within a system boundary. The region surrounding this system boundary is known as the system environment. This system environment acts as a source of all material and energy inputs into the system and as a sink for all outputs from the system. Diagrammatically this concept is shown in Figure 2.10 where the system is represented by the shaded box.

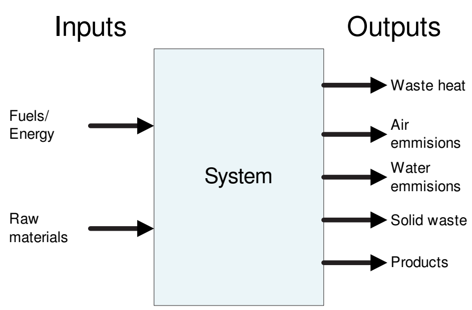


Figure 2.10: Schematic diagram of a system showing inputs and outputs.

An environmental inventory for this system is therefore simply a list of the quantities of all of the inputs which pass from the system environment, across the system boundary into the system and all of the outputs which pass from the system across the boundary and into the environment. When the inputs are all derived from raw materials from Earth and the final products are all waste materials returned to Earth, the inventory is referred to as a life-cycle inventory. It is important to note that in a true life-cycle system there are no usable products, only waste.

Inventory analysis make no value judgements about the relative significance of the different inputs and outputs; instead the analysis aims to provide the quantitative data upon which judgements can subsequently be made. It will however be clear from the above description of an industrial system that the inputs to the system are the parameters involved in discussing conservation problems while the outputs are the parameters of interest in discussing pollution problems.

The simple Inventory → Interpretation → Improvement process of the SETAC 1990 conference has since been replaced (in 1997) by the international standard ISO 14040. The Life-Cycle Assessment framework as laid down in this standard is shown in Figure 2.11.

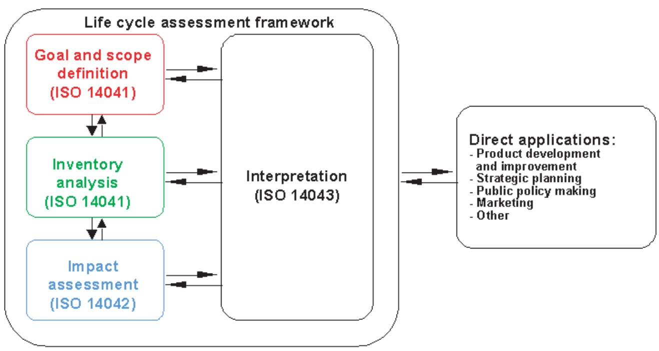


Figure 2.11: Life-cycle assessment framework as laid down in ISO 14040

Whilst extra elements have been added to the framework, it is clear that the sequence Inventory → Interpretation → Improvement (as depicted in Figure 2.9) remains a core component.

Several problems exist in impact assessment [Ekvall et al., 2001; Huijbregts et al., 2003; Kotaji et al., 2003; Dreyer et al., 2003; Baumann and Tillmann, 2004], some of the more obvious are :

- There are not sufficient data to calculate the damage to ecosystems by an impact.
  - Most technological activity requires input (ancillary materials etc.) from other technological activities. For this reason, a traditional LCI cannot include the production of all inputs and, hence, the life cycle is incomplete. Instead, system boundaries must be defined within the life cycle. Furthermore, the analysis is likely to include various kinds of data gaps within the system boundaries.
  - An LCA based on average data clearly does not reflect any marginal effects, i.e., effects of small changes in the production volume; many actions have effects on the electricity system that are small enough to be approximated as marginal effects. In general, most actions can be expected to cause changes that are small enough to be approximated as marginal effects on the production of bulk materials (e.g., steel, aluminium, polyethylene), energy carriers (e.g., electricity, heavy fuel oil, petrol), and services (e.g., waste management) where the total production volume is very high. This means there is a risk that the environment can be harmed by actions that are recommended on the basis of a LCA. On an even more general level, there is a risk that undesirable effects follow from actions that are based on rule ethics, because rule ethics does not take into account the consequences of the individual action.
- There is no generally accepted way of assessing the value of the damage to ecosystems if this damage can be calculated.
  - It is generally impossible to model the full consequences of an action in an LCA. These consequences depend on various types of causal relationships, while a conventional, prospective LCA accounts mainly for very simple causal relationships. For example, the purchase of a product is usually simply assumed to result in the production of the same quantity of that type of product.

There is several well established methods for Life Cycle Impact Assessment (LCIA) to choose among.

2.3.2 The Eco-indicator 99 method of Life Cycle Impact Assessment (LCIA)

Life Cycle Impact Assessment (LCIA) is then the aggregated damage assessment from the inventory of the flows of the process(es). Eco indicator 99, is an often used method for life cycle impact assessment. The main reason for choosing Eco-indicator 99 as the method for life cycle impact assessment in this thesis is that it allows the calculation of single scores, which then can be used in eco-efficiency calculations when comparing processes and alternatives in the study of recycling systems. Eco-indicator 99 based on the following approach [Goedkoop and Spriensma, 2001];

- A completely "top-down" re-engineered impact assessment method with clearly detailed steps such as fate, exposure, effect and damage analysis.
- Resource depletion, land use and radiation are included.
- Uncertainties are calculated for the majority of damage factors.
- Normalization and default weighting data are given. Three different "perspectives" are available, allowing different assumptions on time horizon, manageability etc.
- Only three damage categories (endpoints) are to be weighted. This allows for stakeholder involvement with the help of the weighting triangle.
- The methodology are highly compatible with ISO 14042 requirements.

As with all current LCIA methods, Eco-indicator 99 is not "complete" in its impact assessment, and it is important to be aware of these shortcomings. First of all, Eco-indicator 99 only looks at environmental problems as they occur in Europe, and thus uses a European energy mix (for example more use of fossil fuel in electricity production compared to Norway). Eco-indicator 99 is based on the following three end point damage categories:

'Human Health' contains the idea that all human beings, in present and future, should be free from environmentally transmitted illnesses, disabilities or premature deaths.

'Ecosystem Quality' contains the idea that non-human species should not suffer from disruptive changes of their populations and geographical distribution.

'Resources' contain the idea that that the nature's supply of non-living goods, which are essential to the human society, should be available also for future generations.

Table 2.2, shows the missing impact categories for the three damage categories;

Table 2.2: Missing impact categories in Eco-indicator 99, adapted from Goedkoop and Spriensma [2001]

Human Health	Ecosystem Quality	Resources
Other toxic effects from heavy metals (Can only model carcinogenic effects); - effects on nervous system - effects on the liver	Acidification and Eutrophication by waterborne emissions	There is no acceptable method available to express damage to non-living resources
Other toxic effects; - Missing data on many substances	Damage to Ecosystem Quality by climate change	
Noise	Damage to Ecosystem Quality by increased UV radiation	

Damage assessment and normalization

The calculation of the total scores for the three damage categories concludes the environmental modeling. However, the three damage categories all have different units. Eco-indicator 99 makes these damage categories dimensionless through normalization. Normalization is achieved by dividing the damage value with a normalization value, which returns a dimensionless value. As Eco-indicator is developed for Europe, it uses standardized European normalization values [Goedkoop and Spriensma, 2001].

The damage of the different impact categories then are given in eco-points (Pt.), which are a normalized value. The 'single score', which is used for impact assessment in this thesis is the aggregated normalized impacts from these three damage categories. Figure 2.12 shows a general presentation of the Eco-indicator 99 LCIA method.

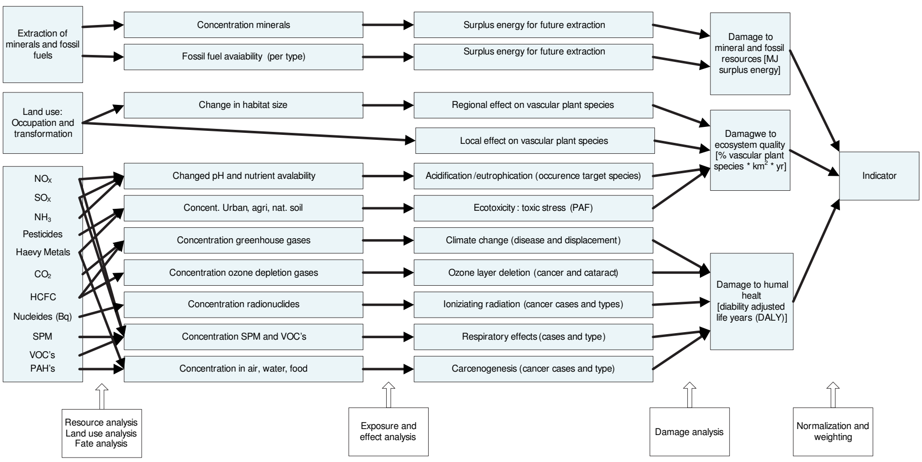


Figure 2.12: General representation of the Eco-indicator 99 methodology. The white boxes refers to procedures, the other boxes refers to intermediate results. Adapted from Goedkoop and Spriensma [2001].

2.3.3 System boundaries and allocation between co-products

In systems modeling, and modeling of environmental impacts (LCA) in particular, co-production (the joint production of two or more products from the same process or system) has been seen as presenting a problem to the modeling. The traditional solution has been co-product allocation (the partitioning and distribution of the environmental exchanges of the co-producing processes over its multiple products according to a chosen allocation key) in parallel to cost allocation [Weidema, 2000; Weidema and Norris, 2002; de Haes, 2002].

Weidema and others [Weidema, 2000; Weidema and Norris, 2002; de Haes, 2002] have demonstrated how co-product allocation always can be avoided by expanding the system to also include product system B: *"the co-producing process (and its exchanges) shall be ascribed fully (100%) to the determining co-product for this process (Product A)"* [Weidema, 2000].

By expanding the system boundaries to also include co-production, I have avoided co-product allocation. Figure 2.13 shows a principal sketch of the system expansion in order to avoid co-production, which we have the applied for a recycling system for C&D waste.

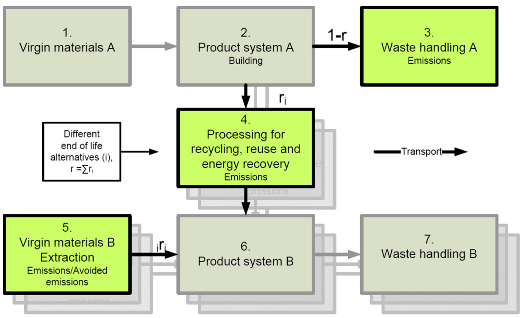


Figure 2.13: System expansion (from A to A+B) for the allocation of influence among co-products, as input to the calculation of eco-efficiency in C&D waste recycling systems.

Highlighted boxes and arrows denote system borders for this study. Arrows denote transport between processes. The layers beyond are further system expansions for different secondary usages, or for different material fractions. r_i represents the ratio of a given waste fraction that enters an alternative end-of-life treatment, and γ_i is the factor for how much virgin materials that is replaced by r_i.

In the recycling system for C&D waste, it is the enterprize owner (of the construction or demolition project) or the entrepreneur in system A who in general determines where and what to do with the waste. However, authorities often seek to influence these decisions through policies.

In this thesis I have chosen to follow Weidema's recommendation of system expansion [Weidema, 2000], since my interest are in the overall system, and the focus point is to maximize overall system performance. Thus I have defined my system analysis boundaries according to Figure 2.13.

2.3.4 Eco-efficiency

Eco-efficiency was first mentioned by [Sturm and Shaltegger, 1989]; *"The aim of environmentally sound management is increased eco-efficiency by reducing the environmental impact while increasing the value of an enterprize"*. Later the Business Council (now the World Business Council) for Sustainable Development (WBSCD) described how to achieve eco-efficiency in a report released just prior to the 1992 Earth Summit in Rio de Janeiro [BSCD, 1993]. Eco-efficiency is now defined as: *"the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impact and resource intensity throughout the life cycle, to a level at least in the line with the earth's carrying capacity"*[Keffer et al., 1999]. This can be expressed mathematically as value added over environmental impact [Keffer et al., 1999],

$$\text{eco-efficiency} = \frac{\text{product or service value}}{\text{environmental influence}} \tag{2.1}$$

On the operational level, eco-efficiency can express the environmental performance of a company or a process. Eco-efficiency is operative through single-indicators i.e. "sales/CO_2-emissions" [€/kg CO_2] or "sales/environmental costs" [€/€]. Eco-efficiency does thus not express any single indicator, but rather an accumulated indicator for the company's or product's total environmental impact with regard to revenues, see [Dahle et al., 2000].

WBSCD [Keffer et al., 1999] has developed a framework with guidelines on how companies can describe, measure, and communicate eco-efficiency, both for internal decision processes and to external stakeholders. The framework has a basis in both the value- and environmental aspect (numerator and denominator in the fraction) of the product or service, and organizes these in three levels; categories, characteristics and indicators. Three categories are chosen; product/service value (numerator), environmental impact of production of value/service (denominator) and environmental impact of the use of the product/service (denominator). These categories are shown in Table 2.3.

Table 2.3: Operationalization of eco-efficiency through categories and characteristics, adapted from Dahle et al. [2000]

Category	Characteristics
Product/service value	Volume, weight, function, money value
Environmental impact of production of value/service	Energy consumption, material use, use of natural resources, pollution, unexpected events
Environmental impact of the use of the product/service	product/service characteristics, waste from packing, energy consumption, pollution through use

These characteristics are further made operative through indicators, shown in Table 2.4.

Table 2.4: Operalization of eco-efficiency through characteristics and indicators, adapted from Dahle et al. [2000]

Characteristics	Possible indicators
Volume	Units sold, numbers of employees, timeframe (years, months), area
Quantity	Quantity produced (kg), quantity sold (kg)
Function	Product performance services delivered, product life time, transport capacity
Money value	Gross sale, turnover, revenue, depths, income, profit, investments, costs, share value
Others	Price of product, market share

The different stakeholders have different success criteria to measure their own performance. This can be for example,

- % recycling
- Reduction of pollution
- Revenue
- Reduction of land use for land fills

WBCSD [BSCD, 1993; Keffer et al., 1999; Verfaille and Bidwell, 2000; Schmidheiny, 2000] and the UNCTAD [2003] advocate using internationally standardized economic indicators when calculating eco-efficiency. Value added is proposed as the indicator of choice for product or service value. Since eco-efficiency primarily was designed for measuring efficiency improvements in production systems, within a company, both value added and environmental influence should be known, at least for internal purposes.

When we are looking at recycling systems, we can not use the term value added in the same way as at the firm level. With a system of many stakeholders who seek to make profit along the way, this picture gets more complicated. Even so, some of this profit does not necessarily increase the value of the material in question, but arises from the stakeholders' performing services; such as collection, transportation, sorting and processing. Processing activities in recycling systems, in fact, despite a lift of value for the material, normally lead to a considerable downcycling of the material, at the same time as the stakeholder makes profit. However, the alternative of no processing would usually be worse, since this gives even less value in the market.

Dynamic eco-efficiency

For eco-efficiency to have any meaning as a tool for decision making, we need to measure the change in eco-efficiency between different alternative solutions. But eco-efficiency is a single number that hides valuable information away from decision makers, especially when more than one alternative process is to be considered. Another issue is that the value of eco-efficiency will increase if the cost increases. Hence we will have to rearrange this parameter in order to better communicate information the way we prefer. Thus what we want to measure is the relative change over time, or the dynamics, in eco-efficiency.

Bohne, Eik, Melum, Michelsen, Støren, Boks, Huisman and Stevels [2004] have therefore suggested that plotting the changes in economic and environmental performance in a two-dimensional plot (xy-plot), will enable decision makers and others to follow the progress of development, or to separate different alternatives in an lucid and intuitive manner. Figure 2.14, shows examples of plots for product substitution, alternative solutions, and product development.

As can be seen from Figure 2.14, we avoid problems that can arise with the traditional eco-efficiency when the denominator is close to zero or changes sign.

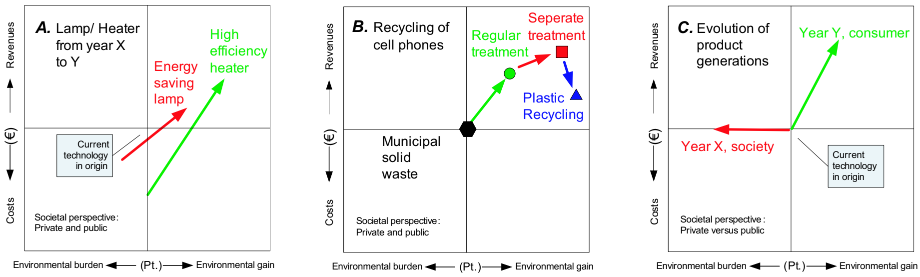


Figure 2.14: Hypotetical dynamic eco-efficiency plots, showing A. product substitution, B. alternative solutions, and C. product development. Adapted from Bohne, Eik, Melum, Michelsen, Støren, Boks, Huisman and Stevels [2004]

In Figure 2.14 A we see that both new technologies with time will be economic and environmental beneficial, thus - this is a "win-win" where an initial subsidy to facilitate technology substitution would be good for society. In Figure 2.14 B we se the different alternatives for recycling of cellular phones, compared to municipal solid waste treatment. From this figure one would suggest following the separate treatment processes, and not do plastic recycling, since this step only reduces revenues without any significant enhancement in environmental performance. And last, in Figure 2.14 C we see that while a consumer can be eco-effective by buying a new TV, this is exactly the opposite for the society. That is, society 'pays' in the form of increases environmental impact (Pt.).

2.3.5 Recycling systems

Recycling may be defined as: *"The process of re-using material for the production of new goods or services on the same quality level"*[GDRC, 2004]. If the quality of the goods and services produced with recycled material is lower, then the process is known as *"downcycling"*[GDRC, 2004].

Thus recycling (and downcyling) is the reuse of materials that would otherwise be considered waste. Those materials can be sources from pre-consumer waste (materials used in manufacturing) or post-consumer waste (materials discarded by the consumer). In theory, recycling would be a continuing reuse of materials for the same quality purpose, but in practice much recycling extends the useful life of a material, but in a less versatile form (downcycling). For example, as paper is recycled, the fibers shorten, making them less useful for higher grade papers. Some materials get mixed in a way that makes recycling to the original quality impossible (i.e. metal alloys), but allows for "downcycling" or dilution by virgin materials. Other materials can suffer from contamination, making them unsuitable for food packaging.

We are surrounded by recycling systems in our daily lives; at home, at work, in the supermarket, at second hand or junk shops, or at public collection points. These systems are economically or policy driven, or a mixture of these two. Only recently have environmental impact of these been discussed and some questions have been asked about their existence. The most challenged recycling systems (for various reasons) are the return bottle system (in Europe), the glass collection points (Europe) and the paper collection systems (Northern Europe) [Clift, 2004]. The reasons for these challenges are both economic and environmental, where the argument goes in the direction that these systems use more energy in the collection and recycling process, than what is saved through recycling. Thus a different collection scheme and end-of-life handling would be better for the environment [Clift, 2004].

In principle, a recycling system consists of;

- infrastructure for the collection of materials
- transport to a processing facility
- processing
- transport to new production site
- new production
- transport to sales point
- transport from sales point
- new use
- recycling or end-of-life

Figure 2.15 shows a principle sketch of a recycle system.

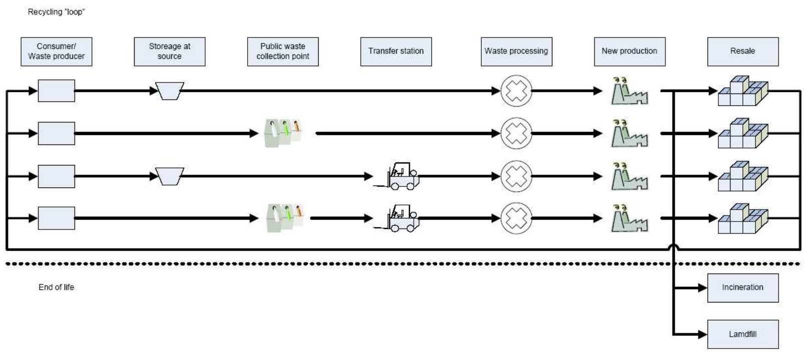


Figure 2.15: A principle sketch of a recycling system, adapted from Heie and Brattebø [2002]

Previously, recycling more or less always has been considered environmental friendly, and thus desirable. Material recycling was also more common in the industrialized countries until the 1950ies. But due to the increase in wages, most material recycling was abandoned in the western world, since virgin materials were competitive in price. For the same reason, we still see a large degree of material recycling in developing countries, where the value of materials are higher compared to wages, and makes material recycling economically attractive.

Today, we see that recycling in the industrialized countries is emerging out of a new context - environmental concern. This means that new systems are designed and optimized with regard to both economic and environmental impact. There are several reasons for this renewed interest in recycling, but most often it is seen as an answer to the growing problem of pollution, land use issues, or depletion of resources.

This development is challenging the existing waste management and industrial production systems, and paving the ground for new industries. Another parallel trend is the rise of the service economy, where goods are often leased, for example a photocopier. The leaser must provide a satisfactory product in place, and see to maintenance and replacements (Which is argued to provides for more economic and environmental friendly service and replacement/ substitution policy).

2.4 Organizations, technology and change

By following the systems engineering approach, we should have assessed available information, defined measures of effectiveness, and provided a tool for trade-off analysis. What is left is to create behavior and structural models. And since we are operating in a socio-technological system, we need to analyze and explain the present system, in order to identify actors and structures that can improve the performance of the system. We must be able to provide the appropriate policies and structures so that the systems move in the wanted direction.

To understand the system and how it works, we must determine who is participating and what structures influence their behavior (actor network theory), and how to change their behavior (organizational learning and policies). By adding these pieces together, we can study the behavior and structure, and perform trade-off analysis to test the performance of the system design. Figure 2.16 shows a model of the nested relationship between the ecological and societal systems.

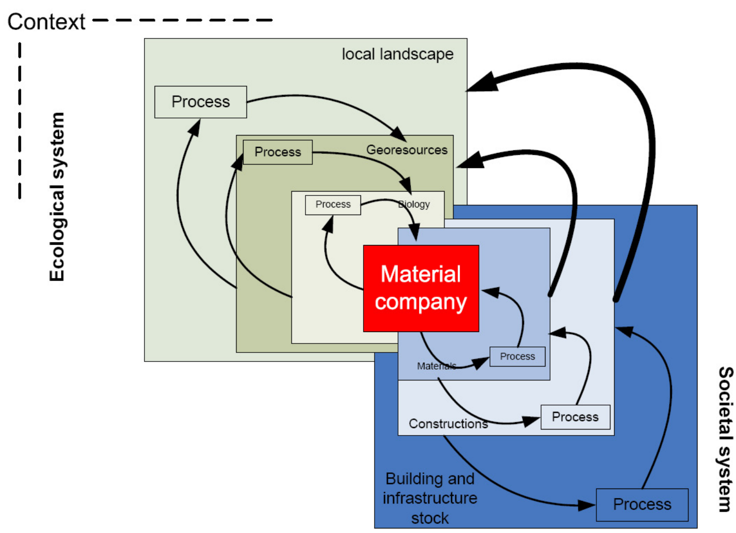


Figure 2.16: Example of a nested model of the eco-societal system with recycling

This model has been made after inspiration from Kay [2002]. It shows the nested relationship between nature – the landscape, the geological resources, and biology on the one side – and the human technosphere on the other side – with its materials, houses and the entire built environment. Traditionally, the flow of materials through society has been one way, and back to nature. By introducing a material company with recycling facilities in between nature and the built environment that returns materials back to the built environment, we can reduce societies environmental impact by recycling and thus lower the extraction of virgin materials.

2.4.1 Organizational learning

According to Heap [1998] pre-conditions for change and innovation are knowledge, involvement and action. Organizations that find, develop and motivate talented people will gain in the competitive market in which they operate. Bain [1995] argues that the key to build and maintain a stock of talented people are related to: *"Excitement of the work place", "involvement in the future", "and a feeling of belonging to the organization"*.

The advantages of feedback on performance and motivation have been widely recognized by researchers from the early 1950s [Ashford and Cummings, 1983]. Feedback processes have been recognized as important means of learning in organizations. Argyris and Schön [1978] describes organizational learning as a process of detecting and correcting error. Error is defined as any feature of knowledge that inhibits learning. When this learning process enables the organization to carry on its present policies, or achieve its present objectives, it may be called single-loop learning. Double loop learning is when a organization challenges its own actions, assumptions, policies, norms or objectives, Figure 2.17:

Both single and double loop learning requires a reference for comparison, but double loop requires the possibility to question the performance. The level of performance can not be effectively questioned without good longitudinal benchmarking data, that is performance measured over time.

In Figure 2.17b, step 2a, the process of double-loop learning depends on asking the right question, i.e. measuring the right criteria. A common failure is to measure productivity or efficiency, not performance (overall) according to intended achievements (the objectives). Recycling systems lack information on

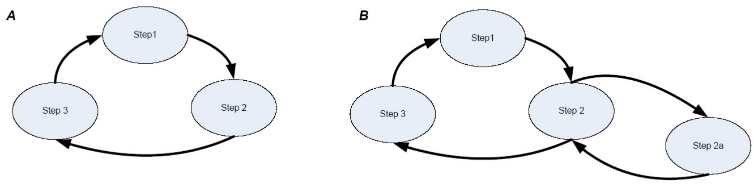


Figure 2.17: "Single-" and "double" loop learning; a) "Single-loop" and b) "double loop". Step 1 the process of sensing, scanning and monitoring the environment; Step 2 Is the comparison of this information against operating norms; Step 2a the process of questioning whether the operation norms are appropriate; Step 3 the process of initiate appropriate action. Adapted from Argyris and Schön [1978, 1996]

environmental performance in a system-wide context. Although some of these data exist, they are not collected systematically and are not used for analytic purposes.

A recurring problem for organizations is to match their "production rate" to the "rate of final consumer sales". It is well known that the production rate often fluctuates more wildly than the actual consumer demand rate. This phenomenon is known as the *bullwhip effect* [Forrester, 1958; Sterman, 1989], where oscillations of orders and supply amplifies as one moves up the supply chain.

With inefficient supply chains, large inventory costs, over investments, and dismissal of staff in periods of low demand may result. These factors often determine the success or failure of a business. Problems of oscillations appear at different scales: for the single firm (business cycles); industry sectors as a whole (commodity cycles); and national economies (boom and recessions).

Senge [1990], used the classical *beer game* to demonstrate the bull-whip effect. The beer game was developed by [Forrester, 1958] to demonstrate the bullwhip effect. Senge argues that the systemic thinking can dampen the effect of the bullwhip, by seeing the patterns behind the oscillations, and thus promote a type II learning. He is thus following Argyris and Schön [1978] in their description of organizational learning as a process of detecting and correcting error.

In addition to "learning failures", there might exist "lock-ins" that effect the system in different ways. It is therefore important to identify such lock-ins and remove the structures supporting them, in order to solve the problem, or facilitate inherent improvement potentials in the system.

2.4.2 Systems thinking

Systems thinking is about the interrelated actions which provide a conceptual framework or a body of knowledge that makes the pattern clearer [Senge, 1990]. systems thinking has its ancestors in; complexity theory, open systems theory, organizational cybernetics, interactive planning, soft systems approach, and critical systems thinking [Flood, 1999]. Of special interest when dealing with environmental studies is complexity theory [Kay et al., 1999]. Complexity theory acknowledges the interrelated nature of things as well as emergence, where the whole is experienced as greater than the sum of its part, as well as spontaneous self-organization (SOHO), a special form of emergence.

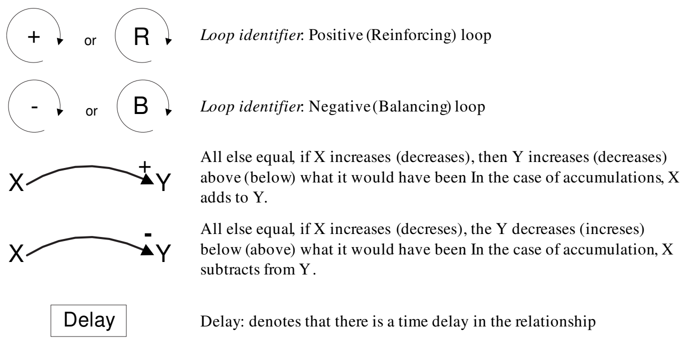
According to Senge [1990] systems thinking is a product of *"five new component technologies"*; Systems thinking, Personal Mastery, Mental models, Building Shared Vision, and team Learning. Where Systems Thinking is the *'fifth discipline that integrates the disciplines, fusing them into a coherent body of theory and practice'*.

Systems thinking seeks to explore things as wholes, through patterns of interrelated actions [Senge, 1990; Flood, 1999]. System dynamics is a tool to visualize and understand such patterns of dynamic complexity, which is build up from a set of system archetypes. As described in Figure 2.1.2, system dynamics visualizes complex systems through causal loop diagrams. A causal loop diagram consists of a few basic shapes [Stermann, 2000], that together describes the action modeled, Figure 2.18.

For each action, there is a feedback or corrective action. This feedback is either positive (escalating) or negative (limiting or slowing). Many feedback processes contain 'delays' in time, interruptions in flow of influence which make the consequence of actions occur gradually. Beside the feedback there is sometimes also a side effect. The side effect is contributing to the overall performance of the action, and are either enhancing or slowing the process (which can be an escalation or limiting process). Senge [1990] suggests there are about 12 system archetypes, which combine to form a generic set, and he describes nine of them.

A problem with systems thinking, and thus system dynamics, is where to draw

Figure 2.18: Basic shapes in causal loop diagrams



the system boundaries. If everything is interrelated, then where is the boundary? Churchmann argues that boundaries surround *'whom is embraced by the action area'*[Flood, 1999]. Boundary determination is then a question of ethics, efficiency and effectiveness, and is always open to debate.

However, Senge et al. [1994] warns that system dynamics can be reduced to process-based thinking alone, whilst the broader argument of system archetypes and underlying structure of behavior goes unheeded.

When introducing a new waste flow for C&D waste, it is necessary to construct a new common knowledge among the involved actors. Thus ideas such as systemic thinking is only useful in so far they stimulate learning and understanding as one possible model for analysis.

Senge [1990] describes five "component technologies" that may converge towards a learning organization;

Personal Mastery , being able to gain dominance over people and things.

Mental Models are deeply ingrained assumptions, generalizations, or even pictures or images that influence how we understand the world and how we take action.

Building Shared Vision The practice of shared vision involves the skills of unearthing shared "pictures of the future" that foster genuine commitment and enrollment rather than compliance.

Team Learning The discipline of team learning starts with "dialogue", the capacity of members of a team to suspend assumptions and enter into a genuine "thinking together".

Systems thinking is the "fifth discipline" that integrates the disciplines, fusing them into a coherent body of theory and practise.

Thus, one need to apply all the disciplines in order to create a learning organization.

So in order to construct a successful recycling system, all of the above musts be in place. Thus the new routines and structures must be designed in a way that allows actors to deal with (master) them, and thus reach personal mastery. Likewise, it is important to create a mental model of *why* and a shared vision of *how*. If the system then is capable of creating good bodies of communication and knowledge transfer, one can move towards a learning organization and success.

2.4.3 Actor network theory

The predecessor for development is a "shared vision", that is a common knowledge among stakeholders. Our understanding of the relationships between our own actions, human activity, our neighborhood, and the world around us is however a social construction [Berger and Luckmann, 1966]. *"The self as an active being-in-the-world who not only is in the world but also actively constructs the world in which he or she is, as one which has meaning for him or herself. The self is both a social constructor of reality and a socially constructed being."* For the knowledge to have common meaning in the society it must therefore emerge out of the discourse of where it originated, and into the *"common knowledge"*. In the case of environmental awareness, Rachel Carson's book "the silent spring" [1962], was an early agent that helped develop the knowledge of pollution problems from the scientific discourse into a "common knowledge". In her book, she describes the results of DDT pollution on the capability of birds and reptiles to produce viable eggs. The book triggered the establishment of many modern environmental protection groups worldwide.

Though knowledge is a social construct, it has to originate somewhere. Latour [1987] showed that scientific knowledge is constructed through a dialog between actors and nature:

> "... a lot of hard work in which heterogeneous bits and pieces - test tubes, reagents, organism, skilled hands, scanning electron microscopes, radiation monitors, other scientists, articles, computer terminals, and all the rest - that would like to make off their own are juxtaposed into a pattern network which overcomes their resistance."

What Latour does, is to include artifacts and non human components in the network of knowledge creation. In fact the actor network is reducible neither to an actor alone nor to a network. But when several actors meet at juxtaposition, the knowledge may start to spread in society, and may end up being the "new truth", i.e. as a new social construct [Callon, 1989; Pinch and Bijker, 1989]. In the case of environmental damage caused by pollution, the nature itself was an actor in the network. Callon [1989] is very explicit on this:

> "The actor network can thus be distinguished from the traditional actors of sociology, a category generally excluding any nonhuman components and whose internal structure is rarely assimilated to that of a network. But the actor network should not, on the other hand, be confused with a network linking in some predictable fashion elements that are perfectly well defined and stable, for the entities it is composed of, whether its natural or social, could at any moment redefine their identity and mutual relationship in some new way and bring new elements into the network. An actor network is simultaneously an actor whose activity is networking heterogeneous elements and a network that is able to redefine and transform what it is made of."

For the case of recycling of C&D waste, we have a network consisting of environmentalists, municipalities, construction industry, politicians, material companies, etc. The common construct of knowledge between them is that deposition of waste in landfills must come to an end, although they do not necessarily share the reason why. What has happened is that the bits and pieces are juxtaposed and translated into new knowledge. The next step according to actor network theory is to condense this knowledge into a punctualized actor with its own inclinations, i.e. agents, institutions or organizations [Law, 1992]. Morgan [1986] suggests that creating metaphorical images of the organizations or systems of interest, will help the construction of such knowledge, and aid the communication to, and learning among, its actors.

The government has by the use of power created an actor network, which through the establishment of new routines, processes and institutions can be viewed as an organization. In the making of the organization, the focus has been more on action than on ideology, which cuts down the need for actors, or organization members, to make their own decisions, as described by Brunson [1989].

In order to further understand why this actor network, or organization, evolved to be the organization we see today, it is necessary to study the organization of the nodes in the network and the communication between them. Although I have chosen to study the whole network as one organization, it is clear that the network consists of many different types of nodes that in turn are different actor networks (and with different organization).

The actor network puts together different nodes with heterogeneous performance targets and organization. The new structures of command and control, have a machine like or bureaucratic organization, where focus will be on target control, surveillance and punishment. Other nodes, i.e. the individual house owners, entrepreneurs or transporters, will have a different organization and focus. Their target and interest in the network will be very different, and their link to the network will therefore be of a varying degree of commitment.

To be able to understand the network, we musty first understand the forces that drive the different nodes in their actions, and the communication between the nodes. Most of the actors or stakeholders did not voluntarily enter the network. They where forced to take part of the network by the government (although many of them took the opportunity to profit from the new environmental policy). The options for these nodes are therefore quite heterogenic in their strategies and of what level of performance they will optimize for. For some, the goal is to obey the environmental laws with as little extra costs as possible (e.g. many house owners), while others have seen a profitable niche, where there is a huge profit margin between the tax for unsorted and sorted C&D waste (e.g. large transport companies and material companies). For some it simply means more business with each customer (e.g. consultants and entrepreneurs).

2.4.4 Policy success in terms of Industrial Ecology- the analytical framework

Robert Dahl's[1] formulation of power, in its most simple form, is that 'A gets B to do what B otherwise would not have done' [Clegg, 1990]. The political enforcement of the waste handling systems used in Denmark was, in this regard, a rather straightforward and one-dimensional character, *"do as I command, or you will be punished"*. Although, its implementation was by use of new structures. This very much follows the views on power that can be followed through the political theory presented by Hobbes through Dahl to Lukes and Giddens [Clegg, 1990]. Lukes agreed in line with Dahl that *'A gets B to do what he/she otherwise would not have done'* - but ads that power is also expressed through influencing and forming peoples thoughts. Giddens [1981, 1984] in his structuration theory includes the introduction of new structures into the game of power.

In the case studied here, the latter is of great interest. The government (A) wanted the waste producers (B) to stop deposition of waste into landfills. (A) wants to do so, because (A) believes that this will be the best solution for everybody in the long run, and that (B) would want to do so if (B) had the knowledge and was free to choose, as in an Habermas' *"free speech situation"* or a Kantian *"outcome of a rational decision"*, which can be found in the arguments of Lukes and Rawl [Clegg, 1990].

The government may here be treated as a sovereign power - although it has got its power though the hegemonic process of elections. The new actors introduced with force from the government in this case are new laws and regulations, which are of structural character, and therefore fits well into Giddens 'structuration theory' [Giddens, 1981, 1984];

> "All interaction involves the use of power, because all interaction is concerned with the production and reproduction of structure, drawing on rules and resources. Power relates to those resources which actors draw upon in interactions, in "making a difference", i.e. structure is 'rules and regulations" '[Giddens, 1981].

The sanctions of power are of disciplinary means which works through the con-

[1] Robert A. Dahl (b. 1915), is a Sterling professor emeritus of political science at Yale University, and one of the most distinguished political scientists writing today.

struction of routines [Clegg, 1990]. As I have described above, the government uses its political power to create structures, which in turn wields a command and control regime on the nodes of the actor network system.

To meet the targeted objective, a number of policy sub-objectives must be met successfully. This is when sub-objectives are understood to be outcomes that must be achieved before and in order to realize further outcomes [Mohr, 1995]. Based on this awareness I have analyzed, with input and stimulation from Opoku in an joint paper [Bohne, Opoku and Brattebø, 2004], the systems in terms of a classical set of conditions for successful policy achievements, set forth by Sabatier and Mazmanian [1979]:

1. The program should be based on a sound theory relating changes in target group behavior to the desired objectives
2. The statue (or other basic policy decisions) contains unambiguous policy directives and structures to maximize the likelihood that target groups will perform as desired
3. The administrators implementing the legislation possess substantial managerial and political skills, and are committed to statutory goals. From the first condition follows that they are given satisfactory information regarding the subject
4. The program is actively supported by organized (constituency) groups and key (legislators) managers throughout the implementation process
5. The relative priority of legal objectives is not undermined over time by conflicting public policies or by changes in relative socio-economic conditions that limit the statue's purposes or political support

As the success of the recycling system for C&D waste eventually relies on the performance of individual actors, two additional categories of sub objectives regarding Sabatier and Mazmanian's first condition- changing target group behavior - are particularly relevant: This is the discovery sub-objectives, referring to the importance of the program personnel to learn something about the targeted part of the world before operating in it; And the behavior prerequisites which is crucial, whenever behavior of people appears as an objective on the outcome line. In the latter category a set of three sub-objectives are challenging to both policy makers and implementers: The target individuals (a) must know what is to be done, (*b*) must be motivated or have the incentive to do it, and (*c*) must have the ability and other resources necessary to carry it out. These are respectively referred to as the knowledge, motivation and resource sub-objectives [Mohr, 1995].

This would require a learning process which concludes with a common vision of change among involved actors. In order to achieve this change, time and efforts are required. A continuous search for new knowledge is important in this sense. When the process is successfully achieved the steps of changes can be incorporated into a model of *"double loop learning"* [Argyris and Schön, 1978]. The purpose of the systemic approach is to see interrelationships rather than linear cause effect chains and to see processes of change rather than snapshots [Senge, 1990].

To place my case studies in a broader perspective both the agenda setting phase and policy evaluation is included in what is referred to as *"the policy implementation analysis"*. This rather broad focus – from the pre decision phase to impact evaluation – is based on the assumption that crucial conducts for the policy outputs can be identified throughout that process.

In order to understand the Copenhagen system, and thus extract knowledge needed to facilitate the establishing of similar systems in Norway, it is necessary to answer the following questions:

i How was the network constructed, and whom participated?

ii What kind of power were used in the construction of the network?

iii What structures were made to support the network?

iv What kind of learning was involved, and how was the learning supported?

a) Do the actors know what is to be done?

b) What are their incentives?

c) Do they have the necessary ability or resources to do it?

2.5 The Construction and Demolition waste handling system

The topic to be dealt with in this thesis is the optimization of recycling systems for Construction and Demolition (C&D) waste. Such systems can be viewed from many possible angles, but I have in this thesis chosen the Industrial Ecology framework, and I am therefore following the material flow through the system. The waste handling system is again a part of the larger system that constitutes the C&D material life cycle, Figure 2.19.

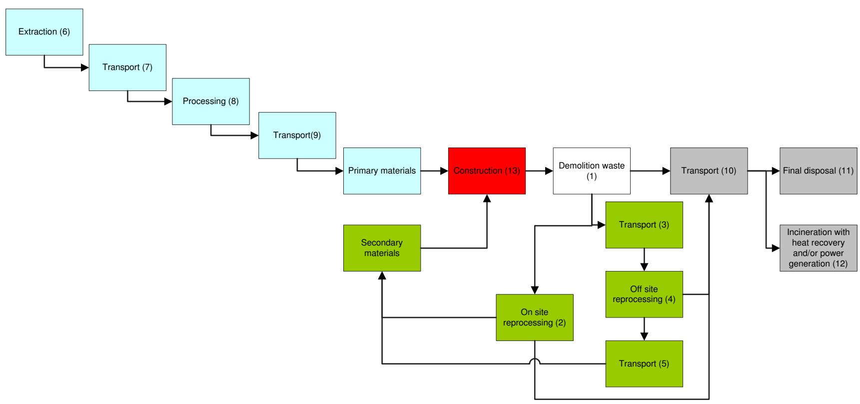


Figure 2.19: The C&D waste lifecycle, after Graighill and Powell [1999]

The systems that are described in this thesis as C&D waste handling system, in principle lead to two different outcomes for the material fraction in question; either a reentry into the building or infrastructure stock or end-of-life disposal. In Figure 2.19 this is shown by the routes in Table 2.5;

Table 2.5: Different outcomes for the material fraction in question

Final destination	Handling option	Route
Virgin to stock	Construction	6 – 7 – 8 – 9 – 13
Re-entry to stock	Reuse after on-site recovery	1 – 2 – 13
	Reuse after off-site recovery	1 – 3 – 4 – 5 – 13
End-of-life	Final Disposal	1 – 10 – 11
	Incineration with heat recovery and/or energy generation	1 – 10 – 12

For each step in the lifecycle, there are a numbers of actors and structures; both directly and indirectly. All these attributes together make the system. Thus the system is complex and dynamic, in the sense that actors enter and exit the system continuously, obeying different laws and regulations present at the time, and exchanging information and money between each other. Typical actors in the system are authorities (governments, municipalities and agencies), house owners, consultants, entrepreneurs, transporters, material companies and others. Typical structures are laws and regulations, contracts etc, infrastructure etc.

It is also worth noting that not all waste from a construction or demolition site are considered C&D waste. The C&D waste is mostly of structural origin, while technical installations enter separate waste streams. This often reflects the composition of the different wastes, and thus its economic value or toxic content. For example, most waste from electrical installations is considered WEEE or hazardous waste, and thus is entering a separate waste stream not discussed in this thesis. If, however, waste from Electrical installation or HWS enters the C&D waste stream, it is in the material form, such as plastics, metal, ceramics, etc.

2.5.1 Laws and Regulations concerning C&D waste

There are several laws and regulations influencing the handling of C&D waste in Norway. The most important ones are the Environmental Protection Act [Forurensningsloven, 1981], the Plan- and Construction Act [Plan- og bygningslov, 1985] and the Waste Regulation [Avfallsforskriften, 2004].

C&D waste is with respect to the pollution act to be treated as ordinary production waste, and are thus under the same regulations as all other waste.

The Pollution Prevention Act §32 treats the handling of production waste (my own translation): *"Production waste (including C&D waste) shall be brought to a legal waste plant unless it is recycled or used for other purposes. The pollution authorities can approve other waste disposal at more further determined terms. The pollution authorities can in regulations or in each specific case instruct producers to deliver the waste to a municipal waste plant"*.

The Ministry of Environment in 1996 empowered the municipality of Oslo with the authority to control the handling of production waste, and has prepared an separate regulation for this.

Through this regulation, the municipality of Oslo demands that all C&D waste is treated for all projects that has to deliver an application for approval. This application is to contain a detailed waste management plan, in addition to a demand for at least 60% source separation of C&D waste, and that as much as possible is delivered to reuse or recycling.

To verify that the given waste handling plan is followed, it is compulsory for the construction firm to deliver a self-certified waste declaration or waste plan, and a end report. In renovation or demolition projects where it is reason to suspect the presence of toxic substances or hazardous waste, a selective demolition can be claimed for.

In 1998 the Ministry of Environment made it voluntary for the municipalities to control the handling of the production waste within their municipality, after the same principles as the regulation for Oslo [Ministry of the Environment, 1998].

2.5.2 Measures of effectiveness

One goal of this thesis is to develop some tools that may be used in the process of optimizing a recycling system, thus there is need to define the criteria for optimization; the effectiveness measures. According to Olivier et al. [1997]; *"these are a small subset of all the requirements; perhaps three to fifteen in number even for large complex systems. They are all criteria for success or failure"*.

Sproles [2000] defines measures of effectiveness (MoE) as *"standards against which the capacity of a solution to meet the needs of a problem may be judged. The standards are specific properties which any potential solution must exhibit to some extent. MoEs are independent of any solution and specify neither performance nor criteria"*.

Given the goal of this thesis, that is to optimize a waste handling system for C&D waste, the selection of efficiency indicators (MoEs) is not necessarily straight forward, since we might need to include several factors, all contributing to sustainability, which also may be difficult to use in practise due to lack of data or difficulties in quantification. I have therefore decided to make use of the notion of eco-efficiency (E/E) as an appropriate MoE for my study, see therefore Chapter 3.3.5. What is needed is; a measure of how much is handled, at what cost, and its corresponding impact on the environment. Ideally, I would have included a fourth indicator - social benefits - but this was abandoned due to fact that there is no data available at the present, with the resolution needed for these kinds of studies. This selection of indicators is also in line with the requirements set forth by both Olivier et.al and Sproles.

Traditionally performance of recycling systems is measured in terms of percentage waste that is recycled. Thus we need to expand the data with two more indicators; cost and environmental impact.

2.5.3 Economic activities in the C&D waste systems

The AEC-industry consumes much of the materials and energy that enters society, plus many services, such as transport and engineering. This means that considerable economic activity is generated in the industry, which is not always easy to identify. Further, there is a huge variation in prices for the various activities and materials, as well as other economic incentives (day penalties, bonuses etc). The C&D waste handling system is a part of this system. I have identified cost as the parameter of interest for the work in this thesis, and though this narrows the economic activities to be handled, there is still the matter of real versus "shadow" prices, as well as other economic realities that make the picture confusing when studying the dynamics of the system. These matters are discussed later in chapters 3, 4, and 5.

2.5.4 Environmental impact from C&D waste systems

The environmental impact of waste management options is a result of processing and disposal methods and transportation types and distances, including all disposal, recycling and reuse options in the system. Moreover, recycling and reuse should give positive downstream environmental benefits when recycling and reuse is applied, due to omitted emissions when secondary materials susbstitute extraction of virgin materials. Some of these benefits should also be allocated to the environmental performance of the initial C&D waste system. According to Bohne and Brattebø [2003], different end-of-life treatments options can be ranked in a general hierarchy according to their environmental impact, where direct reuse is ranked higher than recycling, which in turn is better than energy recovery, etc (see Table 2.6). We have, however, so far not documented that this general hierarchy is actually valid for C&D waste systems.

In practice some of the alternatives in Table 2.6 are either not wanted, not possible, not legal, or too expensive to follow. Some of these processes demand facilities that are expensive to build and maintain. It is therefore of public interest to know as much as possible about the future waste generation and its possible corresponding environmental impact.

Another issue to consider is that it is the aggregated environmental impact that is of importance, and should be used as a design criteria, rather than aggregated volume or weight of the physical flows. Data on environmental impact for the different alternatives for end-of-life treatment is calculated on the basis of data from many different sources using LCA methodology [PRé Consultants, 2002; Kotaji et al., 2003].

The single most important environmental issue with regard to waste handling is the emissions from landfills. These emissions vary from landfill gas emissions (including methane) to fluid leachate of which the organic compound do most environmental damage. These emissions vary over time, from decades for landfill gases, to millenniums for leachate in moderate climates [Belevi and Baccini, 1989; Kylefors et al., 2003]. It is therefore of vital importance to manage waste handling upwards in the waste hierarchy, and limit landfills to fractions which hold “final storage quality”, in order to follow the precautionary principle. The latter can only be achieved by pretreatment of any organic or combustible fractions, and recycling of metal containing fractions. Inert minerals can be stored in landfills if no pollutants are present [Döberl et al., 2002].

Table 2.6: The waste hierarchy of C&D waste

	Landfill	Incineration with energy recovery/ power generation	Recycling after processing	Reuse after processing	Direct reuse
Asbestos	S.L.[a]	N.A[b]	N.A	N.A.	N.A.
Hazardous	S.L.	S.O.[c]	N.A.	N.A.	N.A
Conc/bricks	x[d]	-	X[e]	N.E.[f]	N.E
Gypsum	x	N.A.	X	-	-
Glass	(x)[g]	-	X	x	x
Insul/EPS	(X)	x	x	-	(x)
Metals	(x)	-	X	(x)	(x)
Paper/Plastics	(X)	X	X	x	x
Wood	(x)	X	x	x	x
Unknown	(X)	x	x	x	x

[a]Secure Landfill
[b]Not applicable
[c]Special oven
[d]x = Feasible
[e]Capital X = the most common solution
[f]Not economical
[g]()= the solution is feasible, but not wanted

There are also other important issues to consider when making decisions in C&D waste handling systems, although these are not included in this thesis. I will briefly mention two of them with high importance with regard to environmental impact. First, the issue of renovation and demolition, versus the development of virgin or agricultural land areas. If one is renovating an existing building (or constructing a new one on a demolition site), one is avoiding building on undeveloped land and you are using existing infrastructure like roads, water and sewer lines, electrical connections and so on. All these things contribute to reduce the environmental impact of construction. Secondly, is the risk of spreading toxic contaminants with recycled materials.

The issue of renovation and demolition, versus the development of virgin or agricultural land areas is a political choice, which is decided upon outside our waste handling system. But the issue is highly relevant. Between 1981 and 1998, urban development reduced the earths agricultural areas with 7%. Until 1998, enhanced productivity due to technological development in agriculture balanced this loss of areas, but in 1998 - for the first time - did the worlds production of grains decrease by 2%, at the same time as population grew by 1.4% [Thompson, 2000].

The risk of spreading toxic contaminants with recycled materials is about quality control. Traditionally C&D waste has been regarded as *"clean"* waste, and as such been used as filling material in development projects. Ottesen and Haugland [2003] found that C&D waste in Norway contain more than 30,000 tons of polluted waste and a minimum of 2,500 tons of asbestos. Of these contaminants, it is of vital importance to get control over the metallic and water soluble compounds of mercury and cadmium, water soluble compounds of lead, arsenic, chrome, nickel and tin, pentachlorophenol, PC13 (PCB), PAH, CFC, halons and radioactive substances. Many of these compounds are very slowly degradable and bioaccumulative.

Ideally, contaminated demolition waste should be recycled in such a way that the contamination is not diluted and dispersed into the environment. I will use an additive to concrete - PCB - as an example. PCB was a commonly used as an additive to plaster from 1950, until it was banned in 1981. The most important characteristic was to improve the adhesion of the plaster to walls and floors. From sales figures, construction activity during this time period, and by estimating life time of buildings, we can estimate when it is likely to find PCB in demolition waste [Amlo et al., 2002; Trap Christensen et al., 2002], as shown in Figure 2.20, where dynamic substance flow analysis (SFA) is applied to examine changing PCB stocks and flows over time. This approach also demonstrates the usefulness of substance flow assessments in systems with long life times, as in C&D waste systems. If the renovation or demolition project is a building from the time period in question, toxicity test must be performed. If the building is contaminated, its waste must enter a separate waste stream for such contaminated wastes.

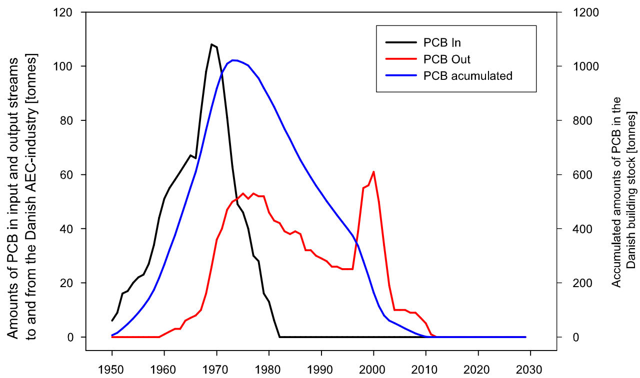


Figure 2.20: Distribution of PCB in the Danish building stock, after Trap Christensen et al. [2002]

Table 2.7 lists the whereabouts of potentially hazardous compounds in buildings.

Table 2.7: Some potentially hazardous elements in C&D waste, adapted from Symonds et al. [1999]

Product material	**Potentially hazardous component(s)**	**Potentially hazardous properties**	**Treatment andor disposal options**
Concrete additives	Hydrocarbon solvents	Flammable	Return to supplier, recycle, remove for specialist disposal.
Damp proof materials	Solvents, bitumens	Flammable, toxic	Return to supplier, recycle, remove for specialist disposal. Allow to cure prior to disposal.
Adhesives	Solvents, isocyanates	Flammable, toxic, irritant	Return to supplier, recycle, remove for specialist disposal. Allow to cure prior to disposal. Seek alternative less hazardous products.
Mastics / sealants	Solvents, bitumens	Flammable, toxic	Return to supplier, recycle, remove for specialist disposal. Allow to cure prior to disposal. Seek alternative less hazardous products. Use water.
Road surfacing	Tar-based emulsions	Toxic	Return to supplier, recycle, remove for specialist disposal.
Asbestos	Respiratable fibre	Toxic, carcinogenic	Remove under controlled conditions for specialist disposal.
Mineral fibres	Respiratable fibres	Skin & lung irritants	Remove for separate disposal.
Treated timber	Copper, arsenic, chrome, tar, pesticides, fungicides	Toxic, ecotoxic, flammable	Recycle. Hazardous components bound into timber, low impact on landfill. Toxic fumes and residue produced on burning.
Fire resistant wastings	Halogenated compounds	Ecotoxic	Possible low impact in landfill if bonded to substrate; high impact in product form; possible toxic fumes on burning.
Paint and coatings	Lead, chromium, vanadium, solvents	Toxic, flammable	Possible low impact in landfill if bonded to substrate; high impact in product form; possible toxic fumes on burning.
Power transfer equipment	PCBs	Ecotoxic	Contaminated transformer oils to be removed under controlled conditions for specialist disposal.
Lighting	Sodium, mercury, PCBs	Toxic, ecotoxic	Recycle, remove for specialist disposal.
Glass			Recycle. Possibly physically hazardous to handle.
Air conditioning systems	CFCs	Ozone depleters	Remove for specialist recovery.

Continued on next page

Product material	**Potentially hazardous component(s)**	**Potentially hazardous properties**	**Treatment andor disposal options**
Fire fighting systems	CFCs	Ozone depleters	Remove for specialist recovery.
Contaminated building fabric (including cont-amination due to previous use)	Radionuclides	Toxic	Specialist decontamination prior to demolition or refurbishment.
	Heavy metals including cadmium and mercury	Toxic	Specialist decontamination prior to demolition or refurbishment.
	Biohazards (anthrax)[2]	Toxic	Specialist decontamination prior to demolition or refurbishment.
Animal products	Biohazards (anthrax)[2]	Toxic	Specialist decontamination prior to demolition or refurbishment.
Gas cylinders	Propane, butane, acetylene	Flammable	Return to supplier.
Resins/ fillers, Precursors	Isocyanates, phothalic, anhydride	Toxic, irritant	Return to supplier, recycle, remove for specialist disposal.
Oils and fuels	Hydrocarbons	Ecotoxic, flammable	Return to supplier, recycle, remove for specialist disposal.
Plasterboard	Possible source of hydrogen sulphide in landfill	Flammable, toxic	Return to supplier, recycle, disperse within landfill.
Road planings	Tar, asphalt, solvents	Flammable, toxic	Recycle if cured and low leachability. Separate for disposal if high leachability solvent content.
Sub base (ash / clinker)	Heavy metals, including cadmium and mercury	Toxic	Recycle if low leachability. Separate for disposal if high leachability.

[2] Horse hair was formerly used as a binder in plaster. Since the disease of anthrax was widespread up to the 19th Century, and the spores of anthrax are very robust and long-lived as well as being hazardous to human health, walls which had been plastered in/before the 19th Century must be treated with great care when they are demolished

Chapter 3

Methods

Chapter 3 describes the research approach, empirical and analytic methods, and calculating and modeling techniques that I have applied on my work. I followed a systems engineering approach, which has resulted in many iterations between the different system engineering core technical processes.

The methods can be broken down into two main categories, qualitative and quantitative methods. The first describe the structures and material flows in the system. The latter the measure of effectiveness, system efficiency and trade-offs between different options for change in the system.

This chapter is divided into three parts; first, a part on the systems engineering methodology, where I draw up the overall framework. Second, a description of the qualitative methods. I have called this section "understanding the system", since this is a retrospective case-study, designed to understand how different policies contribute to recycling and learning in the actor network. The last part, is on the quantitative methods, called "Calculations and modeling". This part identifies what to focus on if one seeks to optimize the overall system. Thus this part deals with projections of future waste, environmental and economic impact and trade-off analysis.

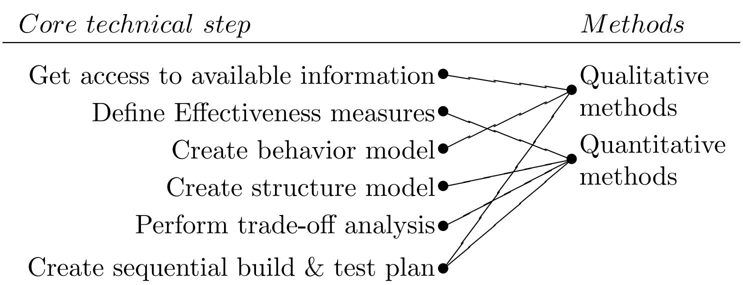
3.1 Systems engineering approach

As mentioned in Chapter 2, Systems Engineering provides the overall methodological framework for this thesis. Only a part of the systems engineering methodology is used; "the Core Technical Process". The reason for only using the core technical processes, is that the scope for this thesis os to provide analysis and models for decision makers use, and hence are not part of the actual decision making.

If we take another look at the Functional Flow Block Diagram (FFBD) view of the systems engineering core technical processes (Figure 2.8), we see the iterative flow of the work. As progress is achieved in one step, it causes changes in another step, and so on.

This thesis is about a socio-technical system. It is therefore not enough to understand the technical properties of the system alone. The system will not perform if the people within the system are not willing to do as required of them. That is, it doesn't matter how well the system is designed technically, if the stakeholders are not acting as anticipated. In order to optimize a socio-technical system, we must also understand how the human actors behave, and the reasons for this behavior. To do this we must understand their knowledge, expectations, preferences, learning, all the factors contributing to their behavior. Therefore, I need to make use of qualitative methods, and combine these with the more traditional quantitative methods of systems engineering. In Table 3.1, I have visualized where in the core technical process I have used the two different approaches in this thesis:

Table 3.1: Core technical processes and type of methods



3.2 Understanding the system

In order to understand the system, it is necessary to study it as an Actor Network - the organization of the nodes in the network and the communication between them (See Chapter 2). Although I have chosen to study the whole network as one organization, it is clear that the network consists of many different types of nodes that in turn are different actor networks (and with different organization).

The actor network combines different nodes with heterogeneous performance targets and organization. There are structures of command and control, surveillance and punishment. Other nodes will have a different organization and focus. Their target and interest in the network will be very different, and their link to the network will therefore be of a varying degree of commitment.

To be able to understand the network, we must first understand the forces that drive the different nodes in their actions, and the communication between the nodes. The options for the nodes are quite heterogenic in their strategies and of what level of performance they will optimize for. For some, the goal is to obey the environmental act with as little extra costs as possible (i.e. many house owners), while others have seen a profitable niche, where there is a huge profit margin between the tax for unsorted and sorted C&D waste (i.e. large transport companies and material companies). And for some (i.e. consultants and entrepreneurs) it simply means more business with each customer.

I therefore;

- started by assessing information about the system, to be able to build an initial model
- Then I studied the structures supporting the system,
- Then the behavior of the actors.
- After this I was able to suggest alternatives, and perform trade-off analysis between these alternatives,
- and after numerus iterations, a came up with a suggestion for system optimization.

I now discuss these steps.

3.2.1 Collecting information and data

The first task in the core technical process, is to assess available information. My approach to this was first to establish an overview of the most relevant literature to create a starting point for the research. The documents reviewed comprised Norwegian and Danish legislative acts and Royal Decreets, white papers, reports, scientific papers and books. In addition several other written information sources were looked into, such as pamphlets price lists, newspaper and, magazines, databases etc. This process was iterative and has continued during the whole period.

Having identified and assessed the written documents, a second task was to extract the prime information of concern through interviews. By doing so, a risk occurred of loosing important information from the interviewees. To minimize this risk all the interviewees were asked to identify the most essential information for their own needs. They were also asked to identify, as far as they could, the information being most important pertinent to other stakeholders. By applying this method, cross-references were achieved to the information believed to be most important.

Table 3.2 gives an overview of the data sources, and the corresponding relevance for this thesis.

3.2.2 Interviews

In connection with the assessment of available information, various important stakeholders were interviewed. To avoid bias in selecting respondents, an initial meeting was held with two of the stakeholders. They were presented the up coming interview plan and asked to suggest interviewee candidates. A list of names was suggested, representing all major stakeholders, and the list was presented to two persons on this list. They were also addressed with the same question, and a final list of candidates was settled.

Based on the list of names, an interview plan was worked out and seven persons were interviewed according to the plan. In order to prevent bias and to obtain traceable and reproducible information, pre-written questionnaires were developed and applied throughout the interview process. The interviewees were provided with background information prior to the interview. All interviews were taped.

Table 3.2: Sources of data

	Laws	Regulations	Reports	Scientific papers and books	Paper/ Magazines	Databases	Interviews
Physical structures		x	x	x	x	x	x
Non physical structures	x	x	x	x			
Policies	x	x	x	x			
Sanctions	x	x	x	x			
Routines			x	x	x		x
Actors	x	x	x	x	x		x
Common knowledge			x	x	x		x
Expectations			x		x		x
Learning			x	x	x		x
Costs		x	x	x		x	x
Environmental impact			x	x		x	

The interviews followed the Kvale's suggested procedure for interviews [Kvale, 1996]. In order to reduce bias in the results and to verify common understanding, several "cross-reference" questions were asked. The questions were designed to gather descriptive data, facts and exploratory information.

Finally, and as an important ethical principle, the information was processed and aggregated into the information models in such a manner individual stakeholders' answers or views are anonymous. The following groups of stakeholders were interviewed:

- Representative from the authorities
- Representative of a material company
- Representative of a transport company
- Representative of a demolition entrepreneur
- Representative of a house owner
- Representative of a consultant
- Representative of a system designer

The interview guide, which shows the information sought and the corresponding questions to the interviewees, can be found in Appendix B.

3.2.3 Describing the system as an actor network

In describing the system I have used an Industrial Ecology perspective using actor network theory. This means that I have begun by following the flow of materials through the system, making up the initial nodes of the actor network. By doing so, I also get the actors directly and indirectly involved in material handling, Figure 3.1 A. Through literature studies and interviews one can trace and add the following to the network: communication pathways, (Figure 3.1 B), quality control systems (Figure 3.1 C) and laws and regulations that affect the different stakeholders (Figure 3.1 D).

By following the pattern that emerges from these different connections, one can then extract vital information on flows and pathways, bottlenecks, missing

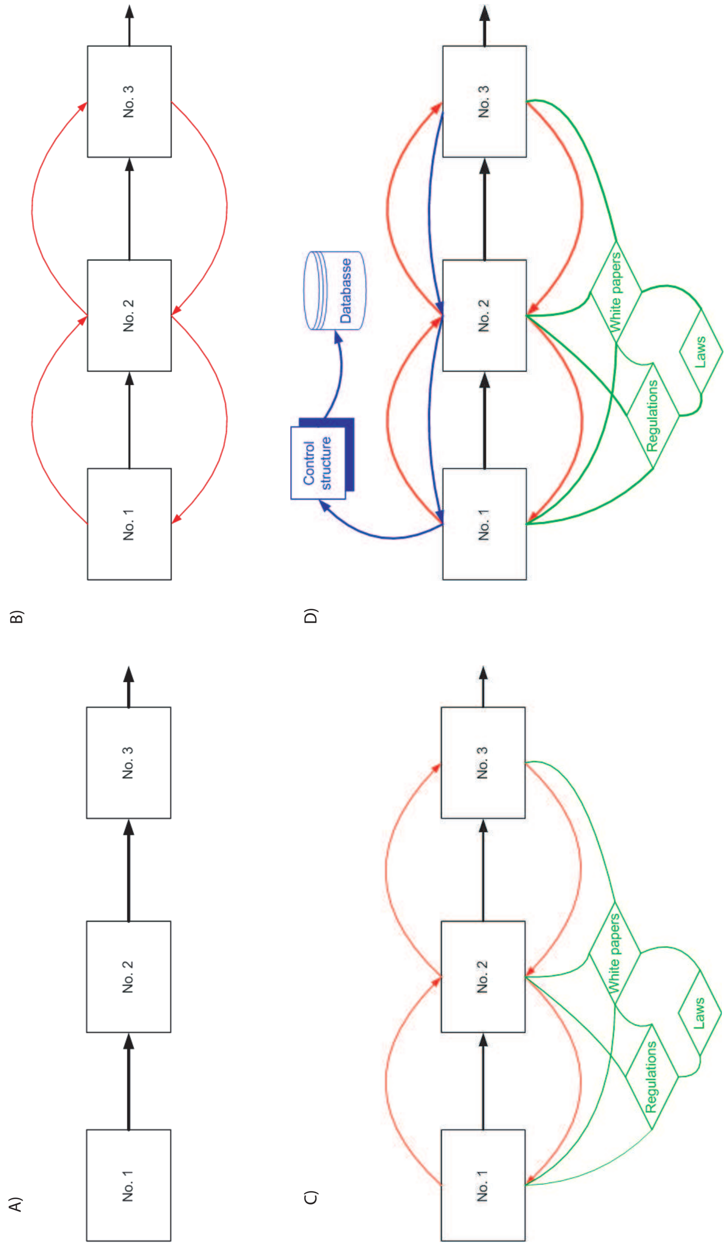


Figure 3.1: The construction of an Actor Network, schematically

activities or structures, information failures, inefficiencies, and lock-ins. These can then be investigated in more detail.

3.2.4 Measuring effectiveness

Learning in C&D waste systems can be measured by the system's or subsystem's level of optimization, that is the systems or subsystems effectiveness. This is measured by a set of indicators, in the case of C&D waste, we have selected three;

- % recycled
- cost, and
- environmental impact.

These measurements are then confirmed by interviews; what measurements are guiding their target, what kind of routines are established and so forth.

To measure a these indicators, we need data on the trends in waste recycling, the corresponding unit cost, and environmental impact over time on a per ton basis; Table 3.3. Environmental impact is the related both to the transport and the process emissions for the various waste handling options.

Table 3.3: Indicators for measuring effectiveness: amount of waste recycled (tons), unit costs (€/ton), or environmental impact (Pt./ton)

Waste fraction: example	t_0	t_1	...	t_n
Landfill				
Incineration				
Incineration with heat/energy recovery				
Downcycling				
Recycling				
Reuse				

The results can then be plotted, as seen in Figure 3.2.

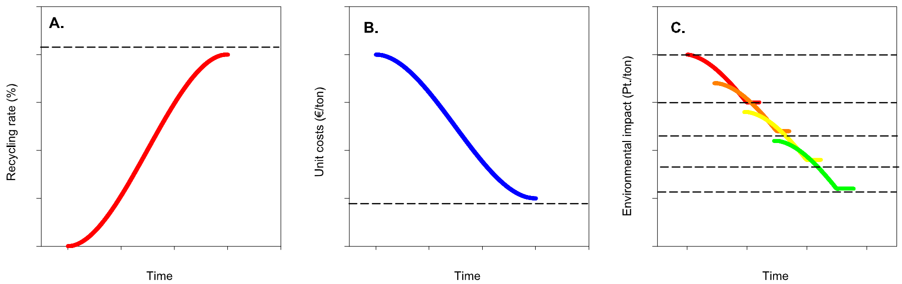


Figure 3.2: Hypothetical S-curves showing system performance in recycling systems, where A: shows increased recycling, B: the corresponding unit costs, and C: the environmental impact (per ton) from the system (over time).

When analyzing waste handling scenarios over time, we have to calculate the aggregated economic and environmental impacts over the period. Cost data will be presented as Net Present Value (NPV) in Euro (€). Environmental impact are however just summed up.

In a new system, its level of optimization is normally low, although its learning curve can be steep. Therefore the effectiveness of recycling and the corresponding environmental impact is a good measure of the degree and type of learning of the actual system. That is, to improve environmental performance (on a per ton basis), the process must improve, or substitute with better process (which usually means that they move up in the waste hierarchy). Often we see that the per unit cost and environmental impact decreases as recycling increases, as collection and handling becomes more efficient (economics of scale). This is *'Type I'* learning. But if the costs and environmental impact continue to decrease after the recycling ratio has leveled off, due to process optimization or process substitution, we have a *'Type II'* learning. Interviews, were then used to verify these findings.

Alternatively, system performance can be plotted as dynamic eco-efficiency (Section 2.3.4, Figure 2.14), but this requires more input data, since we then also need information on the expanded system that also involves all co-products, and their systems.

3.3 Calculations and modeling

The main focus of this thesis is to develop a framework and methods for the optimization of recycling systems for C&D waste. In order to do so, it is necessary to know the amounts of C&D waste that can be expected in the given period in question. Then one need to know the different waste handling options, with the corresponding costs and environmental impact, on a per ton basis. When these figures are known, a trade-off between different options can be made. I have conducted such a study as a team effort, by Håvard Bergsdal, Helge Brattebø and myself. I was the principal investigator of the project together with Brattebø, with the responsibility for the overall research design and principal author of the publication on *"waste handling and the environmental impact"* [Bohne, Brattebø and Bergsdal, 2004*b*], see Appendix D. Bergsdal was responsible for data collection, programming and calculations and the principal author of the publication on *"waste projection for Trondheim"* [Bergsdal et al., 2004], see Appendix C. Within the team I was responsible for all collaboration and field work towards the actors on the cases, as well as overall research methodology development.

I therefore start this section by giving a brief account of the method used for the prediction of the future amount of C&D waste. I then discuss the corresponding environmental impact of the different waste handling options and the associated costs. Finally, I will explain how the trade-off analysis between the different options, that is the eco-efficiency analysis of the system options is carried out.

3.3.1 Projection of future waste generation

The procedure applied for making solid waste projections from the AEC-industry in this work[1] , includes the following steps:

1. Estimate the volume of activity (in m^2 floor area per year) of
    (a) construction
    (b) renovation, and
    (c) demolition of buildings.

[1] For more details and mathematical descriptions, see Appendix C [Bergsdal et al., 2004]

2. Determine the specific waste generation factors (kg/m^2) for different fractions of solid waste related to each type of activity.

3. Calculate the overall waste generation projections (kg/year), on the basis of defined development scenarios.

The volume of activity is related to size, ageing history and characteristics of the building stock. The counties in Norway have very different characteristics regarding population patterns and therefore also number of buildings as well as the relative distribution of types of buildings. Some have densely populated areas and cities, while others consist mainly of areas with dispersed population. There is a diversity of building types, each with their own characteristics regarding size, method of construction and materials composition, which results in differences in waste amounts and the composition of these. Buildings are classified into 161 building types, Norwegian Mapping Authority [2003], and includes many different types of residential and non-residential buildings. Reliable data on numbers and sizes, in square meters, of buildings are available from Statistics Norway [2003*a*]. The materials composition, and accordingly the amount of different waste components, for every building type is however not known. The building types are therefore classified and reduced to three main categories, according to size and the degree of furnishing, being; residential buildings, larger buildings and other buildings, as shown in Table 3.4.

Table 3.4: Classification of building types

Category	*Buildings*	*Area*	*Furnishing*
Residential	Single houses, Chained houses etc.	Small	High
Larger	Office buildings, High houses etc.	Large	High
Other	Industrial-, Agricultural buildings etc.	Large	Low

Waste generation factors are used for the calculation of waste amounts. The factors represent empirical data on the amount of waste per square meter of floor area, related to each of the three activities and for each of the building categories. Combining these waste generation factors with information on how many buildings, and their average size, that are constructed, renovated and demolished, waste amounts can be calculated. Before these factors are used, the amount of activity has to be found.

Waste generation

Knowing the amount of activity related to each building category, waste generation factors are coupled with this to find waste amounts. The waste generation factors do not only give total waste amount per square meter for each activity and building category, but also the composition of this, as displayed in Table 3.5.

Table 3.5 represents estimations of waste amounts per square meter, which are the empirical results from more than 300 projects of construction, renovation and demolition in the municipality of Oslo [Statistics Norway, 1998]. Numbers from 311 different projects are reported. The waste generation factors are further adjusted based on experiences from other projects in Norway as well as Finland.

Although these waste generations factors at the present are static values, they are expected to be broken down in more detailed numbers, both with regard to age and geographical location of the building stock as more data is gathered. This is necessary in order to forecast future waste production at a more accurate level than what will be presented in this work, since the material input to the building stock has changed dramatically since WWII [Brunner and Stämpfli, 1993]. A promising way to do this, is by the use of a "building type and age matrix" [Gruhler et al., 2002; Kohler and Hassler, 2002]. Such a matrix is designed in a way that each entry (building type and age, which vary with time and location) has it own characteristic composition. These matrixes will thus alter the resolution and the precision of the waste generation factors. There is however, not enough empirical data available for Norway at present to make such matrixes.

As can be seen from this table, waste generation is naturally very different for the activities, with demolition clearly dominating for total waste amounts. There is however variation regarding waste generation factors for the different waste fractions. Demolition creates a very large amount of the heavy fraction concrete and bricks, compared to the other activities, making this the main contributor to the total figures.

The major waste fraction is concrete and bricks, accounting for two thirds of the total waste amount. For demolition the waste fraction for concrete and brick is 85%, which is much higher than the contribution for construction and renovation. The second largest waste type is wood, with about 15% of the total,

Table 3.5: Waste generation factors and composition (kg/m^2), from [Statistics Norway, 1998].

	Construction			Renovation			Demolition		
Composition	Resid	Large	Other	Resid	Large	Other	Resid	Large	Other
Asbestos	-	-	-	0.50	0.50	0.50	2.14	2.14	2.14
Hazardous	0.07	0.07	0.07	0.03	0.03	0.03	0.40	0.42	0.23
Conc/bricks	6.50	19.11	17.52	40.40	30.45	18.77	394.30	1.012.46	519.34
Gypsum	3.04	1.38	0.80	5.90	2.44	2.30	3.37	0.01	0.31
Glass	0.24	0.12	-	0.29	0.29	0.29	2.59	0.44	0.20
Insul/EPS	1.20	0.21	0.10	0.62	0.14	0.10	1.69	-	0.09
Metals	0.11	0.48	0.79	0.38	4.06	6.05	4.45	7.70	45.31
Paper/Plastics	2.92	0.46	0.26	0.71	0.68	0.14	0.92	0.32	2.57
Wood	5.68	2.75	4.05	37.94	8.06	2.30	105.84	48.55	17.09
Unknown	9.60	6.19	7.91	2.70	13.48	2.70	59.02	31.21	14.67
Total	29.36	30.77	31.50	89.47	60.13	33.18	574.72	1.103.25	601.95

and as high as 30% of the waste from renovation. The table further shows that about 10% of the total waste amount from the AEC-industry is of unknown composition, making it the third largest category. For construction, as much as 25% of the waste amounts are of unknown composition.

Waste projection for Trondheim

Estimation of future waste amounts from construction, renovation and demolition on a local level would contain too high uncertainty if deducted from the national or regional level, since there is great variation related to AEC-activity for the different parts of Norway. Furthermore it does not include variations resulting from previous economic cycles, which affect the AEC-activity and the building stock both in the past and for the years to come. More specific knowledge of building stock and activity is essential to estimate future activity and waste amounts for any local area under investigation. For the development of a waste projection method, the municipality and city of Trondheim was used as a case study.

Information related to the building stock in Trondheim is obtained from the Norwegian Mapping Authority and their GAB-register (Ground property, Address and Building Register), which is a national register started in 1980, containing an inventory for existing buildings and their year of erection. This is the most detailed information available, and will serve as the foundation for activity- and waste projections. Data quality for projects of renovation and demolition in this register, is however not satisfactory, leading to a need to calculate this. These calculations will be based on expected average lifetime of the different building categories. Residential buildings are assumed to have a longer lifetime than the other two building categories, as displayed in Table 3.6. This is supported by the findings in Kotaji et al. [2003], which is a state-of-the-art report for Life-Cycle Assessment (LCA) in building and construction.

Table 3.6: Expected average time span until renovation and demolition (years).

Activity	*Residential buildings*	*Large buildings*	*Other buildings*
1st renovation	30	20	20
2nd renovation	60	40	40
Demolition	90	60	60

Renovation of residential buildings are assumed to be carried out every 30th year, as opposed to every 20th for the rest of the building stock. These lifetime expectancies and renovation frequencies are important in this approach to estimate future waste amounts. Since the information on previous activity on renovation and demolition is poor, future waste projections will be based on previous construction activity combined with life- and renovation expectancies. Information on construction activity from the GAB-register includes all kinds of buildings, which are first grouped together by the premises set in Table 3.4. The total area constructed can be found for each year by using information on average size of buildings from Statistics Norway [1998]. Average size of buildings have grown over the last century, and not very much detailed information on this is obtainable. From Myhre [1995], a general trend for this increase is calculated for residential housings the last 4 decades. Extending this trend backwards and applying it also to the other building categories, gives an approximation of the average size of buildings with time. By combining these numbers with the waste generation factors from Table 3.5 and the information in Table 3.6, future waste generation in Trondheim is projected.

The calculation is performed for residential buildings with a lifetime of 90 years. There are, however, some uncertainties related to different inputs in the calculations. The method of Monte Carlo simulation is therefore applied to determine the sensitivity of the waste projection with variation in input variables. Monte Carlo analysis involves conducting and then comparing repeated trials with inputs that sample the distributions of the system parameters. The normal distribution with standard deviation is used for the parameters, which are shown in Table 3.7. This simulation is a stochastic technique, meaning it is based on the use of random numbers and probability statistics to investigate the problem. For each trial, the waste amounts are determined with normally distributed input parameters. The distribution of the waste amount gives an indication of how sensitive the results are to variations in the input variables.

Table 3.7: Input parameters in Monte Carlo simulation of waste amounts.

Parameter	*St.Deviation*	*Conf.interval*
Number of buildings	10%	95%
Average area of buildings	10%	95%
Activity frequency	5 years	95%
Waste generation factors	10%	95%

Activity frequency in Table 3.7 means the periods between construction, renovation and demolition. Figure 3.3, shows a principle sketch for the Monte Carlo simulation for the projection of C&D waste in Trondheim, Norway.

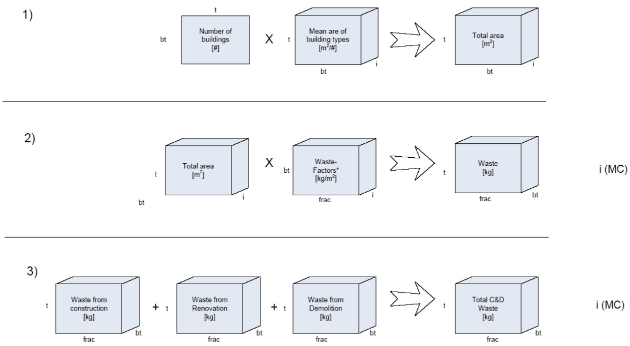


Figure 3.3: Principal sketch of the Monte Carlo simulation for the projection of annual waste amounts in Trondheim.

3.3.2 Waste handling and environmental impact

The environmental impact of waste management options is a result of processing and disposal methods and transportation types and distances, for all disposal, recycling and reuse options in the system. Moreover, recycling and reuse should give positive downstream environmental benefits when recycling and reuse is applied, due to omitted emissions. Some of these benefits should also be allocated to the environmental performance of the initial C&D waste system.

Data on environmental impact for the different alternatives for end-of-life treatment is calculated on the basis of data from many different sources using LCA methodology [PRé Consultants, 2002; Kotaji et al., 2003]. A problem with these calculations for recycling systems is that we deal with a wide range of products, of different age and from many different producers. Hence, it is a challenge to make use of appropriate system borders, cut-off rules and allocation rules when doing the analysis. Another issue is that it is the aggregated environmental impact that is of importance, and should be used as a design criteria, rather than aggregated volume or weight, parameters that often are used in industry's evaluations of system performance in the AEC sector.

Brick and concrete are by far the largest fraction, and will also be the fastest growing fraction in the coming years [Bergsdal et al., 2004]. But this does not necessary mean that this is the most important fraction to deal with in order to reduce environmental impact. In order to examine this question we need to determine the aggregated total environmental impact (Ψ_j^*) for each waste fraction during the whole period we are studying, and then for the different waste fractions, including all transportation and end-of-life treatment activities, over the time period in question. The aggregated total environmental impact is given by,

$$\Psi_j^* = \sum_t \psi_j w_{j,t} \tag{3.1}$$

where, ψ_j is the environmental impact per ton from the end-of-life treatment of each waste fraction (j) (transport included), $w_{j,t}$ the weight of the waste fraction in tons and t is the number of years studied.

For most waste fractions (j), there are several end-of-life alternatives (i) to consider and a mix of these alternatives may oftne be used in practice. The total annual environmental impact of the waste fraction, Ψ_j, is thus the sum of the environmental impacts (ψ_i) from all these end-of-life treatments for each fraction,

$$\Psi_j = \sum_i \psi_i r_i w_j \tag{3.2}$$

where, r_i is the share of a given waste fraction that is sent to each end-of-life treatment alternative (i) in question for each waste fraction (j), see Figure 2.13.

The aggregated total environmental impact, Ψ_j^*, is then calculated by summarizing Ψ_j over the years of interest,

$$\Psi_j^* = \sum_t \sum_i \psi_i r_{i,t} w_{j,t} \tag{3.3}$$

where, (t) indicates the different years in the time period studied.

Calculating Ψ_j^* for all waste fractions will thus identify which fractions that should be of greatest concern in order to minimize environmental impact.

3.3.3 Economic data

Decisions can not be made from environmental data alone. A system owner would want to optimize the system for the best performance possible, in order to reduce pay-back-time for their investments as much as possible.

However, when dealing with reuse or recycling, which are in fact "de-production" systems in which you are dealing with a number of different stakeholders, the picture gets more diffuse. Due to the complexity of recycling systems with many stakeholders and products of different origin and age, economic efficiency is often difficult to measure.

For C&D waste, a typical recycling chain involves several stakeholders with different interests, who each seeks to maximize their own profit, and is traditionally less driven by minimizing environmental impact. The system owner is often the municipalities, who also (in part) are responsible for the policies affecting the system.

Given these constraints, we can categorize the economic data in three categories, Table 3.8, according to the source, type and availability of data.

Table 3.8: Availability and source of economic data

Category	1	2	3
Source	Public taxes	Price lists	Pers.com and/or best estimates
Availability	Very Good	Very good/ good	Good to unavaileable
Type of data	Static	Dynamic	Rapidly changing
Data quality	Very good	Very good/ good	Good to fair

It is most often the values on process expenses that are unavailable due to competition (cat 3), but also prices on transportation and waste delivery for large deliveries have been found to be lower than the official prices (and therefore shift from cat 1 to cat 2). Hence for the same reason such data would be hard to get.

It is also a problem that some economic values have a considerable dynamic variation. E.g. the price on transportation, which shifts with fuel prices. We have therefore used historically observed data and corrected those data according to the corresponding statistical index [Statistics Norway, 2004].

By using cost as the economic indicator (see below) we have managed to limit our data sources to category 1 and 2. Our method is to aggregate all annual costs (on a per ton basis) for all system elements, i.e. all transport and processing activities in the C&D waste system. For the calculations of Net Present Value (NPV), we have used the interest from Norwegian State Obligations (4% for obligations with 10 years running time) as the costing interest in order to estimate the present value of future costs.

3.3.4 Sensitivity analysis

For these calculations to be useful in the actual decision making processes, the uncertainty and sensitivity of the data must be known.

The economic data, costs, are well known, and only need to be corrected for dynamic variations. In our case, transportation costs are the most relevant with respect to such variations.

From literature [Kotaji et al., 2003; PRé Consultants, 2002] its generally known that CO_2-emissions are well studied, and therefore has lower uncertainties, while toxic emission, dust and noise are less studied, and therefore possess greater uncertainties. On the other hand, the sensitivity questions are indeed important for environmental impact data. We base our impact data on Life Cycle Assessment Inventory data, with a combination of data from commercial LCIA databases and our own empirical data, and it should be stated that inaccuracy is not widely published with LCIA data. Goedkoop and Spriensma [2001] consider three fundamental types of uncertainty;

1. Operational, or data uncertainty, which deals with technical uncertainties in the data. Such uncertainties are relatively simple to document by adding the information on the statistical distribution (e.g. standard deviation)

2. Fundamental, or model uncertainties are caused by unavoidable ethical and thus value based choices. Adding standard deviations or a range on the calculated figures can not cover this type of uncertainty.

3. Uncertainty on the completeness cannot be documented at all, except for providing a specification of possibly important, but not included damages.

The Eco-indicator 99 method is intended to quantify uncertainty estimates for operational uncertainty whenever they are relevant. Some of the sources used include uncertainty analysis in their result. For example for each step in the calculations from fate analysis to the amount of DALYs[2] resulting from an emission a quantitative uncertainty estimate is given as a squared standard deviation(σ_g^2), assuming a log-normal distribution. The squared geometric standard deviation expresses the variation between best estimate and the upper and lower confidence limits (97.5% and 2.5%).

- Lower limit of the 95% confidence interval = best guess/σ_g^2
- Upper limit of the 95% confidence interval = best guess*σ_g^2

The uncertainties are intended for use in software tools that apply Monte Carlo type analysis. The Monte Carlo method is a method to solve a mathematical problem by an experiment with random number. Thus in our case we have done 100 000 runs where the standard errors have been independent and uniformly distributed. The uncertainty is then calculated from the results. For the resources damage category no uncertainties are given.

Monte Carlo simulations were run to find standard deviation for our expressions (operational uncertainty), which gives a uncertainty of $\pm 5 - 10\%$.

We have not used any fundamental or uncertainty on completeness in our studies.

3.3.5 Eco-Efficiency in recycling systems

When one are looking at recycling systems, the term value added can not be used the same way as at the firm level. And with a system of many stakeholders who seek to make profit along the way, this picture gets more complicated. Even so, some of this profit does not necessarily increase the value of the material in question, but arises from the stakeholders' performing services such as collection, transportation, sorting and processing. Processing activities in recycling systems, in fact, despite a lift of value for the material, normally lead to a considerable downcycling of the material, at the same time as the stakeholder makes profit. However, the alternative of no processing would of course be worse, since this gives even less value in the marked.

[2]DALY (Disability adjusted life years) is a measure for Human Health

The formulae have therefore been rewritten , Equation (3.4), to include all economic transactions (for the extended system);

$$\text{Eco-efficiency} = \frac{\sum_i \text{costs}}{\sum_i \text{environmental impact}} \tag{3.4}$$

The term *costs* is used to denote all economic transactions when the material is transferred from one process to another. Equation (3.4) can be expressed mathematically as;

$$\varepsilon_j = \frac{\kappa_j}{\psi_j} = \frac{\sum_i \kappa_{i,j}}{\sum_i \psi_{i,j}} \tag{3.5}$$

where;

ε_j = eco-efficiency of a given waste fraction on a per ton basis,

$\kappa_{i,j}$ = process costs of a given waste fraction and end-of-life process alternative on a per ton basis, discounted to the Net Present Value cost.

$\psi_{i,j}$ = environmental impact of a given waste fraction and end-of-life process alternative on a per ton basis,

i = the different end-of-life processing alternatives

j = the different waste fractions

Figure 2.13 shows that all processes are included in the overall system when calculating κ_j and ψ_j in Equation (3.5). Hence one will avoid the difficulties of allocation. However, when comparing different treatment alternatives, one may exclude all processes with similar costs and environmental impacts (so that only processes 3, 4 and 5 are actually calculated in the comparison).

Most of the C&D waste (by weight) is handled by different material companies within Trondheim, but some of the fractions have to be handled long distances outside the city if they shall be recycled. Table 3.9 shows the nearest recycling facilities for these fractions, and the transport methods and distances for each fraction. These transport distances are used in our calculations even though waste fractions may be sent to other more distant places also.

Table 3.9: Distances to the nearest recycling facilities for waste fractions that are not being recycled in Trondheim

Recycling of:	Where	Distance	Recipient	By
Gypsum	Drammen	539 km	Gyproch	Truck
Cardboard	Skogn	73 km	Norske Skog AS	Truck
Glass	Stjørdal	33 km	Glava AS	Truck
Plastics	Folldal	197 km	Plastretur	Truck
Metals	Mo i Rana	482 km	Fundia Armeringsstål AS	Truck (train)

In order to make qualified decisions on what to do with the different waste fractions, one needs to compare the eco-efficiency for the different end-of-life options for each fractions against each other. This will then be a basis for further qualified decisions in the overall C&D waste management system. However, for eco-efficiency to have any meaning as a tool for decision making, it needs to measure the change in eco-efficiency between different end-of-life treatment options, or waste handling scenarios, for each of the different waste fractions [Saling et al., 2002; Huisman, 2003; Bohne and Brattebø, 2003]. Thus what is wanted, is to measure the relative change in eco-efficiency (ε') of a proposed alternative end-of-life treatment option, or set of options (b) compared to the current practise (a);

$$\varepsilon_j{}' = \frac{\kappa_j{}'}{\psi_j{}'} = \frac{\sum_b \kappa_{b,j} - \sum_a \kappa_{a,j}}{\sum_b \psi_{b,j} - \sum_a \psi_{a,j}} \tag{3.6}$$

where the subscripts;

a = a given mix of end-of-life process alternatives that are made use of in the current (reference) system, and

b = a given mix of end-of-life process alternatives that are made use of in the proposed alternative system.

However eco-efficiency, is a one dimensional number (€/Pt.) on a per ton basis that hides valuable information away from decision makers, especially when more than one alternative process is to be considered. Another issue is that the value of eco-efficiency will increase if the cost increases. Hence, this parameter will have to be rearranged in order to better communicate information the preferred way.

This study therefore follows Huisman [2003] in his attempt to visualize the change in eco-efficiency by the BASF method [Saling et al., 2002]. In the BASF method, eco-efficiency is visualized by plotting the numerator ($\kappa_j{}'$) and denominator ($\psi_j{}'$) for a given waste fraction (j) in an XY-plot like Figure 3.4, where a positive value for the numerator expresses increased economic value (the Y-axis), and a negative value for the denominator expresses less environmental impact (the X-axis). By comparing several alternative end-of-life process alternatives this way, decision makers can make more qualified decisions on what solution to follow A benefit of this method is that it is very easy to communicate the relative differences between two given treatment options, or two given mix of options, or even a large number of such options or mix of options .

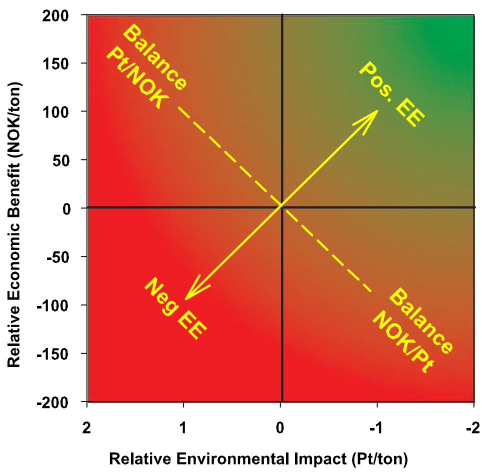


Figure 3.4: Principal sketch of eco-efficiency (after [Saling et al., 2002; Huisman, 2003]), where origin represents the baseline scenario

Another interesting feature of this two dimensional figure, is that policy makers here can test how different policies will affect the eco-efficiency of the different end-of-life treatments within the system.[3]

[3]be aware of that origin of the plot also changes (relatively) by introducing new policies.

Chapter 4

Results

This thesis is a study on recycling systems for C&D waste in Denmark and Norway. The study started by looking at the existing policies that regulate this sector, their laws and regulations, with the corresponding structures of enforcement. The Norwegian system is to some extent build upon Danish experience. It was therefore natural to start with the municipality of Copenhagen as my first case study; how was it initiated and started, what worked and what failed?

The next case then, is a study of the first initiative in Norway, the "Oslo model". Oslo was the first municipality that introduced a recycling system for C&D waste in Norway, in something that looks as a national test-case. The last case is a study of the municipality of Trondheim, one of the first municipalities to take on the new voluntary regulation for C&D waste in Norway.

Since the Trondheim case is also about a future system, work have been done with forecasting the future waste production as well as modeling different waste handling options, and the following trade-off between them through an eco-efficiency framework. A product of this work, was the study on transport and supply chains. These two points are of some importance for the following two reasons. First, in a country like Norway, with long transport distances, it is not necessarily wise to do all types of recycling in all municipalities. From an environmental perspective it may sometimes be a better option to do less recycling if transportation dominates the system, but then only after an impacts analysis. Second, for a recycling system to work, there has to be a well functioning supply chain. It is therefore of interest to understand the dynamics of such systems.

4.1 Case 1: The "Copenhagen system" for C&D waste recycling

During the late 70's and early 80's, Danish authorities registered an increase of toxic pollutants in their groundwater reservoirs. Investigations isolated leakage from legal and illegal landfills as the main course of this pollution. To secure the freshwater supply, the national waste treatment scheme had to be reorganized [Bohne and Opoku, 2003]. The problem identification left the policy developers with only two alternative strategies. These were either to stop deposition of waste in landfills, or to stop the leakage from the landfills. In practice only the first solution, avoiding deposition of waste, was realistic. Stopping the leakage from legal and illegal landfills would invoke unrealistic expenses. Therefore, ways of stopping the deposition of waste in landfills had to be found [Lauritzen, 1996]. National policy makers now had to consider alternative pathways for waste handling. As a market for the waste did not exist in neighboring countries export was not an alternative. In other words, the waste problem had to be solved nationally. The first step in this direction was to establish an overview of waste sources. This revealed the distribution [Lauritzen, 1996], in Table 4.1:

Table 4.1: Waste distribution in Copenhagen 1980 (per tonne % distribution) [Lauritzen, 1996]

Household (municipal) waste	30-35%
Construction and demolition (C&D) waste	40-50%
Industrial waste	15-20%
Garden waste	7-10%
Hazardous waste	3-5%

Further investigations revealed that if one could hold these waste streams separate, it would be possible to deal with them effectively. To secure the ground water reservoirs from further pollution it was necessary to end deposition of waste into landfills, both legal and illegal. It was therefore decided to put a general ban on all depositions of waste into landfills (except a few very special fractions, for example asbestos). This ban was made effective through the Danish Environmental Protection Act of 1986. It was also decided to establish a separate waste stream for C&D waste. There were two reasons for this; first, it was the largest fraction of waste (almost 50%); second, this fraction contained huge amounts of non combustible materials. If the C&D waste was singled out it would expose what was left of the waste which now should be incinerated [Lauritzen, 1996].

4.1.1 Application of policy instruments

The new national regime started with a general ban on land filling of waste. However, it was not until 1990 the real implementation started with the introduction of a waste tax of 90 Danish Kroner (DKK) per ton waste, combined with an instruction for the municipalities to develop regulatory plans for the handling of all wastes within their area. This was the tool the municipalities needed to implement and enforce the new policies. The introduction of a waste tax came with an exception for recycling, which introduced three important changes: First, the registration and weighing of all waste that had not been done before. Second, the introduction of a tax. The legal framework for the handling of illegal deposition was expanded to also deal with tax evasion, which in turn made it easier to bring charge against, and to prosecute violations (of the law), and the penalties also became more severe. Finally, materials delivered to recycling were no longer termed waste by definition, but materials [Bohne and Opoku, 2003].

Simultaneously the authorities introduced regulations for demolition and renovation projects and the corresponding waste management. This required demolition and renovation projects to submit notification of a project to the municipalities before initialization, making control of the project possible. It also requested that all fixed inventory and insulation should be stripped before demolition (a method called selective demolition), and that fees would be issued if the process of selective demolition was not followed. Anybody producing more than one ton of demolition waste should now sort the materials and waste in separate fractions. All waste and materials that are not reused directly, should be delivered to certified material companies. A fee of DKK 60-70.- per ton was issued for sorted fractions, and DKK 800.- per ton for waste (unsorted materials). And finally, all transport of materials and waste had to be performed by certified transporters.

4.1.2 Facilitating changes in target group behavior

In response to the new policy framework, the municipalities of Copenhagen made four initiatives to facilitate the establishment of the new system for handling of C&D waste. First, the material company RGS90 was established as a joint venture between the municipalities and industrial interests. Second, the municipalities of Copenhagen guaranteed to purchase all recovered materials in a period of transition. Third, the material company, RGS90, sold virgin materials in addition to recycled materials, which allowed made use of existing infrastructure and transport capacity. And last, information and meeting services for coordanation were facilitated.

The guarantee was important to avoid the development of new material deposits (per definition, materials which are processed for reuse is not waste). The sale of virgin materials was also an important economic incitement for the transporters to coordinate their payloads to be driven both ways. This was a win-win arrangement as it was cost effective for the transporters, and saved the municipalities considerably amounts due to reduced expenditure on maintenance of public roads, and reduced environmental impact from less transportation. Figures show that an averages of 85% of the trucks delivering materials to RGS90 also took a payload back from the material company. Estimates also showed that this reduced heavy transport in the construction sector by 80% within Copenhagen, which according to Nejrup gives a reduction of yearly CO_2-emissions of approximately 500,000 tons. However, it was experienced that it was only the heavy fractions that were suitable for local processing and recycling. All the other fractions either had to be deposited (asbestos etc.), recovered (metals, plastics etc) or incinerated (wood, plastics, paper, insulation etc.). By moving the combustible waste away from landfills to incineration with heat recovery or incineration with both heat recovery and power generation, the CO_2-emissions from landfills were reduced with the comparable amount to all emissions from traffic, and enough power was generated to support 20,000 households, when the combustible waste replaces coal [Nejrup, 1999, 2001].

For the municipalities of Copenhagen it was important that all stakeholders received good and reliable information about their role and responsibilities throughout the process. Focus was also very much on follow-up in the beginning, especially on prosecutions of those who did not follow the new regulations. This can be visualized by the fact that all entrepreneurs had to use certified transporters and material companies dealt only with certified transporters to deliver waste. This, combined with special training for transporters during the certification process, made transporters become what we may call "change agents", since transporters were charged with a 10 fold increase in delivery fees if they delivered contaminated fractions or unsorted materials. Therefore, they efficiently asked for correct sorting at the demolition sites.

The municipalities also established a common meeting place for stakeholders in order to facilitate communication and knowledge transfer. These meeting places were controlled by two agencies, GRU[1] and KGB[2]; which both consisted of representatives from all types of stakeholders.

During the period from 1989 to 1994, these agencies together used more than DKK 50 million on developing projects, which led to knowledge transfer through: handbooks, standards, houses built from recycled materials, and quality control of recycled materials.

The facilitating process helped create a network of actors where information flow became an important tool to support the emergence of an efficient system for recycling.

4.1.3 Shifting focus

Practical experience has shown that it is more difficult to reuse materials from modern houses than materials from old houses, due to the complexity of the materials used in more modern buildings. Furthermore materials from post WWII buildings contain more toxic pollutants than pre-war ones. This lead to a shift in focus. At the beginning, quantitative recovery of construction material was in focus. As the system evolved, focus shifted more and more towards qualitative recovery of construction materials. This agian led to requirement of quality before materials can be approved for recycling or recovery purposes. Today it must also be documented that the materials are intended to substitute virgin materials.

[1]"Genanvendelse, Rådgivning og Utvikling", which translates to: "Reuse, Counselling and Development".

[2]"Koordineriingsgruppe for genbrug af BA-affald", which translates to: "Coordination group for the reuse of C&D-waste".

Table 4.2: Distribution of C&D waste in Copenhagen 2002 (per tonne %)

Recycling	93%
Energy recovery	6%
Deposition and landfill	1%

4.1.4 Knowledge and motivation

By following the material flows through the system I have outlined a qualitative model of the whole recycling system, which focuses on flow of information among actors and activities, see Figure 4.1 below. Literature studies and interviews made it possible to trace communication pathways, quality control systems, and laws and standards that affect the nodes between the materials and actors in a functional network. At the basis for the figures are the actors and the material flow through the system, shown in black. Communication, shown in red, was then added. Finally, the laws and regulations and the quality control scheme, shown in green and blue, were drawn. We see clearly from Figure 4.1 that the transporters hold a key position in the network, in the sense that all mass flow, communication and quality control passes through the transporters. Thus they were the vectors of change both from a top down and bottom up driven change.

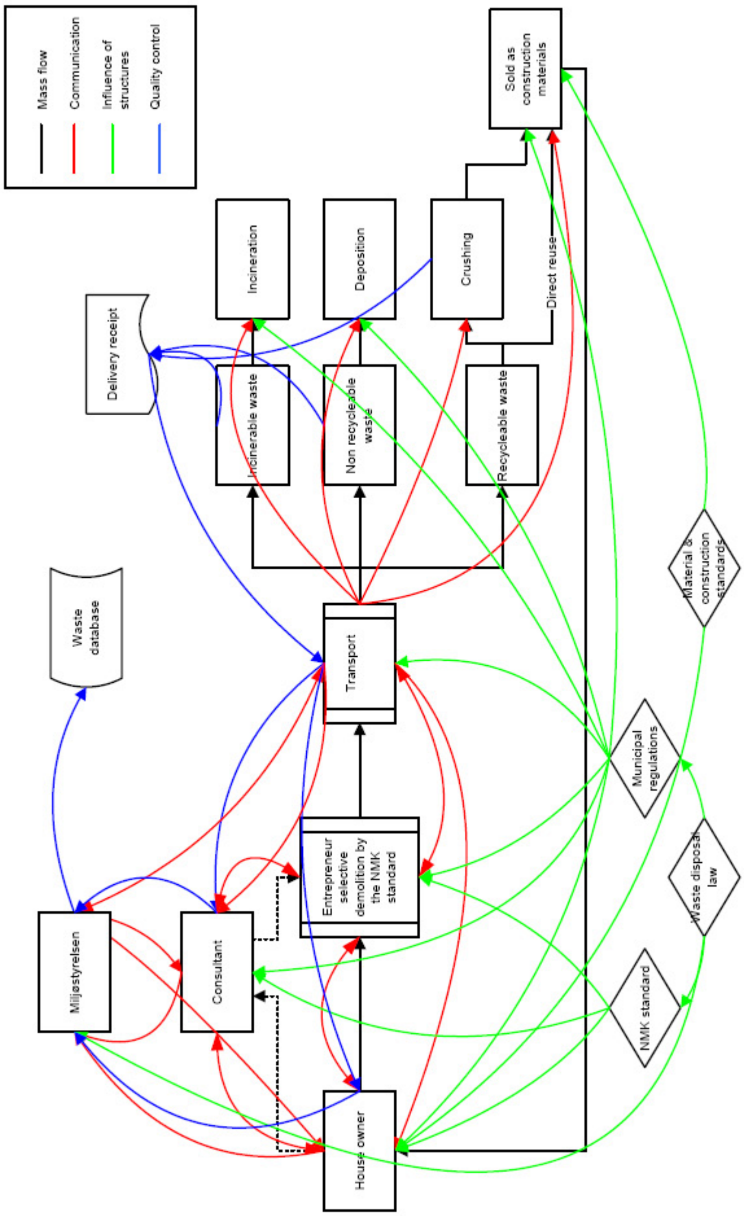


Figure 4.1: An actor network model of the C&D waste recycling system in Copenhagen

4.1.5 Policy instrument

Of the above mentioned policy instruments, the most important one is the waste tax. It is documented that the degree of recycling and energy recovery in the Copenhagen case has followed the level of taxation (Figure 4.2).

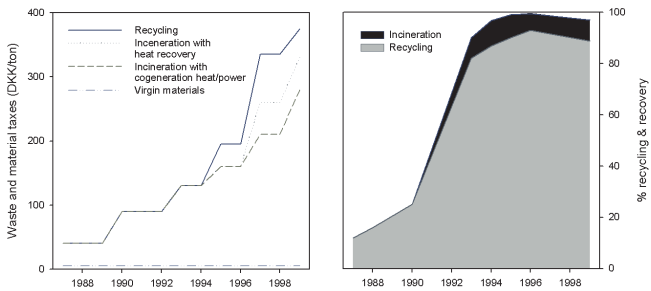


Figure 4.2: The historic relationship between waste taxes and recycling or energy recovery in Copenhagen, DK.

Surprisingly, it is not the tax level itself that made most influence to the actors, with the exception of the differentiation in tax for incineration. The most important role of the tax was that when someone was found to dump C&D waste illegally, they could be charged with tax aviation, not an environmental crime. This was more transparent to the legal system, led to more convictions, and more severe punishments.

Thus, the Copenhagen case became a success due to the following reasons:

- Long term policies,
- supported by legal structures, and
- bodies of information and control.
- Enforcement of sanctions.
- The establishment of necessary infrastructure.
- Economic incitements for all involved actors in the network.

4.2 Case 2: The “Oslo system” for C&D waste recycling, learning from Danish experience

The “Oslo system” for the recycling of C&D waste is in many aspects a copy of the “Copenhagen system”, with some important differences. The most important difference is the structural character; both related to policy and infrastructure.

4.2.1 Application of policy instruments

The applied policy instruments in the “Oslo system” differ from the “Copenhagen system” in two important ways. First, the municipalities in Oslo are only given the power to supervise what to do - not how or where [Renholdsverket Oslo Kommune, 1997]. Second, there is no system of certifying actors within the system, that is neither entrepreneurs nor transporters need certificates or civil law contracts (with respect to recycling) to do business.

Figure 4.2.1 shows a schematic view of the action for a demolition case in Oslo, where similar approaches exist in the case of construction, renovation and mass movement. Each project must have an approved waste handling plan prior to initiation. For the waste handling plan to get approved, the municipality demands that 60% is source separated, and that the rest is delivered to a licensed material company or landfill. If there is a deviation between the waste handling plan and the actual waste handling, the municipality has the power to impose a compulsory fine (NOK 2000.- per ton, for the diverging mass of waste). The municipality seeks to be flexible if they are notified during the progress of a project, allowing negotiation, but it is strict if deviations are discovered during inspections or after the audit of the end report. Since landfilling is not banned, this means that it is perfectly legal to deliver 40% of the waste as mixed waste to landfill, but one then has to pay the full waste tax.

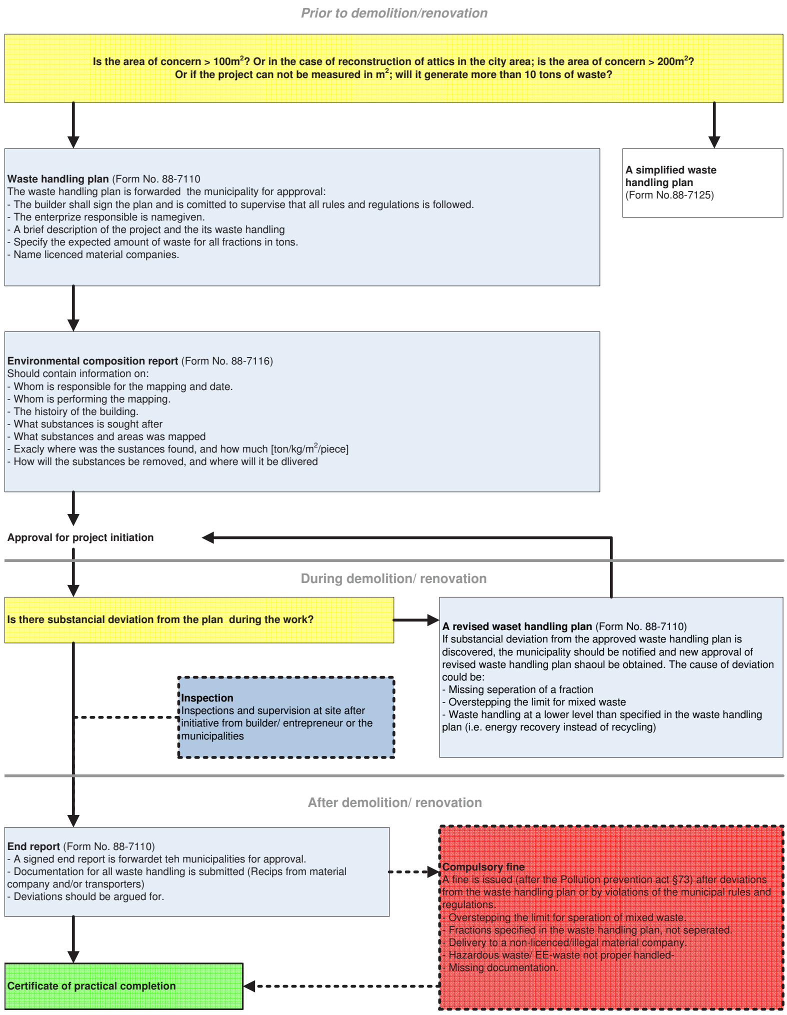


Figure 4.3: Schematic view of the cause of action for a demolition case in Oslo, adapted from Plan- og byggningsetaten, Oslo kommune [2004]

With regard to infrastructure, there are also some differences between Oslo and Copenhagen. In Oslo and environs there were already established private and public recycling facilities prior to the regulation in 1997. From recycling facilities' point of view, it is beneficial to maximize the waste delivered as mixed waste (at full tax prize), for then to sort the waste into fractions for further treatment. These businesses are often in close affiliation with large entrepreneur groups, and in many cases part of the same industrial conglomerate, so that that there is a strong link between whom is doing the work and where the waste is treated. In many cases, this creates unnecessary transport.

4.2.2 Facilitating creation and transfer ofknowledge among stakeholders

The Norwegian authorities were aware of the Danish success in creation and transfer of knowledge through GRU and KGB. Another interesting feature is the Økobygg programme, a competence and development programme, financed by the government and the AEC-industry. This five-year programme funded many projects and facilitated knowledge transfer among the stakeholders. The two most important products from this programme, are the National Action Plan for Construction and Demolition waste [GRIP/Økobygg, 2001] and the "Recycled Aggregates for the AEC industry"(RESIBA) project [RESIBA, 2004]. As discussed in Chapter 3.3, the NAP 2005 set the standard for the total Norwegian efforts with C&D waste handling. The RESIBA project, deals with the advantages and disadvantages of recycling the heavy fractions; brick, concrete and asphalt. It has also played a crucial role in explaining the material properties of the heavy fractions, developing standards of recycled aggregates and their best practice for use, as well as documenting environmental risks. Although the recycling practise still has to be defined as downcycling, it substitutes a higher grade of gravel.

When it comes to waste treatment, one tend to do the same as in Denmark; that is to recycle paper and plastics, incinerate wood and downcycle the concrete and brick fraction. One important difference is, however, that Norway has to some extent, screened the waste for toxic compounds (e.g. PCB), and withdrawn these from the recycling stream.

4.2.3 Programme impact

A problem with studying the Norwegian C&D waste systems including the data on the Oslo case, is the lack of accurate waste statistics. Figure 4.4, Table 4.3, and Table 4.4 show the waste statistics for C&D waste generation in Oslo January and August 2004.

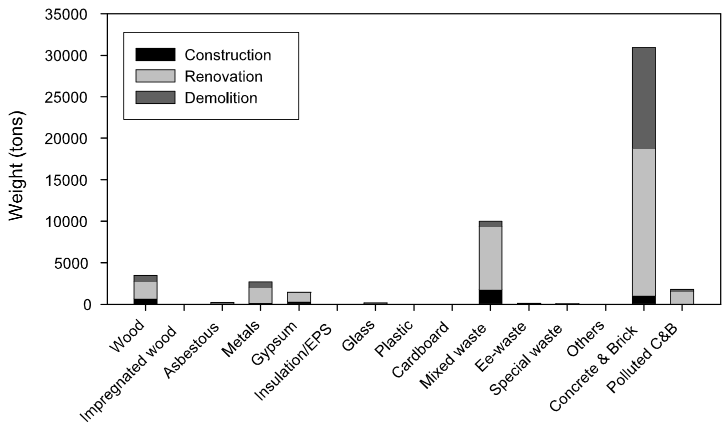


Figure 4.4: Waste composition (tons) for C&D waste in Oslo, Jan-Aug 2004 [Valde, 2004].

The data in Table 4.3 and Table 4.4 reveal some interesting trends. First, a good recycling rate is determined by the amount of structural materials in the waste. Thus demolition activities perform better than renovation activities, which perform better than construction activities with respect to recycling. All this is due to the fact that recycling is measured in weight percentage. Second, demolition is mainly done by a few specialized actors, which in turn are in close association with the material companies. Thus, both the entrepreneurs and the material company are highly motivated in achieving a high degree of source separation, since all the profit stays within the same industrial conglomerate. Third, the size of the project matters. Much of the renovation is related to larger projects run by large companies. Both the size of the projects and the professional infrastructure of these companies provides a high degree of recycling but lower performance than for demolition due to less structural components. Construction projects, and to some extent renovation projects, tend to involve smaller wooden houses, which are the domain of the small and medium sized entrepreneurs, with less industrial infrastructure. This, combined with the weight ratio among the materials, make these projects less "effective" in terms of weight percentage.

The data show the same trends as the waste generation factors given by Statistics Norway [1998], se Table 3.5, with the exception for renovation projects; where the increase of the mixed waste and decrease of the wood fraction are both significant. One reason may be that much of the wood has entered the mixed waste fraction. Another explanation can be the number and nature of the projects. The trend may be more visible as more data is collected.

The findings suggest that the recent increase in system performance of the Oslo system is due to three important changes within the actor network:

- The policy changed from a temporary to a permanent structure, and
- the body of quality control started performing better, and thus enforced more sanctions due to better control.
- This created better incentives for actors to comply with the policies.

Further, the findings also suggest that there is an ongoing adjustment to the policies within the industry. There has been a significant reorganization within the industry, towards a more industrialized approach, where industry conglomerates seek to establish themselves at all levels of the value-chain. In Oslo, three big conglomerates, Veidekke AS, Onyx Norway AS and AF-gruppen AS, already control more than 80% of the marked for the demolition, collection, transportation and handling of C&D waste. Hence, we in fact experience a process of consolidation towards few companies covering larger marked shares in this sector. This change probably also calls for more competence, focus on profitability and margins, as well as productivity. It is believed that a focus on eco-efficiency, will also increase during coming years, in line with the demand for competence, profitability and environmental regulations.

Table 4.3: Waste generation factors and composition (kg/m^2) in Oslo Jan-Aug 2004, from Valde [2004]

	Construction (kg/m^2)			Renovation (kg/m^2)			Demolition (kg/m^2)		
Fraction	Res.	Large	Others	Res.	Large	Others	Res.	Large	Others
Wood	13.4	18.4	4.3	19.3	32.2	6.7	138.5	67.6	20.0
Impregnated wood	0.0	0.0	0.0	0.0	0.0	0.0	2.0	2.3	0.1
Asbestos	0.0	0.0	0.0	0.0	1.6	0.3	1.0	0.2	1.6
Metal	0.5	6.0	0.5	0.0	15.8	4.2	8.2	78.9	76.1
Gypsum	3.2	9.3	1.6	0.0	12.2	2.7	0.8	3.0	0.0
Insulation/EPS	0.2	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0
Glass	0.0	0.0	0.0	0.0	1.5	0.0	0.4	1.4	0.0
Plastic	0.4	0.4	0.1	0.0	0.3	0.1	0.0	0.4	0.0
Cardboard	0.3	1.3	0.2	0.0	0.4	0.1	0.0	0.4	0.2
Mixed waste	18.5	39.2	21.4	59.4	84.8	22.1	49.3	129.1	97.3
WEEE	0.0	0.0	0.0	0.0	1.0	0.1	1.0	3.5	2.6
Hazardous waste	0.0	13.3	0.0	0.0	0.5	0.1	0.8	2.8	1.5
Other	0.0	0.0	0.0	0.0	0.4	0.0	0.5	0.0	1.7
Concrete and brick	2.1	76.1	6.6	101.1	216.0	57.7	333.2	2787.3	848.1
Contaminated C&B	0.0	0.0	0.0	0.0	0.0	21.9	19.2	19.4	0.0
Sum	38.6	164.0	34.7	179.8	366.7	116.1	554.9	3096.3	1049.2
# cases	20	15	7	2	37	34	7	9	3
Tot. A (m^2)	12825	74317	30355	379	159751	71385	1885	14375	803

Table 4.4: Waste composition for different activities (tons) in Oslo Jan-Aug 2004, from Valde [2004]

Fraction	Construction		Renovation		Demolition		Total	
	tons	%	tons	%	tons	%	tons	%
Wood	709.7	16.8	2020.5	6.3	745.9	5.1	3476.1	6.8
Impregnated wood	1.2	0.0	0.9	0.0	14.5	0.1	16.6	0.0
Asbestos	64.0	1.5	127.0	0.4	4.7	0.0	195.7	0.4
Metal	125.8	3.0	1909.6	5.9	690.0	4.7	2725.4	5.3
Gypsum	367.9	8.7	1079.9	3.3	20.6	0.1	1468.4	2.9
Insulation/EPS	3.2	0.1	4.5	0.0	0.0	0.0	7.7	0.0
Glass	1.2	0.0	161.8	0.5	7.2	0.0	170.2	0.3
Plastic	13.6	0.3	20.5	0.1	0.2	0.0	34.3	0.1
Cardboard	27.7	0.7	32.6	0.1	0.4	0.0	60.7	0.1
Mixed waste	1790.6	42.4	7590.6	23.5	667.4	4.6	10048.6	19.7
WEEE	0.2	0.0	90.8	0.3	18.7	0.1	109.7	0.2
Hazardous waste	20	0.5	37.9	0.1	27.4	0.2	85.3	0.2
Other	0.0	0.0	11.7	0.0	2.4	0.0	14.1	0.0
Concrete and brick	1096.4	26.0	17660.1	54.7	12171.5	83.4	30928.0	60.5
Contaminated C&B	0.0	0.0	1566.0	4.8	230.2	1.6	1796.2	3.5
Sum	4221.5	100.0	32314.4	100.0	14601.1	100.0	51137.0	100.0

4.3 Case 3: Long term C&D waste projections and handling strategies in the city of Trondheim

In 2003, the Norwegian government passed a voluntary regulation scheme, that enables the municipality who wants it to introduce a waste handling scheme for C&D waste, according to the Oslo model that i described in case 2. Trondheim is one of the municipalities that has introduced such a regime (since January 2004). Since there is no actual performance data to draw upon, this case study explores the type of modeling and trade-off analysis that could be made as basis for long term strategies. To establish a reasonable and efficient system in such municipalities, decisions should be based on more qualified analyzes than what often is the case in the present situation. This analysis should give answer to questions like; What fractions to concentrate on, and what waste handling option to build infrastructure for. These questions are of great importance, since we are dealing with huge and costly infrastructure with a long service time.

4.3.1 Projection of future C&D waste

Figure 4.5 displays the results for projection of waste amounts, and their composition, in Trondheim for the next 15 years. Results for the recent years are included as well, on the basis of reported construction, renovation and demolition activity (m^2). Recent (empirical) data involve cyclical fluctuations, however, future data do not.

Waste amounts are increasing for all waste types, due to increasing construction activity and size of buildings in the past sixty years. The change is especially dramatic for concrete/bricks which will increase more than four times during the coming fifteen year period. The projections are based on previous construction activity and estimation of lifetime of buildings as explained in Chapter 3. From Table 3.6 the lifetime of buildings , except residential, is assumed to be 60 years. For the waste projections, this brings us back to World War II, where construction activity was naturally low. Knowing also from Table 3.5 that demolition of “Large” and “Other” buildings are the activities generating the most concrete/bricks, this explains the very high increase for this waste fraction, as construction activity rose significantly in the post war period. A corresponding drop in waste amounts are shown for projections based on the pre war period,

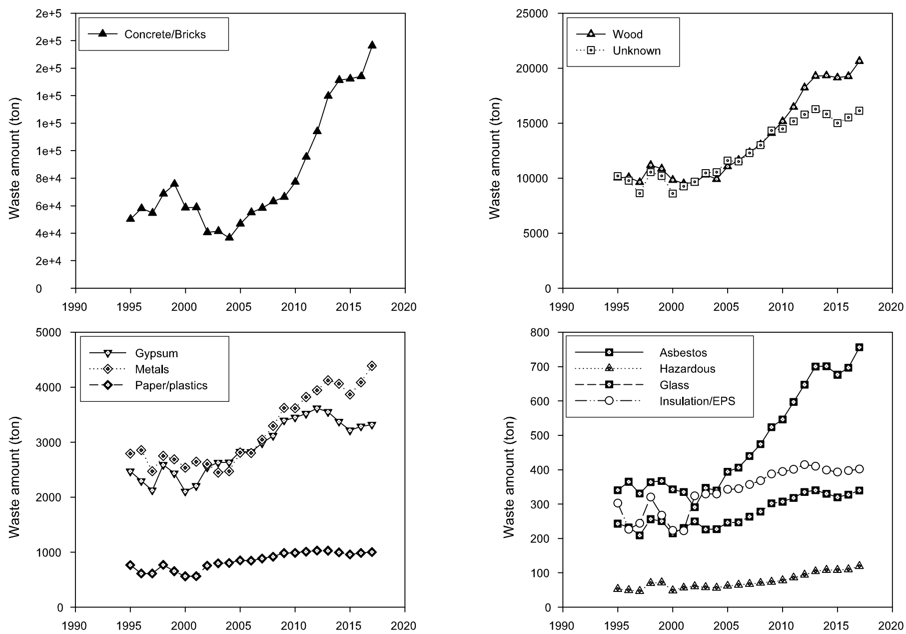


Figure 4.5: Projected waste amounts in Trondheim.

but this findings can also be due to cyclical fluctuations in construction and demolition activity between 1995 and 2000. Wood, metals, asbestos and waste of unknown composition will also increase considerably, and the increase in asbestos amounts is worrying because of its potential for causing harm both to the environment and to humans. Waste of unknown composition constitutes a large share of the total waste amounts, and the considerable increase for this waste type calls for more attention and better tracking of this. The growth in waste generation for the minor waste types are much less dramatic, but still there is growth for these as well.

4.3.2 Eco-efficiency and waste management optimization

In order to examine the eco-efficiency of C&D waste systems at the local level, such as at the level of a city, the future waste projections for the city of Trondheim has been estimated. Trondheim is the third largest city of Norway, with a population of 150.000 inhabitants, and a building structure which is characterized by many small wooden family houses covering a large area, together with larger residential and office buildings of concrete in the center and some clusters around the center of the city. The results presented here are drawn from Paper 2 [Bohne, Brattebø and Bergsdal, 2004*b*], se Appendix D.

The projections of local C&D waste fractions for Trondheim, as given in Figure 4.5, are accumulated for the whole period 2003-2018, and the aggregated amounts are shown in Figure 4.6. One can clearly see the dominant role of the concrete and brick fraction, in addition to wood wastes, even for a city with a large share of buildings made of wood.

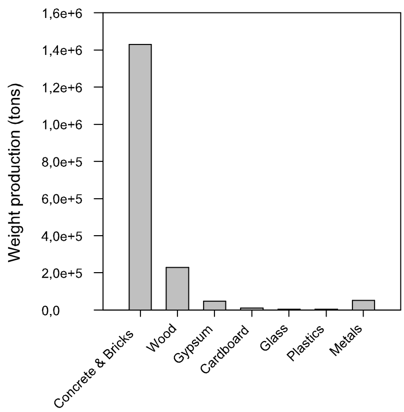


Figure 4.6: Cumulative weight of selected C&D waste fractions for the city of Trondheim from 2003 to 2018.

The next step is to identify scenarios for the distribution of C&D waste fractions between various end-of-life treatment options. Table 4.5 shows the distributions for two scenarios, where "Scenario 0" assumes the continuation of the current end-of-life process alternatives during the whole period, while "Scenario NAP" assumes that waste fractions are being directed more towards recycling and reuse options, according to the National Action Plan, as one can see in Table 4.5 for the whole period.[3]

Table 4.5: Distribution of C&D waste fractions (on a mass basis) between different end-of-life treatment options in Trondheim. Landf. = sent to landfilling, Rec. = sent to materials recycling, En. = sent to energy Recovery, and Reuse = sent to reuse without processing

C&D Waste	Scenario 0				Scenario NAP			
Fract.	Landf.	Rec.	En.	Reuse	Landf.	Rec.	En.	Reuse
Concrete & brick	0.70	0.30	0.00	0.00	0.20	0.80	0.00	0.00
Wood	0.60	0.00	0.39	0.01	0.20	0.00	0.70	0.10
Gypsum	0.95	0.05	0.00	0.00	1.00	0.00	0.00	0.00
Cardboard	0.50	0.30	0.20	0.00	0.20	0.70	0.10	0.00
Glass	0.80	0.20	0.00	0.00	0.20	0.80	0.00	0.00
Plastics	0.40	0.20	0.40	0.00	0.10	0.80	0.10	0.00
Metals	0.10	0.90	0.00	0.00	0.10	0.90	0.00	0.00

The distribution of waste fractions demonstrates that there must be realized an ambitious shift away from landfill towards recycling for concrete/brick, gypsum, cardboard and plastics, if the current end-of-life practice (Scenario 0) is to be replaced by Scenario NAP. Likewise, wood waste will have to be redirected from landfills towards energy recovery and direct reuse.

On the basis of data in Figure 4.6 and Table 4.5 the Net Present Value (€) and environmental impacts (Pt.) was calculated for each waste fraction over the 2003-2018 period. Cost data are achieved directly from the actors in the system, and environmental impact data are achieved from LCA software [PRé Consultants, 2002] by using the Eco-Indicator 99 valuation method.

The results are given in Figure 4.7 and 4.8, where 4.7A and 4.8A shows Net Present Value (€) and Environmental impact (Pt.) for each waste fraction in Trondheim during the next 15 years, according to Scenario 0. Similarly, 4.7 and 4.8 B shows the results if Scenario NAP is applied for the whole period, and finally 4.7C and 4.8C shows the net difference between the two scenarios.

[3]Scenario 0 is the reference point for our examination, since it is equal to the current practice. Hence this scenario will be represented by κ_a and ψ_a in Equation 3.6, and the origin location in the eco-efficiency plot. Likewise, the Scenario NAP will be represented by κ_b and ψ_b in Equation 3.6, and located away from origin in the plot.

The reader should be reminded that these are calculations for the extended system, and as such not representative for the individual stakeholders, but for the system as a whole, see Figure 2.13, involving all activity on process no. 3, 4 and 5.

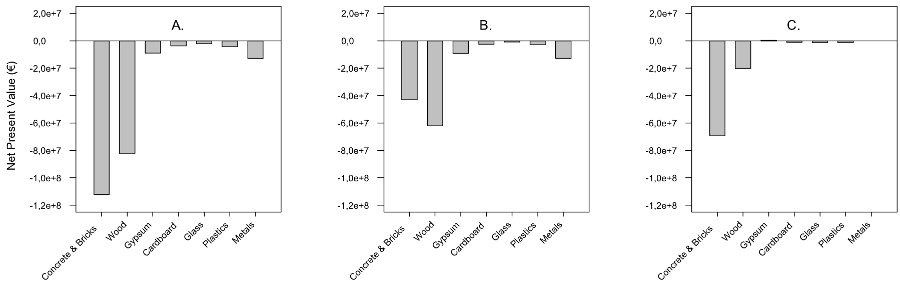


Figure 4.7: Net Present Value (€) of C&D waste handling in the city of Trondheim from 2003 to 2018
A: Scenario 0
B: Scenario NAP
C: Relative difference A-B.

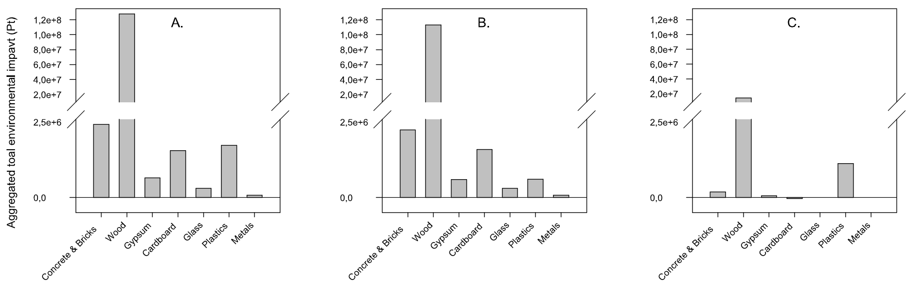


Figure 4.8: Aggregated environmental impacts in Ecopoints (Pt.) of C&D waste handling in the city of Trondheim from 2003 to 2018
A: Scenario 0
B: Scenario NAP
C: Relative difference A-B.

Figure 4.9 shows two-dimensional relative plots of the eco-efficiency parameters according to the BASF method. Plots is provided for each of the waste fractions, and the data show how different end-of-life treatment options position themselves relative to the current treatment practice (as found in Scenario 0), which always is represented by the origin. The difference in environmental impact, between a given treatment option or scenario and the current treatment scheme, is given along the x-axis, where reduced impact gives a position to the right of origin. The difference in cost is expressed as net economic benefit, on the y-axis, so that a reduced cost gives these are relative numbers. End-of-life options that are part of both current situation and the suggested Scenario NAP will be placed on a straight line, since the numbers are interconnected. In order to compare on a straight forward method, the results are presented on a per ton basis, i.e. €/ton and Pt./ton. The better treatment options will always position themselves in the upper right corner of the plot.

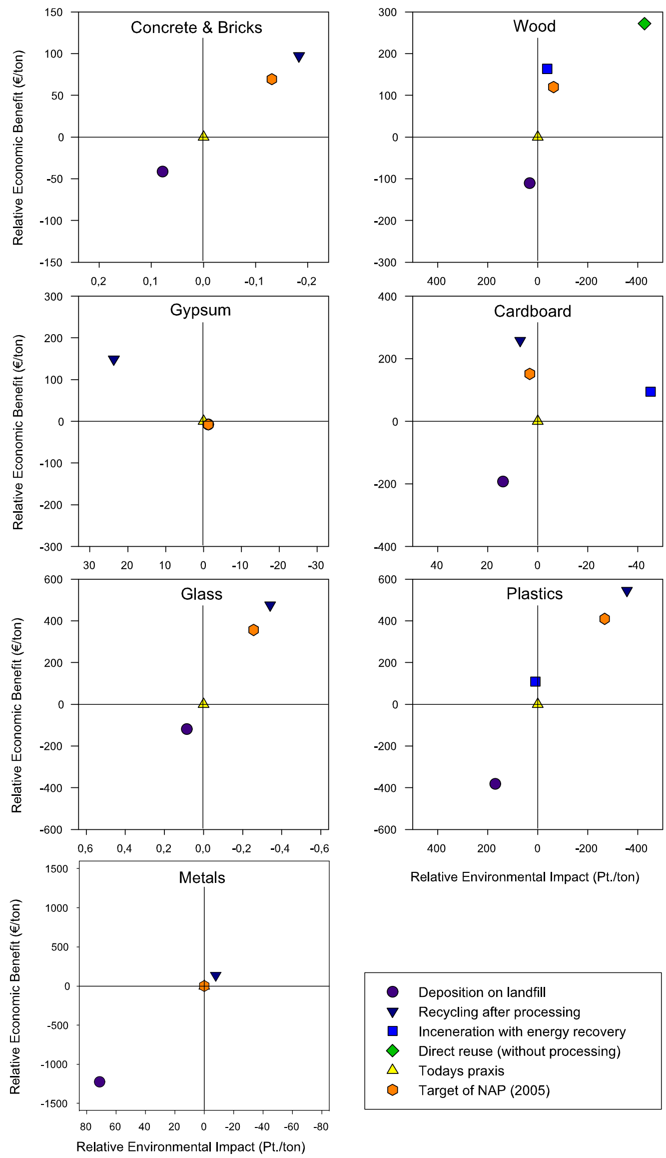


Figure 4.9: Relative change in eco-efficiency for the different end-of-life treatments for selected fractions of C&D waste in Trondheim, Norway. Be aware of the large variations of scale between the different waste fractions in the figure

4.4 Recycling and transport distances

The above eco-efficiency plots, Figure 4.9, show the relative difference for the waste handling alternatives with the existing infrastructure in Trondheim. Since transportation is a major issue with regard to environmental impact, calculations is done on the environmental impact for the different waste handling alternatives, and then converted to equivalent transport distances, Table 4.6. This excludes all existing infrastructure; for example, if one downcycles concrete and brick aggregate as a substitute for gravel, then only the making of the gravel is included. Thus the table shows how much longer recycled materials can be transported compared to virgin materials for recycling to be environmentally favorable.

Although Table 4.6 shows obvious and some interesting results, they should be used with caution and therefore only used as an indication of magnitude, for the following reasons;

- The calculations are based on European LCIA data, which are not always the best data to use.
- The negative long term environmental effects from landfill leachate are underestimated, or not accounted for.
- The numbers are not weighted, and there are differences in the role of transportation between cities and rural areas.
- All energy recovery substitutes oil as fuel. Oil is of course not the only fuel alternative being used in practise.

It is however interesting to see how big impact fossil fuel and organic compounds have on the environmental performance of the different materials, and hence the difference between renewable and non-renewable resources. Table 4.6 shows the difference in environmental impact for the different waste handling options for selected fractions of C&D waste, converted to transport distances. Thus the distances given in Table 4.6 are the increase in transport distances that can be tolerated for an waste handling option to be environmental friendly versus an alternative waste handling option.

Table 4.6: Tolerable transport distances in recycling systems for some selected waste fractions

		C&B		Wood		Gypsum		Cardboard			Plastic			Glass	
		LF[a]	DC	LF	I.ER	LF	RC	LF	I.ER	RC	LF	I.ER	RC	LF	RC
C& B	LF[a]		15												
	DC	-15													
Wood	LF				2823										
	I.ER			-2823											
Gypsum	LF						5								
	RC					-5									
Cardboard	LF								5053	233					
	I.ER							-5053		-4830					
	RC							-233	4830						
Plastics	LF											10972	36404		
	I.ER										-10972		25452		
	RC										-36404	-25452			
Glass	LF														149
	RC													-149	

[a] With landfill, a safe deposition in a controlled manner is assumed, i.e. in a landscaping project or as sound barriers.

Chapter 5

Analysis and synthesis

The results in chapter 4 have shown that the recycling systems that were established have achieved good recycling rates, but still have an unfulfilled potential for optimization. This part of the thesis analyzes the events that led to the construction of these systems, and their possible future optimization. While doing so, I will also look at the trade-off's that are required, and some tools and models that can be used to illuminate and highlight the issues in a process of qualified decision making.

5.1 Actor network, policies and organizational learning

The study has shown that for both the Copenhagen and the Oslo case, the recycling system for C&D waste has originated from an extended actor network. Although there are three important differences between the two systems; time, origin and organization. Common for the two cases is that the actor network identified deposition of C&D waste as an environmental problem, and proposed solutions to solve this problem.

Both from systems thinking and an Industrial Ecology perspective the Danish approach to reduce toxic pollutants entering the aquifer had a promising system optimization of the resource flow in focus. The Danish authorities and other stakeholders recognized the decline in water quality and were able to identify the interrelationship between the practise of waste deposition and a following leakage of toxic pollutants into the ground. The authorities took steps beyond prevention and management of singular material chains. Never-the-less, the systems approach has not been optimally utilized due to a number of barriers in the policy design and implementation process.

The Norwegian system originated over a decade later, and drew upon Danish experience. A similar approach, but more incremental, was taken in establishing a Norwegian recycling system for C&D waste.

5.1.1 The actor network and organizational learning

Both Danish and Norwegian authorities recognized the importance of educating their personnel on the issues, but they used different approaches to achieve their goals. Both used political power to create an actor network, or organization, with new routines, processes and institutions.

Through the introduction of the Danish Environmental Protection Act and other regulatory means, the Danish government used political power in order to force "a vision" and "a mental model" onto the nodes in the network (stakeholders). Through this, they made structures to ensure team learning (KGB and GRU) and personal mastery. They also made the actors believe in the new system, and that the new actions was necessary for a sustainable future. Figure 5.1 shows a schematic view of this process.

To deal with the pollution of the aquifer, the Danish authorities had to eliminate the source of pollution, which originated in landfills. To achieve this, one had to deal with the waste in a different manner than before. New structures were built, and as a consequence the new recycling system for C&D-waste was established.

The construction of the recycling system was the direct result of a learning process and knowledge creation from systems thinking and an Industrial Ecology way of thinking regarding eco-systems and resource utilization. Figure 5.2 shows a framework that clarified the situation about the pollution of the Danish aquifers, and the need for alternatives.

It is worth noting that at the early stage of the process, the separate waste stream for C&D waste was a practical and organizational solution, it was not

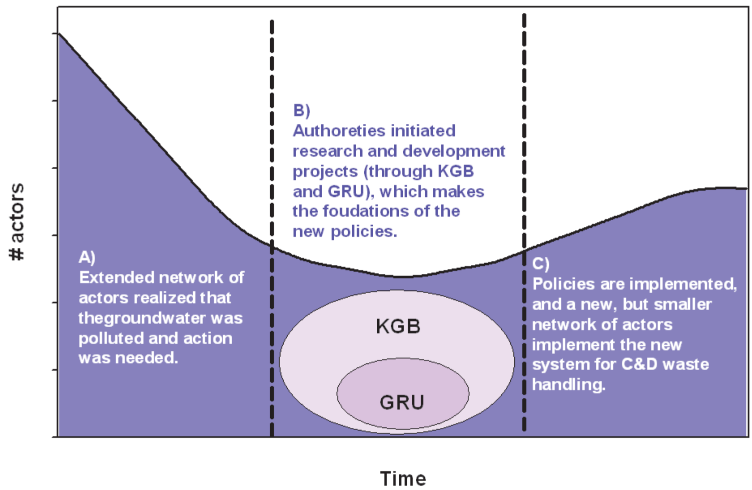


Figure 5.1: Development of the extended Network of Actors in the Copenhagen case, A) realizing that the groundwater was polluted and that action was needed, B) authorities initiated research and development projects (through KGB and GRU), which makes the foundation of the new policies, and C) policies was implemented, and a new, but smaller Network of Actors implement the new system for C&D waste handling.

made from environmental concerns for the content of the C&D waste which at that time was thought of as mostly inert and non toxic.

The Norwegian system had a different origin. More than a decade later than the Danes, Norwegian authorities started to worry about possible pollution from legal and illegal landfills of C&D and other types of waste, as well as the ever increasing amounts of waste production. At the same time the Danish system was up and running, and reported high recycling rates.

The Norwegian government, drawing on previous positive experiences in cooperation with industry on environmental issues, started discussing the problems with the AEC industry. This resulted in the authorities adjusting their environmental protection act and other laws and regulations. Soon after Oslo started as a pilot case for a future Norwegian recycling system [Renholdsverket Oslo

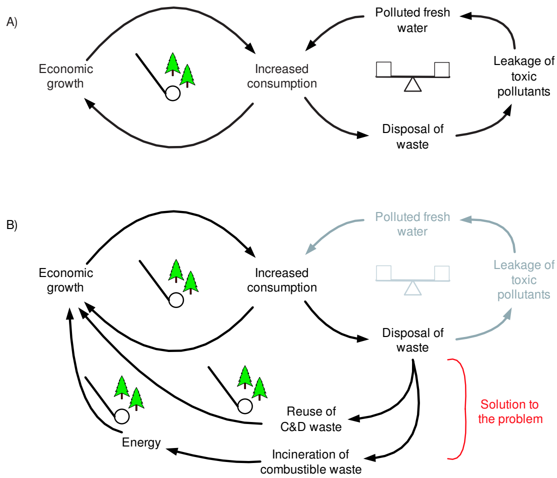


Figure 5.2: A causal loop diagram showing the solution to the Danish pollution problem.The figure shows the system development from the initial systems approach
a) to the identification of structures supporting the problem, and finally
b) the identification of a way to solve the problem.

Kommune, 1997]. At the same time the AEC-industry launched the "Økobygg programme" and the "National Action Plan" working group. Both these were based on the Danish GRU and KGB. There are however three important differences. First, while the Danes started with the whole country, Norway started with one big region only (Oslo). Second, while the Danes initially focused on how to use recycled C&D waste, the Norwegian programme investigated in more detail the content, environmental performance, and technical performance of the various material fractions and their possible reuse. And third, while the Danish authorities instructed the industry what to do, the Norwegian authorities invited industry to put forward solutions in order to meet the agreed upon target for waste reduction.

The result of the Norwegian approach, is a pragmatic and process oriented (read economic) driven recycling system, that will deliver results within a relatively short period of time. This approach, however, does not necessarily contain any efforts for a systematic system optimization with respect to reducing the total environmental impact. The targets of less than 30% deposition in landfills can be met by simply downcycling the concrete and brick fraction to aggregate and by using the wood fraction for energy recovery in the four most populated cities (Oslo, Bergen, Trondheim and Stavanger). These are processes that are sound economically given the new policies, when the infrastructure is in place, and therefore viable resource economy for affected stakeholders, but not necessary the most environmental friendly alternative.

There is however reason to believe that this will change, as the proposed ban on deposition of organic waste will be implemented from 2005, with full effect from 2011 [Statistics Norway, 2003*b*].

5.1.2 Policies

When it comes to policy implementation, both Norwegian and Danish authorities have used a classical command and control approach, based on taxation and structures of control. Both systems follow the general idea that the enterprize that produces more than a given amount of waste, or involves more than a given area of building(s), should apply to the authorities for permission prior to initialization. The authorities can then approve on the proposed plan, or demand changes.

It is where we find the main differences between the policies. While the authorities in Copenhagen have the power to decide what to do and where to direct the generated waste, the authorities in Oslo are only empowered to say what to do with the waste. Both authorities are empowered with the possibility to apply sanctions if the approved waste handling plan is not followed. It is the latter that is of importance to get the system working, this is discussed further below.

We have seen that recycling has increased with the tax rate, Figure 4.2. The reason for this is in the setup of the policies and the supporting structures. The most important element of these structures, are the laws and regulations with the associated sanctions. This setup follows what is known as “a team game”, a non-competitive game, in economic (game) theory [Binmore, 1992]. The mechanism of this is best illustrated through a game, with two players (the authority and the waste producer), and their possible strategies;

Authorities The authorities have the following two strategies with regard to the actual policy:

I) Control and enforcement. That is they create and maintain a structure that can both control the system, and has the power to enforce sanction to players that seeks to avoid taxation. The sanctions should be set at a level where it covers player one's expenses of the new structures, and at a level that really hurts player two if player two tries to "cheat".

II) No control and enforcement. No means to get the other player to do as planned.

Waste producer The waste producer has the corresponding two strategies:

I) Follow the regulations, which will give the same cost whether the authorities are following their strategy I or II.

II) Trying to cheat. This strategy will give a return instead of cost if the authorities do not discover it and enforce sanctions. However, if the authorities discover an attempt to cheat and enforce sanctions, there will be a big loss.

These strategies can be illustrated in a strategic form, Figure 5.3.

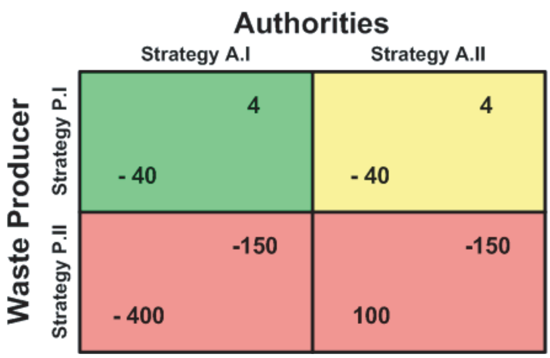


Figure 5.3: A strategic form of the non-competitive "team game" of waste tax, where the waste producers expected revenue for each option is shown in the lower left corner of each square, and the authorities expected revenue for each option is shown in the upper right corner of each square.

The numbers given are expected revenue or cost for the various actions, Table 5.1;

Table 5.1: Economic values in the non-competitive "team game" of waste tax

Actor	Action	Revenue/cost
Authorities	Revues from legal waste handling	4.- €
Waste producer	Average gate fee at material company	- 40.- €
Authorities	Cost of cleaning up after illegal waste dumping	- 150.- €
Waste producer	Total savings, if cheating and getting away with it	100.- €
Waste producer	Total cost of compulsory fine and waste tax, if caught cheating	- 400.- €

As the figure shows, in this example there is a huge incitement for both players to cooperate, and thus settle for the Nash equilibrium [1]in the upper left square, which will happen if both player use the strategy I. But this will only happen if this is then the best strategy for both players, that is when the probability that player II (when applying strategy II) is getting caught enough times so that the expenses are bigger than if strategy I is followed (in this example the waste producer must be caught more than every 4th time). So, to place a successful policy, there must be structures of surveillance and enforcement of sanctions,as in the Oslo case.

Another interesting feature of the tax recycling relationship in Copenhagen, is that the tax has increased several times after the recycling target has been reached. This may lead to speculations of whether this is to cover the actual costs, or if it is a way for the government to increase income.

Thus it is not the tax in itself that is interesting as a policy, but the possible enforcement of sanctions. But when the policy is working, tax differentiation can be used to push development in the wanted direction. An example of this, is the separation of waste tax in Denmark, depending on what end-of-life treatment the waste was delivered (incineration, incineration with energy recovery or landfill).

[1] Nash equilibrium arises when each players strategy response is a best reply to the strategy choices of the other players [Binmore, 1992]

Behavior pre-request

At first glance it may seem that the systems is functioning quite well, and with regards to the percentage of waste recycled it is. Yet detailed literature studies and interviews of stakeholders suggest that the result of the strong policy actions from the municipalities in Copenhagen and elsewhere in Denmark lead the system into several “lock-ins” and a following sub-optimization of the overall measure of effectiveness (MoE) of the waste recovery system.

If we look closer at Figure 4.1, there is especially “lock-in” that we would like to stress. By following the quality control and communication pathways, it becomes clear that as long as the stakeholders perform within the given regulation, the government will not exert power. This characteristic of the organization or network makes the network work by command and control, but at the same time stimulates the nodes to only perform “good enough”, in order to maximize their own benefits within the network. It is apparent that the same rationale that could be used by the government in the argument of optimizing the network, could be used by the individual nodes in their optimization, on the contrary turns out to be a sub optimization of the overall system.

As a result, the individual nodes reenter a single-loop mode of operations with the corresponding sub-optimizing of overall performance. It may also seem like the organizational learning process started as a “double loop”, but ended as a “singe loop” [Argyris and Schön, 1978], and further enhancements are blocked by routines [Trist and Bamforth, 1951]. The forced establishment of new routines within a command and control framework creates new structures and blocks the tacit knowledge from being mobilized [Baumard, 1999]. This will in turn hinder a shift back to double-loop learning or to enter the four modes of conversions and thus to enter the spiral of organizational knowledge creation.

The second lock-in, is the satisfaction of a well working system. There are little or no incitements to improve the Danish system. Since the only measure of effectiveness (MoE) used is percentage of waste recycled, one fails to ask whether the system is performing good or not. The system and its stakeholders then go from a learning II type organization (where one tries to improve performance) back to a learning I type organization (where focus is on maintaining positions) [Senge, 1990; Argyris and Schön, 1996]. This last lock-in has also a second driving force: economy. According to economic theory, all players within a functioning market will strive to maximize their own position within the system, which is believed to be a equilibrium [Nelson and Winter, 1982]. This means that within the given economic framework in Copenhagen, the participating firms will maximize their own profit. Profit maximizing within this type of industry is equivalent to "just good enough" - in terms of environmental performance [Bohne and Mathiassen, 2003; Bohne and Opoku, 2003].

Although the Norwegian system has tried to avoid such lock-ins by demanding a high degree of source separation and by letting the actors themselves decide where to deliver the waste, we see that the ongoing merging of companies within the industry, especially in the Oslo region, has a similar effect. An entrepreneur that is part of a diverse corporation, delivers as much of the waste it produces as possible to the material company associated with this corporation, although this leads to longer transport distances.

5.1.3 About "lock-ins"

Shifting focus from quantitative recovery to qualitative recovery of materials is not regarded as an foreseen obstacle. The practice was adjusted based on experience, showing flexibility in the system rather than lock-in. The lack of sufficient data collection, on the other hand, is rather an indicator of a system default. For the field of Industrial Ecology the latter indicates an interest for further improvement of information provision.

In addition to the learning failure, there are two more lock-ins that effect the Danish system in different ways. The first is the local practice of using civil law contracts between municipalities and certified actors, in this case the transporters, and the strict practice of which material companies that are certified to receive the C&D waste. This leads to suboptimal use of transport, and thus higher CO_2-emissions than necessary. Since each municipality in Denmark has its own rules and regulations, some transport companies have to be up to date on as much as 40 different rules and regulations on waste transport alone. this is, as I see it, the second lock-in related to transport

Implications of data supply

The Danish and Norwegian C&D wasterecycling systems (and most other recycling systems) lack information on environmental performance in a system-wide context. Although some of these data exist, they are not collected systematically and are not used for analytic purposes. I have proposed that there should be at least three different measures of effectiveness when monitoring recycling systems; percentage waste recycled, cost and environmental impact. If such measures of indicators had existed, they could have been used in a simplified quantitative models. Below is shown an example of how such a model could be used to follow changes in emissions, for example the change in aggregated CO_2-emissions, to optimize the system with respect to an increased environmental performance, Figure 5.4:

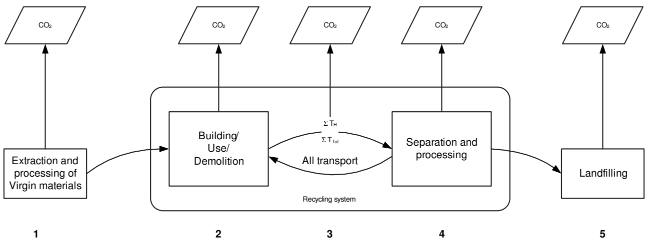


Figure 5.4: A simplified model for evaluating environmental performance (CO_2-emissions) in a C&D waste recycling systems.

It is easier to identify where changes in CO_2-emissions have occurred, and where new improvements can be made, through the simplified model in Figure 5.4. Most of the recycling, >90 %, is actually downcycling of brick and concrete by crushing. CO_2-emissions from this process roughly equal the emissions from extraction and processing of virgin materials. Since the materials are downcycled, there is no "change" in CO_2-emissions from the Building/Use/Demolition phase. Hence this leaves two actions where emissions are reduced, namely transport and landfill.

It is however important to note that CO_2 only serves as an example in this model, and that such models should be made for all relevant emissions according to decisions made by key stakeholders and the analyst. In this thesis, environmental impact is calculated by the use of LCA methodology and the Eco-indicator99 index.

While the Copenhagen system also focused on transport, this has not been the case for Oslo. In Copenhagen this has been achieved mostly by the geographical localization, and by the fact that the material company is selling virgin materials in addition to recycled aggregate. Numbers show that both lorry transport and CO_2-emissions from landfills have been reduced with 80% [Nejrup, 1999] in

Copenhagen. The challenge is now to improve the system by focusing recycling instead of downcycling, and thereby reducing emissions from both extraction and the Building/Use/Demolition phase of the material cycle.

For the Oslo system there is an unknown potential for CO_2-reduction due to reduction of transport within the system. This should be investigated in addition to the ever present challenge of moving from downcycling and energy recovery, to more recycling and reuse when these options are preferable with regard to environmental performance.

Thus I have shown that the construction of the recycling system for C&D waste in Copenhagen was a success due to the following:

- The actor network was created with representatives from all stakeholders.
- The authorities established the system by the use of political power, by command and control. The most important was the introduction of regulations of what to do, and the enforcement of sanctions.
- The authorities established structures that enabled stakeholders to perform as told.
- Learning and knowledge transfer was facilitated by the establishment of several development projects and the establishment of bodies of knowledge and information. Thus:

  a) the actors knew what to do,

  b) were motivated to do it, and

  c) were given the ability to do it.
- The process was initiated and supported by key legislators and major stakeholders
- The process was a one way street, with an all-party political agreement with an "everlasting" time horizon.

The Oslo system was build on the same template, and has increased its performance substantially over the last two years. My findings suggest that the main reason for this, in addition to the findings for Copenhagen, is threefold:

i) The time horizon of the policy changed. The regulation has moved from a temporary to a permanent structure

ii) The body of control and sanctions started to function, with the will and power to enforce sanctions

iii) The economic incitements for the actors in the network.

5.2 Waste projection

Public infrastructure is expensive to build and maintain, and should therefore be built for a long service time. Thus, in the case of infrastructure for waste handling and recycling, it is necessary to have good projections for the future waste production to build structures that are capable of meeting future demands. Good projections also enable system owners to optimize both the economic and the environmental performance of the future recycling systems.

There are almost no historic data on waste production from the AEC industry, and the data that has been estimated for the last decade is of poor quality [Statistics Norway, 1998, 2002]. To my knowledge there has only been two attempts to project the future production of C&D waste for Norway [Bruvoll and Ibenholdt, 1999; Senneset, 2004]; Bruvoll and Ibenholdt [1999] offer a statistic forecast based on previous waste production, Senneset [2004] is working based on economic forecasting. Both of them predict a steady increase in C&D waste, Bruvoll and Ibenholdt predicts 12% by 2010, Senneset 21%. These results are lower than our predictions, Figure 4.5, which show a higher increase in waste production. For a system owner it is of great interest to obtain good data on future waste projections prior to investment in waste handling infrastructure.

I believe waste projections can not be made as a statistical forecast based on previous waste statistics, and I have three arguments for this view. First, there are no reliable statistics to forecast from. The one statistical forecast performed assumes that the C&D waste is in proportion to the economic growth and to some extent "follows" the municipal waste production, which is disputable. Second, the material composition of the building stock is changing rapidly [Brunner and Stämpfli, 1993], so also the future waste composition. Third, and this is my main objection, is that we are dealing with products (buildings and furnishing) with a long lifetime (60 to 100 years for structural components, 20-30 for most furnishing). This means that after the expected service time, it is a fair assumption that the building is renovated or demolished. Also the demand for housing per capita and the demography is changing, and we are constantly increasing our demand for housing per capita. Thus projection of future C&D waste production should be based both on a stock and flow model, combined with previous economic cycles and a demographic model. A problem for these kind of calculations is again that there is little statistics on material flows to build upon. But there is work in progress to abate this.

Our waste projections are partly following such an approach based on what statistics that are available (see Section 3.3.1 for details), and predict a higher waste production in the years to come. The main reason for this difference is that we expect a high output flow from building stock that was erected in the post WWII period (1950-60), during the coming years, something that does not seem to be accounted for in the earlier forecasts of C&D waste, neither with regard to the amount nor the material composition of the future C&D waste.

Waste predictions make an important fundament for qualified decision processes for future recycling systems together with trade-off analysis based on environmental impact and costs. Eco-efficiency is a highly effective and powerful method for making such trade-off analysis.

5.3 Eco-efficiency

I have used the municipality of Trondheim as the case for my calculations for system optimization based on the eco-efficiency model. The results shown in Figure 4.6, 4.7, 4.8 and 4.9, reveal some interesting issues. The main finding is that there is no automatic link between the amount of waste in any given fraction, and the corresponding cost or environmental impact. Thus in order to optimize a recycling system, it is of great importance to evaluate all available information. I will discuss the details below.

As the figures show, the concrete and brick fraction is dominating, by far, the material composition of the C&D waste (Figure 4.6). This is also reflected in the system costs Figure 4.7A, while its corresponding environmental impact is less obvious (Figure 4.8A). If we look at Figure 4.8A alone, we would suggest that the wood is the fraction worth focusing on from an environmental point of view.

As can be seen from Figure 4.8C, the picture is somewhat different from the picture in Figure 4.8A. From Figure 4.8C; wood and to some extent plastics, are the only fractions worth focusing on from an environmental point of view. This also corresponds well with how developed the recycling systems for these fractions are. These result are also supporting the upcoming ban on deposition on organic waste.

Monte Carlo simulations have shown that the standard deviations for the calculations are ≤ 10 %, which is very good given the input sources of data. The results are therefore believed to give a representative view of the eco-efficiency in Trondheim, given that the trend for waste production in Figure 4.5 are correct. Here it should be noted that the results above will not necessarily be valid for other cities with different built environment structures and transport distances for the waste materials.

5.3.1 Recycling of renewable versus non-renewable materials

Let us first take a look at the results from Figure 4.6, 4.7 and 4.8. Although the concrete and brick fraction is dominating waste production and the cost of waste handling, it does not have a corresponding high impact on the environment. A second interesting finding is that the figures show that wood has the largest environmental impact of all fractions, and it is also the fraction that has the largest possibilities for further environmental savings. Third, there is a general trend that for the waste fractions where a recycling system is up and running, the costs for recycling are lower and the environmental impact relative to the current practice has a negative value. There is however one important exception to this - the concrete and brick fraction. This is most likely due to the fact that this recycling represents crushing these materials into aggregate that is used as a substitute for gravel. Hence, the materials are downcycled, and most of the energy once put into the materials is lost.

For the same reason there is an interesting potential for plastics, if one manages to shift from energy recovery to recycling.

It is worth mentioning here that in theory it is possible to increase environmental savings even more for the wood fractions, if wood is reused instead of being sent to recycling or energy recovering. Such a shift may also be more profitable for stakeholders. However, this is difficult due to altered construction practices, and the required handling of materials for reuse. If such a system should be implemented at a large scale, the costs would also increase beyond what we have used in our calculations, and as a result the corresponding eco-efficiency would decrease.

5.3.2 Eco-efficiency and the recycling targets of NAP 2005

Not surprisingly, we find that all of the targets of the National Action Plan are economically favorable, which is natural since the action plan and the policies are closely linked. However, I do not find evidence for that the suggestion in the National Action Plan is economic and process oriented, not always optimized with regard to minimizing the environmental impact, especially with regard to materials of renewable origin.

It is also important to point out that the calculations are made on best available data, and do not cover all feasible waste handling options. This means that the results serve as an example of how to perform a trade-off analysis for system optimization, and should be used and referred to as such.

This is an especially important remark in concern with the suggested relationships between waste handling options and transport distances given in Table 4.6. But again, these are the type of calculations that should be made in order to create a viable recycling system for C&D waste in Norway, a system that incorporates the environmental impact from transport into the waste planning scenarios. These results also support the upcoming ban on deposition of organic waste.

Thus, eco-efficiency proves to be a powerful analytic tool for more qualified decision making within waste management.

The findings suggest that more qualified decisions have to be made, in order to make future waste management systems sustainable, and in accordance with the precautionary principle. Todays efforts are too much economically driven and process oriented, and do not foresee the changing volumes or composition of C&D waste.

Dynamic modeling and eco-efficiency calculations will provide the necessary inputs for more qualified decisions and trade-off analysis. This will in turn allow legislators and regulators to make more targeted and effective policies.

Chapter 6

Conclusion and recommendations

In this thesis I have shown that recycling of C&D waste is of great importance for society. I have also shown that the targets of the National Action Plan for recycling of C&D waste, less than 30% to deposition within 2005, is within reach (but somewhat delayed).

I have also shown that the suggestions in the National Action Plan and the corresponding policies are eco-effective, but I have questioned the guiding target of the policy. From my results it seems some of the targets of the action plan are set with focus on existing process technology and economics, not with regard to future environmental impact.

The environmental impact of recycling system for C&D waste is demonstrated to be very transport dependent. Thus there is a great potential for a further decrease in total environmental impact through an optimization of the logistics within the recycling system.

The study has also shown that there is a great need to focus on future waste composition in the design of recycling systems for C&D waste, but such waste projections are difficult due to poor statistics for both the composition of the building stock and historic waste production of C&D waste.

Through policy analysis I have shown that the present policies are working as planned. The policies are working through the existence of structures, that is, through bodies of information and control, and the power exercised through sanctions (compulsory fines). I have also demonstrated the need of constantly monitoring system performance by key indicators, to follow system performance and system learning, and thus enable continuous policy changes if necessary.

6.1 Conclusion

There is a need for municipalities and governments to make more qualified decisions on environmental issues, with regard to the long term management of waste handling systems and natural resources.

I have shown that long term models combined with environmental and economic information can make a powerful tool for analysis. Total environmental impact and eco-efficiency calculations can be used by system owners and stakeholders to evaluate their options, their system performance, and to decide which waste fractions to focus on, and what end-of-life alternatives to give priority.

Of special interest to waste handling systems is the possible effect of different policies and alternative end-of-life solutions within each policy. Important to decision makers will be how different system alternatives meet given policy targets. Our model is able to simulate such issues.

However, even though I have demonstrated that recycling and reuse often are the most eco-efficient choices in most systems, there are many examples where this is not the case. I assume that this is often due to the fact that other economic processes overrun the environmental issues in waste handling decisions. Time penalties for delays in construction or demolition projects is an obvious example of this. These issues need more investigations.

6.2 Recommendations

Based on these findings, I will propose the following recommendations:

There are huge savings to be made by optimizing recycling systems for C&D waste, particulary related to transportation and total environmental impact.

Municipalities should build up a structure of competence, which can act both as a body of information and power. This body should monitor system performance through key indicators. I have shown that knowledge transfer is of vital importance for system performance, and such a municipal body should be active towards system actors in this regard. With respect to environmental performance, studies of logistics within a future recycling system, has the potential of increasing system performance considerably.

My reflection on dynamic modeling and eco-efficiency studies is that the approach looks very promising. This way of presenting specific and aggregated results on eco-efficiency in C&D waste systems is intuitive and attractive with respect to communication towards stakeholders as a basis for decision making. However, there are two aspects that need improvement:

1. One needs to refine the dynamic model to estimate future waste volumes more precisely. This model should be based on detailed data of the building stock, including its material composition and lifetime distribution. This would give much more robust projections for waste generation.
2. We also need more precise data on important processes in the C&D waste system, including environmental and economic parameters. Only then it would be possible to offer models that would be meaningful to the industry in decision making.

Thus, by using dynamic modeling and eco-efficiency as the guiding scientific principle for makeing qualified waste management decisions, authorities and industry can achieve significant savings both with regard to future investments in infrastructure (for waste handling) and in environmental impact from the waste handling system.

Such models will also be of high value for the forest and mineral industry in their planning for future demands.

In turn, these finding should become a strong incentive for legislators to focus more on what materials that should be allowed as input into the building stock, whic later becomes the source of future C&D waste.

The AEC-industry is so important in term of its waste amounts and total environmental impact, that such research work should be given high priority.

Chapter 7

Suggested future work

Concluding this thesis, a few suggestions for future work are provided. The topics selected here are, in my view, the three main problem areas that have to be solved to make the scientific foundation for further development and optimization of recycling systems for C&D waste. It is my hope that such work may be conducted in the future.

1. The quality of statistical data on the stock of existing built infrastructure, both with regard to age and material composition
2. We need a better understanding of the dynamics in the building stock, that is the lifetime of structural and furbishing of buildings
3. We need better data on production and recycling processes, both on economy and environmental impact.

Thus, what is needed is to quantify and categorize the building stock. Earlier work has shown that these data are of poor quality, if not unavailable for Norway [Bergsdal et al., 2004; Bohne, Brattebø and Bergsdal, 2004*b*]. There are, however, some data from Germany that can be used as a starting point for our quantifications [Kohler and Hassler, 2002; Gruhler et al., 2002]. On the basis of the existing Norwegian GAB register, which holds records of buildings, we propose to expand this information with information on area (m^2), renovation/refurbish intervals, expansions, demolition and material composition of buildings in all categories and areas. This information may then be linked together with the dynamic information.

To do so, one need to investigate typical buildings within each time period (if still standing), look at house drawings or environmental impact reports affiliating the application of demolition/renovation of buildings. Interviews with elder craftsmen and engineers would be required. There are also waste statements to investigate. A starting point for such empirical data from outside Norway, will be the German data [Kohler and Hassler, 2002; Gruhler et al., 2002], and data from the EU project INVESTIMMO [2004] although they have focused on maintenance. This will provide data with better resolution than what we possess today. The data should be stored and made available in a useful format through a database.

We also need better environmental data for both construction materials and C&D-waste, including improved LCI data for these processes. Today, most LCA tools, such as SIMA PRO, have European data. However, many building and construction materials are produced locally in Norway, with a Norwegian energy mix, and different transportation patterns. Therefore there is a need to investigate and locate, where and how materials are produced, transport routes, including storage, handling, and sales points. Following each of these activities we need to find the corresponding economic values and environmental impacts. Thus I propose to develop new regional Life-Cycle-Cost and Life-Cycle-Inventory databases for Norway. This should also be done for the different waste handling processes. Such data is of crucial importance in order to make reliable calculations with regard to system optimization, as a basis for developing long term robust strategies in C&D waste systems.

Bibliography

Allenby, B. and Cooper, W. [1994], 'Understanding industrial ecology from a biological systems perspective', *Total Quality Environmental Management* (spring), 343–354.

Amlo, S., Trap Christensen, N. and Egebart, C. [2002], Identification of PCB and decontamination of PCB-containing buildings in Norway, *in* T. Pettersen, ed., 'Sustainable Building 2002'.

Argyris, C. and Schön, D. [1978], *Organizational Learning. The theory of action perspective*, Addison-Wesley Publishing Company.

Argyris, C. and Schön, D. [1996], *Organizational Learning II. Theory, methods and practice.*, Addison-Wesley Publishing Company.

Ashford, S. J. and Cummings, L. L. [1983], 'Feedback as an individual resource: Personal strategies of creating information', *Organizational Behavior and Human Performance* **32**, 370–398.

Avfallsforskriften [2004], 'FOR 2004-06-01 nr 930: Forskrift om gjenvinning og behandling av avfall (avfallsforskriften)'.

Ayres, R. [1993], 'Cowboys, cornucopians and long-run sustainability', *Ecological Economics* **8**(3), 189–207.

Bain, N. [1995], *Successful management*, MacMillan Pres Ltd.

Baumann, H. [2004], 'Environmental assessment of organizing: towards a framework for the study of organizational influence on environmental performance', *Progress in Industrial Ecology* **1**(1/2/3), 292–306.

Baumann, H. and Tillmann, A.-M. [2004], *The Hitch Hiker's Guide to LCA*, Studentlitteratur, Lund, Sweden.

Baumard, P. [1999], *Tacit knowledge in organizations*, Sage Publications, London.

Belevi, H. and Baccini, P. [1989], 'Long-term behavior of municipal solid waste landfills.', *Waste Manage Res* **7**, 43–59.

Berger, P. and Luckmann, T. [1966], *The social construction of reality*, The Penguin Press.

Bergsdal, H., Bohne, R. and Brattebø, H. [2004], Projection of waste amounts from the AEC-industry in Norway. Paper submitted Journal of Industrial Ecology.

Binmore, K. [1992], *Fun and Games. A text on Game Theory*, Houghton Mifflin.

Blanchard, S. and Fabrycky, W. [1990], *Systems engineering and analysis*, Prentice Hall, New Jersey.

Bohne, R. [2003], 'Why we need a better understanding of ecology and environmental dynamics in industrial ecology', Letter to the editor of journal of Industrial Ecology, No. 1. Vol 7.

Bohne, R., Bergsdal, H. and Brattebø, H. [2004], 'Eco-efficiency as a tool to optimize performance of a recycling system for C&D waste. The case of Trondheim, Norway', Poster at the Gordon Research Conference 2004, Oxford.

Bohne, R. and Brattebø, H. [2003], Eco-efficiency in Norwegian C&D waste recycling systems, *in* 'ILCEDES', Kuopio, Finland.

Bohne, R., Brattebø, H. and Bergsdal, H. [2004*a*], 'A consistent framework for the evaluation of strategies for recycling of C&D waste, based on Eco-efficiency'.

Bohne, R., Brattebø, H. and Bergsdal, H. [2004*b*], Evaluation of eco-efficiency based strategies for C&D waste recycling at the level of a city. Paper submitted the Journal of Industrial Ecology.

Bohne, R., Eik, A., Melum, F., Michelsen, O., Støren, S., Boks, C., Huisman, J. and Stevels, A. [2004], 'Dynamic Eco-efficiency definitions for environmental value chains', The 1st International Eco-Efficiency Conference; "Eco-Efficiency for Sustainability - Quantified methods for decision making".

Bohne, R. and Mathiassen, E. [2003], 'Construction of a recycling system, knowledge production and the distribution of power - the case of Copenhagen', Poster at Industrial Ecology for a Sustainable future.

Bohne, R. and Opoku, H. [2003], Recycling C&D waste in Copenhagen - An impact analysis, *in* 'Industrial Ecology for a sustainable future', Ann Arbor (MI), USA.

Bohne, R., Opoku, H. and Brattebø, H. [2004], Construction of a recycling system; an industrial ecology perspective on construction & demolition waste policy in Copenhagen. Submitted Journal of Industrial Ecology.

Brattebø, H. [1997], Industrial production and sustainability - a conseptual framework for making environmental improvements in industry, *in* 'European environmental science: towards sustainability', Open University, The Netherlands, pp. 191–274.

Bringezu, S. and Moriguchi, Y. [2002], Material flow analysis, *in* R. Ayres and L. Ayres, eds, 'A handbook of Industrial Ecology', Edward Elgar Publishing, chapter 8, pp. 79–90.

Brunner, P. and Stämpfli, D. [1993], 'Material balance of a construction waste sorting plant.', *Waste Manage Res* **11**, 27–48.

Brunson, N. [1989], *The Organization of Hypocrisy*, John Wiley & Sons.

Bruvoll, A. and Ibenholdt, K. [1999], Framskrivning av avfallsmengder og miljøbelastninger knyttet til sluttbehandling av avfall, Technical Report 1999/32, Statistics Norway.

BSCD [1993], Getting eco-efficient, Technical report, Report of the Business Council for Sustainable Development, First Antwerp Eco-Efficiency Workshop, Geneva.

Callon, M. [1989], Society in the making. The study of technology as a tool sociological analysis, *in* W. Bijker, T. Huges and T. Pinch, eds, 'The social construction of technological systems', The MIT Press, pp. 83–106.

Carson, R. [1962], *The silent spring*, Hugton Mifflin, Boston.

Clegg, S. [1990], *Frameworks of power*, Sage Publications, London.

Clift, R. [2004], 'What a waste', *MaterialsToday* **7**(2), 64.

Dahle, Ø. Brattebø, H., Sanderud, I., Bjotveit, I., Kronen, T., Østmo, T. and Røine, K. [2000], Øko-effektivitet og industriall utvikling. Fagpanelets anbefalinger, Nasjonal konferense 21st. - 22nd. mars 2000, NFR.

de Haes, H. [2002], Industrial ecology and life cycle assessment, *in* R. Ayres and L. Ayres, eds, 'Handbook of industrial ecology', Edward Elgar Publishing, chapter 12, pp. 138–148.

Deilmann, C., Müller, B., Banse, J., Effenberger, K.-H., Gruhler, K., Neumann, I. and Schiller, G. [2001], *Nachhaltige Entwicklung des Wohnungsbestandes in sächsischen Großund Mittelstädten: Entwicklungsszenarien ausgewählter Wohngebiete unter ressourcen- und nutzerorinetierten Aspekten*, NAWO, Dresden.

Döberl, G., Huber, R., Brunner, P., Eder, M., Pierrard, R., Shönbäck, W., Früwirth, W. and Hutterer, H. [2002], 'Long-term assessment of waste management options - a new, integrated and goal-oriented approach.', *Waste Manage Res* **20**, 311–327.

Dreyer, L., Niemann, A. and Hauschild, M. [2003], 'Comparison of three different LCIA methods: EDIP97, CML2001 and Eco-indicator 99', *J LCA* **8**(4), 191–200.

Ehrenfeld, J. and Chertow, M. [2002], Industrial symbiosis: the legacy of Kalundborg, *in* R. Ayres and L. Ayres, eds, 'A Handbook of Industrial Ecology', Edward Elgar Publishing, chapter 27, pp. 334–348.

Ehrenfeld, J. and Gertler, N. [1997], 'Industrial ecology in practise', *Journal of Industrial Ecology* **1**(1), 67–69.

Ekvall, T., Tillmann, A.-M. and Molander, S. [2001], 'Normative moral philosophy and methodology for life cycle assessment', Int. Workshop on Electricity Data for Life Cycle Inventories.

Flood, R. [1999], *Rethinking the fifth discipline. Learning within the unknowable*, Ruthledge, London.

Forrester, J. [1958], 'Industrial dynamics: A major breaktrough for decission makers', *Harward Business Review* **36**, 37–66.

Forurensningsloven [1981], 'Lov 1981-03-13 nr 06: Lov om vern mot forurensninger og om avfall (forurensningsloven)'.

Frosh, R. and Gallopoulos, N. [1989], ‘Strategies for manufacturing’, *Scientific American* **261**(3), 94–102. Special issue on ’Managing Planet Earth’.

GDRC [2004], ‘The Global Development Research Center web page’, http://www.gdrc.org/.

Giddens, A. [1981], *A contemporary critique of historical materialism*, MacMillan Pres Ltd, London.

Giddens, A. [1984], *The constitution of society*, Polity Press, Cambridge, Massachusetts.

Goedkoop, M. and Spriensma, R. [2001], The Eco-indicator 99. A damage oriented method for life cycle impact assessment. Methodology report, Technical Report 36A, PRé Consultants B.V.

Graedel, T. and Allenby, B. [1995], *Industrial Ecology*, Prentice Hall.

Graighill, A. and Powell, J. [1999], ‘A life cycle assessment and evaluation of construction and demolition waste’, CSERGE Working Paper WM99-03.

GRIP/Økobygg [2001], Nasjonal handlingsplan for bygg- og anleggsavfall, Technical report, GRIP/Økobygg, Oslo.

Gruhler, K., Böhm, R., Deilmann, C. and Schiller, G. [2002], ‘Stofflich-energetische Gebäudesteckbriefe - Vergleiche und Hochrechnungen fuer Bebauungsstrukturen’, IÖR-Schriften Band 38, Dresden.

Harte, J. [2001], ‘Roundtable discussion on ’Business as a living system: the value of industrial ecology’, comments by John Harte’, *California Management Review* pp. 16–25.

Heap, K. [1998], *Gruppemetoder for sosial og helsearbeider*, Universitetsforlaget AS, Oslo.

Heie, A. and Brattebø, H. [2002], ‘En innføring i hindring, minimering og håndtering av avfall’, Institutt for vassbygging, NTNU.

Holling, C. S. [2001], ‘Understanding the complexity of economic, ecological, and social systems’, *Ecosystems* (4), 390–405.

Huijbregts, M., Norris, G., Bretz, R., Ciroth, A., Maurice, B., Mahasenan, N., von Bahr, B. and Weidema, B. [2003], A framework for evaluating data uncertainty in life cycle inventories, *in* A. de Baufort-Langeveld, R. Bretz, R. Hishier, M. Huibregts, P. Jean, T. Tanner and G. van Hoof, eds, 'Code of life-cycle inventory practice', SETAC, pp. 113–121.

Huisman, J. [2003], The QWERTY/EE concept, PhD thesis, TU Delft, Delft.

INVESTIMMO [2004], 'ERBAD / BDAG / BEIG', CD-rom from the EU-programme INVESTIMMO. Published 2004 by the National observatory of Athens.

Kay, J. [2002], On complexity theory, exergy and industrial ecology: Some implications for construction ecology, *in* K. Sendzimir and J. Guy, eds, 'Construction Ecology, Nature as the Basis for Green Buildings', Spon Press, pp. 72–107.

Kay, J., Regier, H., Boyle, M. and Francis, G. [1999], 'An ecosystem approach for sustainability: addressing the challenge of complexity', *Futures* **31**, 721–742.

Keffer, C., Shimp, R. and Lehni, M. [1999], Eco-efficiency Indicators & Reporting, Technical report, WBCSD, Geneva.

Kohler, N. and Hassler, U. [2002], 'The building stock as a research object', *Building Research & Information* **30**(4), 226–236.

Korhonen, J. [2004], 'Theory of industrial ecology', *Progress in Industrial Ecology* **1**(1/2/3), 61–88.

Kotaji, S., Shuurmans, A. and Edwards, S. [2003], Life-cycle assessment in building and construction, State of the art report, SETAC.

Kvale, S. [1996], *Interviews. An Introduction to Qualitative Research Interviewing*, Sage Publications, London.

Kylefors, K., Andreas, L. and Lagerquist, A. [2003], 'A comparison of small-scale, pilot scale, and large-scale tests for predicting leaching behavior of landfilled wastes.', *Waste Management* **23**, 45–59.

Latour, B. [1987], *Science in action*, Harvard University Press, Cambridge, Massachusetts.

Latour, B. [1997], The trouble with actor-network theory, *in* F. Olsen, ed., 'Om aktør-netverksteori. Nogle få afklaringer og mere end nogle få forviklinger', Vol. 25 of *Danish philosophy journal*, pp. 47–64.

Lauritzen, E. [1996], *Genanvendelsesindsatsen i bygge- og anlægsektoren 1986-1995*, Orientering fra miljøstyrelsen nr. 10, Copenhagen.

Law, J. [1992], 'Notes on the theory of the actor-network: Ordering, strategy and heterogony', *Systems Practise* **5**(4).

Lifset, R. and Graedel, T. [2002], Industrial ecology: goals and definitions, *in* R. Ayres and L. Ayres, eds, 'A Handbook of Industrial Ecology', Edward Elgar Publishing, chapter 1, pp. 3–15.

Lovelock, J. E. [1979], *Gaia: a New Look at Life on Earth*, OUP, Oxford.

Meadows, D., Meadows, D., Randers, J. and Behrens, W. [1972], *The Limits to Growth: A report for the Club of Rome's Projects on the Predicament of Mankind*, Universe Books, New York.

Ministry of the Environment [1998], 'Opplysninger om bygg- og anleggsavfall - delegering av myndighet etter forurensingsloven'.

Mohr, L. [1995], *Impact Analysis for Program Evaluation*, Sage Publications.

Morgan, G. [1986], *Images of Organization*, Sage Publications, London.

Müller, D. [2005], Stock dynamics for forecasting material flows – A case study for housing in The Netherlands. Submitted to Ecological Economics.

Myhre, L. [1995], Some environmental and economic aspects of energy saving measures in houses, Technical report, Norwegian University of Science and Technology, Trondheim.

Næss, P. [2000], Bærekraftig utvikling, hva kan arealplanleggeren gjøre?, *in* H. Fiskaa and T. Skjeggedal, eds, 'Planlegging og bærekraftig utvikling', Tapir forlag, Trondheim.

Nejrup, J. [1999], 'Towards zero commercial and construction waste, the experience of Copenhagen', Lecture in London.

Nejrup, J. [2001], 'The Copenhagen waste strategy', Lecture in Krzyzowa, European Eco-Center.

Nelson, R, R. and Winter, S. [1982], *An evolutionary theory of economic change*, Belknap press of Harvard University Press.

Newmann, P. [1992], Sustainable urban structures - overcoming automobile dependence, *in* O. Jensen, ed., 'Bæredygtighet i den kommunale planlægning', Vol. 92 of *SBI-meddelelse*, SBI, pp. 29–44.

Norwegian Mapping Authority [2003], RiksGAB, instruction for registration of GAB-data, Technical report, Norwegian Mapping Authority, Hønefoss.

Oldenburg, K. and Geiser, K. [1997], 'Pollution prevention and/or industrial ecology', *J. Cleaner Prod.* **5**(1-2), 103–108.

Olivier, D., Kelliher, T. and Keegan, J. [1997], *Engineering complex systems with objects and models*, Mc Graw Hill, New York.

Opoku, H. [2002], Policy implications of industrial ecology conceptions, Technical report, Industrial Ecology Programme, NTNU. Working paper.

Ottesen, R. and Haugland, T. [2003], Trygg disponering av rive- og anleggsmasser, Technical report, Norwegian Pollution Control Authority (SFT).

Pinch, T. and Bijker, W. [1989], The sosial construction of facts and artifacts: Or how sociology of science and the sociology of technology might benefit from each other, *in* W. Bijker, T. Hughes and T. Pinch, eds, 'The sosial construction of technological systems'.

Plan- og byggningsetaten, Oslo kommune [2004], 'Retningslinjer for behandling av BA-avfall i Oslo kommune'.

Plan- og bygningslov [1985], 'Plan- og bygningslov.'.

PRé Consultants [2002], *SimaPro 5 User Manual*, PRé Consultants.

Regier, H. and Kay, J. [1996], 'An heuristic model of transformations of the aquatic ecosystems of the Great Lakes- St. Lawrence River Basin', *Journal of Aquatic Ecosystem Health* **5**, 3–21.

Renholdsverket Oslo Kommune [1997], 'Kommunal forskrift om styring av produksjonsavfall'.

RESIBA [2004], 'The RESIBA-project web-page', http://www.byggforsk.no/prosjekter/resiba/.

Rønningen [2000], Bygg- og anleggsavfall, Technical Report 8, Statistics Norway.

Sabatier, P. and Mazmanian, D. [1979], *The Implementation of Regulatory Policy*, Davis, California: Institute of Governmental Affairs.

Saling, P., Kicherer, A., Dittrich-Krämmer, B., Wittlinger, R., Zombik, W., Schmidt, I., Schrott, W. and Schimdt, S. [2002], 'Eco-efficiency Analysis by BASF: The Method', *J LCA* **7**(4), 203–218.

Schmidheiny, S. [2000], Eco-efficiency. Creating more value with less impact, Technical report, WBCSD.

Senge, P. [1990], *The fifth discipline*, Currency & Doublepay.

Senge, P., Kleiner, A., Roberts, C., Ross, R. and Smith, B. [1994], *The Fift Discipline Fieldbook*, Century, London.

Senneset, K. [2004], 'Prognosesenteret.no', Pers com.

Spiegelman, J. [2003], 'Beyond the food web', *Journal of Industrial Ecology* **7**(1), 17–23.

Sproles, N. [2000], 'Coming to grips with measures of effectiveness', *J Systems Engineering* **3**(1), 50–58.

Statistics Norway [1998], Construction and demolition waste, Technical report, Statistics Norway, Oslo.

Statistics Norway [2002], Construction and demolition waste, Technical report, Statistics Norway, Oslo.

Statistics Norway [2003*a*], Buildings statistics, Technical report, Statistics Norway, Oslo.

Statistics Norway [2003*b*], Rapport om SFTs høringsforslag til strategi for nedbrytbart avfall., Technical report, Statistics Norway.

Statistics Norway [2004], 'Cost index for road goods transport, march 2004', www.ssb.no.

Sterman, J. [1989], 'Modeling managerial behavior: Misperceptions of feedback in a dynamic decision making experiment', *Management Science* **35**, 321–339.

Stermann, J. [2000], *Business Dynamics.Systems Thinking and Modeling for a Complex World*, Mc Graw Hill.

Sturm, A. and Shaltegger, S. [1989], 'Ökologieinduzierte Entscheidungsinstrumente des Managements'.

Symonds, ARGUS, COWI and PRC Bouwcentrum [1999], Construction and demolition waste management practices, and the economic impact, Technical report, Report to DGI, European Commission.

Thompson, D. [2000], 'Asphalt jungle', *Times* (Special edition on Environment).

Trap Christensen, N., Egebart, C. and Krogh, H. [2002], Harmful substances in building waste in the future, inventory and prediction of twelve substances, *in* T. Pettersen, ed., 'Sustainable Building 2002'.

Trist, E. and Bamforth, K. [1951], 'Some consequences of the longwall method of coal getting', *Human Relations* **4**(1), 3–33.

UNCTAD [2003], A Manual for the Preparers and Users of Eco-efficiency Indicators, Technical report, UNCTAD.

Valde, S. [2004], 'Plan og byggningsetaten, pers.com'.

Verfaille, H. and Bidwell, R. [2000], Measuring eco-efficiency. A guide to reporting company performance, Technical report, WBCSD.

von Weizsäcker, E. and Jesinghaus, J. [1992], *Ecological Tax Reform*, Zed Books Ltd.

Wallace, R. A., King, J. L. and Sanders, G. P. [1986], *Biology the Science of Life*, 2nd edn, Scott, Foresman, and Company, Glenview.

Weidema, B. [2000], 'Avoiding co-product allocation in life-cycle assessment', *Journal of Industrial Ecology* **4**(3), 11–34.

Weidema, B. and Norris, G. [2002], Avoiding co-product allocation in the metals sector, *in* 'Presentation for the ICMM International Workshop on Life Cycle Assessment and Metals', Montreal, Canada.

White, R. [1994], Preface, *in* B. Allenby and D. Richards, eds, 'The greening of industrial ecosystems', National Academy Press, Washington, D.C., chapter Preface, pp. v–vi.

Whyte, A. [1985], 'Ecological approaches to urban systems, retrorespect and prospect', *Nature and Resources* **21**(1), 13–20.

Appendix A

Terminology and definitions

I have used the following terminology in the thesis;

Terminology

AEC ; Architecture, Engineering and Construction

BCSD ; Business Council for Sustainable Development

CFCs ; chlorofluorocarbons

C&D waste ; Construction and Demolition waste

DDT ; dichlorodiphenyltrichloroethane

FFBD ; Functional Flow Block Diagram (in systems engineering)

FSQ ; Final Storage Quality, term used to describe a landfill whose leachate is compatible with the environment.

GDP ; Gross Domestic Production

GRU ; "Genanvendelse, Rådgivning og Utvikling", which translates to: "Reuse, Counselling and Development".

HSE ; Health, Safety and Environment

HWS ; Heat, Water and Sanitation

ISO ; International Standard Organization

KGB ; "Koordineriingsgruppe for genbrug af BA-affald", which translates to: "Coordination group for the reuse of C&D-waste".

LCA ; life Cycle Assessment

LCIA ; Life Cycle Impact Assessment

LCI ; Life Cycle Inventory

MoE ; Measure of effectiveness

NAP (2005) ; The National Action Plan for recycling of C&D waste. Overall target of 70% recycling within 2005.

PAH ; Polycyclic aromatic hydrocarbons

PCBs ; Polychlorinated Biphenyls

SETAC ; The Society of Environmental Toxicology and Chemistry

SE ; Systems Engineering

SMEs ; Small- and Medium sized Enterprizes

UNCTAD ; United Nations Conference on Trade and Development

UN ; United Nations

WBCSD ; Word Business Council for Sustainable Development

WEEE ; Waste Electric and Electronic Equipment

I have used the following notations in this thesis;

Notations

κ = Costs (€/ton),

κ' = Relative Costs (€/ton),

Ψ = Annual total environmental impact (Pt.),

ψ = Environmental impact (Pt./ton),

Ψ^* = Aggregated total environmental impact (Pt.),

ψ' = Relative environmental impact (Pt./ton),

ε = eco-efficiency (€/Pt.),

act = activity,

AC = Area per capita,

A = Area (m^2) of buildings,

a = Processes of product system A,

bt = building type,

b = Processes of product system B.

$frac$ = composition of W

F = Amount of waste per m^2

f = county,

i = End-of-life treatment alternative,

j = Waste fraction,

$Pt.$ = Eco Point, environmental performance indicator after the Eco indicator 99 method.

r = Recycling ratio,

r_f = population growth within each county

t = Time (years),

W = Total waste amounts (tons)

w = Waste generation (tons),

€ = Euro (currency).

Appendix B

Interview Guide

The interview guide, which shows the information sought and the corresponding questions to the interviewees;

Table B.1: Interview Guide

Scientific questions	*Questions to interviewees*
Get access to available information	Why does your company participate in the recycling of C&D waste?
Define goal of action	Do you think that recycling of C&D waste is important?
Define measure of effectiveness	What did you expect to be the effect (for you) of starting with recycling of C&D waste
Make principal systems organizational model for actors, materials and communication	How do you measure if you reach your targets?
	What effect has the introduction of the recycling system for C&D waste had on your daily operations?
What sanctions are empowered	Can you make a drawing of the processes you participate in, and whom you are dealing and communicating with?
Understand enforcing and limiting loops	Can you sketch the recycling system (as you see it), the material flow, communication pathways (agreements, regulation, laws etc)?
Understand the learning processes (”single” or ”double” loops)	Identify the single most important action (from the authorities) that has contributed most in making the system work?
Have new routines been established (tacit versus expressed knowledge)	What effect has the waste tax had on your actions within the system? a)What would you do if the tax was increased? b)What would you do if the tax was lowered?
	What role has the transporters had in the system?
	Has the introduction of the recycling system affected the economy of your company?
	Are you satisfied with the system as it is today?
	Do you see something that should be improved in the system? a) What are you doing with this?

Appendix C

Paper 1

Bergsdal, H., Bohne, R. and Brattebø, H. [2004], Projection of waste amounts from the AEC-industry in Norway. Paper submitted Journal of Industrial Ecology.

Projection of Waste Amounts from the AEC-Industry in Norway

H. Bergsdal, R.A. Bohne* and H. Brattebø

Norwegian University of Science & Technology, Industrial Ecology Programme

Abstract

Present generation of C&D-waste from the AEC-industry in Norway is at nearly 950.000 tons per year. This paper establishes a procedure for projection of future waste amounts by estimating the activity level in the AEC-industry, determining specific waste generation factors related to this activity and finally calculating waste generation projections. Monte Carlo simulation is used in the calculations to account for uncertainties related to the input parameters, making the results more robust. The results show a significant increase in C&D-waste for the years to come, especially for the main fractions. These projections can be a valuable source of information to predict future need of treatment capacity, which waste fractions that will be the dominating ones and what will be the challenges in future waste handling systems. The method we have proposed is used for eco-efficiency modelling within C&D waste system evaluation in a following paper.

Key words: AEC-Industry, C&D-waste, Waste fractions, Projections

1 Introduction

In the recent years, more attention has been paid to waste from the Architecture, Engineering and Construction industry (AEC), both from national environmental authorities as well as authorities in the European Union. This calls for better knowledge concerning waste generation related to this industry (C&D-waste). C&D-waste amounts are considerable and represent a source causing stress on the environment. The share of waste to reuse and material recovery, as well as incineration with utilization of the energy produced, is today relatively low. It therefore exists a great potential for increasing the

* Corresponding author.
Email address: Rolf.Bohne@ntnu.no (R.A. Bohne).

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amounts to these treatment options, and decreasing the amounts to landfilling accordingly. Disposal of about 40% of C&D-waste in Norway are not known today. The purpose of this work is to estimate the amounts of waste from the AEC-industry in Norway, and to investigate the differences between various regions of the country. A model of waste generation is to be created to allow for changes in activity in the AEC-industry and for projections of waste amounts and their composition. Improved knowledge of the system and the trends forming the basis for the calculations can then easily be incorporated into the model to give more reliable results as more information become available. This paper is the first in a series of two, and models and results from this will be used as the basis for the second one, "Evaluating eco-efficiency based strategies for C&D waste recycling at the level of a city", focusing on eco-efficiency in the Norwegian AEC-industry.

2 Method

The procedure applied for making solid waste projections from the AEC-industry in this work, includes the following steps:

1st Step = Estimate the volume of activity of i) construction, ii) rehabilitation and iii) demolition of buildings.

2nd Step = Determine the specific waste generation factors for different fractions of solid waste related to each type of activity.

3rd Step = Calculate the overall waste generation projections, on the basis of defined development scenarios.

The volume of activity is related to size and characteristics of the building stock. The counties in Norway have very different characteristics regarding population patterns and therefore also number of buildings as well as the relative distribution of types of buildings. Some have densely populated areas and cities, while others consist mainly of areas with dispersed population. There is a diversity of building types, each with their own characteristics regarding size, way of construction and materials composition, which results in differences in waste amounts and the composition of these. Buildings are classified into 161 building types, which are found in Norwegian Mapping Authority (2003), and includes many different types of residential and non-residential buildings. Reliable data on numbers as well as sizes, in square meters, of buildings are available from Statistics Norway (2003a). The materials composition, and accordingly the amount of different waste components, for every building type is however not known. The building types are therefore classified and reduced to three main categories, according to size and the degree of furnishing, being;

residential buildings, larger buildings and other buildings, as shown in Table 1.

Table 1: Building categories

Category	*Buildings*	*Area*	*Furnishing*
Residential	Single houses, Chained houses etc.	Small	High
Larger	Office buildings, High houses etc.	Large	High
Other	Industrial-, Agricultural buildings etc.	Large	Low

Waste generation are related to these building categories, and to three different activities; i) construction of new buildings, ii) rehabilitation and iii) demolition. Waste generation factors are used for the calculation of waste amounts. The factors represent anticipated amount of waste per square meter, related to each of the three activities and for each of the building categories. Empirical data from the municipality of Oslo are the basis for the waste factors, where waste generation from projects of construction, rehabilitation and demolition are included. Numbers from 311 different projects are reported. The waste generation factors are further adjusted based on experiences from other projects in Norway as well as Finland, from Statistics Norway (1998). Combining these waste generation factors with information on how many buildings, and their average size, that are constructed, rehabilitated and demolished, waste amounts can be calculated. Before these factors are used, the amount of activity has to be found.

3 Activity

Area of buildings related to each activity are found in Statistics Norway (1998) for every county. To be able to make projections of future waste amounts, the activity data is linked to population and population growth. More specific projections for each activity, building category and waste fraction would be preferable, but no reliable trends or information exist for this, so the uncertainty would be very large if such assumptions were to be made. However, the model created during this work allows for including such information later if it becomes available. Statistics Norway has prepared population projections since the 1950s, and today they update their projections every third year. Population projections are therefore thought of as a reliable source of information, with a low degree of uncertainty. For the projections, scenarios with low, medium and high national growth are used, with different growth rates for each county. Equation 1 gives population projections (P) for each county

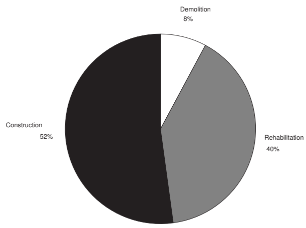

Fig. 1. Activity distribution in 1998 (Percent of activity, m2/year)

(f) and each year (t)

$$P_{f,t} = P_f^{2002} \cdot (1 + r_f)^t \quad \forall f, t \tag{1}$$

where r_f is the population growth rate within each county, from Statistics Norway (2002). Waste generation is based on the amount of square meters of buildings (A), so this area has to be related to population size for making projections concerning this. In Equation 2, area per capita (AC) is calculated for each county, activity (act), building type (bt) and year

$$AC_{f,act,bt,t} = A_{f,act,bt,t} \ / \ (P_{f,t}) \quad \forall f, act, bt, t \tag{2}$$

Summarizing for building types and counties, as shown in Equation 3, gives the total amount of square meters related to each activity for the country as a whole.

$$A_{act,t} = \sum_{f,bt} A_{f,act,bt,t} \quad \forall act, t \tag{3}$$

The relation between the activities is shown in Figure 1, displaying the differences in 1998.

Construction clearly has the highest level of activity, accounting for more than 50% of the total activity. Demolition is very low, with only 8%, and rehabilitation accounts for 40%. These figures vary when looking at different counties, as displayed in Table 2. The relation between the activities are based on numbers from 1998, and assumed to be the same for 2002, since no time series regarding this is available.

Table 2: Differences in activity between counties.

Activity	*Lowest*	*Highest*	*Average*
Construction	37%	64%	52%
Rehabilitation	30%	48%	40%
Demolition	4%	26%	8%

In Table 2, the values for *Lowest* and *Highest* do not necessarily refer to the same county, but are simply the extreme values related to each activity. For construction and rehabilitation, most counties are fairly close to the average value, while the range for demolition is much bigger, with the upper value being more than three times the average. There is also a greater difference from the average for the rest of the counties. This difference might be partly due to poorer information on the amount of buildings demolished. The efforts on producing statistics regarding demolition has not been as strong as for construction, which is very well covered by Statistics Norway. The results on which Table 2 is based, show no correlation in activity between the counties for neither population density nor population growth.

As described, the activity is related to three types of buildings, and the relative contribution from each of these to the different activities vary for the counties. The range of variation of these results are displayed in the first column in Table 3, which represents a subdivision of the results in Table 2.

Table 3: Differences in activity between building types and counties (1998 data).

	Range	*Average*	*St.Dev*	*Area*(1000*m*2)
Construction				
Residential	16% – 53%	40%	8.5%	2668
Larger	28% – 66%	39%	9.9%	2603
Other	14% – 35%	22%	7.1%	1481
Rehabilitation				
Residential	21% – 60%	50%	8.6%	2584
Larger	29% – 70%	39%	9.2%	1993
Other	8% – 14%	11%	1.9%	593

Table 3: Differences in activity between building types and counties (1998 data).

	Range	*Average*	*St.Dev*	*Area*(1000*m*2)
Demolition				
Residential	14% − 42%	28%	8.2%	278
Larger	4% − 44%	12%	11.1%	124
Other	42% − 78%	60%	9.7%	606

The average distribution for all counties is shown in the second, while the third column represents the standard deviation from the average distribution for each activity and building type, in column two. Column four is the number resulting from combining the average value with the total area related to the prevailing activity for the country as a whole, giving an idea of the magnitude. These area values are projected from figures in 1998, from Statistics Norway (1998).

There is considerable variation from the average values when looking at the range. However, most counties does not have a very different distribution from the average for the building types. The county of Oslo is the one who differs the most, possessing the lowest value related to residential buildings for all activities, and the highest share related to larger buildings. There exists no information on the distribution shown in Table 3 for any other years. As for the total amount of activity displayed in Table 2, the breakdown to building types show no correlation between the counties for neither population density nor population growth.

4 Waste generation

Knowing the amount of activity related to each building category, waste generation factors are coupled with this to find waste amounts. The waste generation factors do not only give total waste amount per square meter for each activity and building category, but also the composition of this, as displayed in Table 4. Total waste amounts (W), and its composition ($frac$), from different activities and building categories are found from Equation 4 for all counties and all years

$$W_{f,frac,act,bt,t} = A_{f,act,bt,t} \cdot F_{frac,act,bt} \quad \forall f, frac, act, bt, t \tag{4}$$

with F being the amount of waste per square meter from Table 4.

Table 4: Waste generation factors and composition (kg/m^2), from Statistics Norway (1998).

	Construction			Rehabilitation			Demolition		
Composition	Resid	Large	Other	Resid	Large	Other	Resid	Large	Other
Asbestos	-	-	-	0,50	0,50	0,50	2,14	2,14	2,14
Hazardous	0,07	0,07	0,07	0,03	0,03	0,03	0,40	0,42	0,23
Conc/bricks	6,50	19,11	17,52	40,40	30,45	18,77	394,30	1.012,46	519,34
Gypsum	3,04	1,38	0,80	5,90	2,44	2,30	3,37	0,01	0,31
Glass	0,24	0,12	-	0,29	0,29	0,29	2,59	0,44	0,20
Insul/EPS	1,20	0,21	0,10	0,62	0,14	0,10	1,69	-	0,09
Metals	0,11	0,48	0,79	0,38	4,06	6,05	4,45	7,70	45,31
Paper/Plastics	2,92	0,46	0,26	0,71	0,68	0,14	0,92	0,32	2,57
Wood	5,68	2,75	4,05	37,94	8,06	2,30	105,84	48,55	17,09
Unknown	9,60	6,19	7,91	2,70	13,48	2,70	59,02	31,21	14,67
Total	$29,36$	$30,77$	$31,50$	$89,47$	$60,13$	$33,18$	$574,72$	$1.103,25$	$601,95$

Table 4 represents estimations of waste amounts per square meter, which are the empirical results from more than 300 projects of construction, rehabilitation and demolition in the municipality of Oslo. As can be seen from this table, waste generation is naturally very different for the activities, with demolition being the clearly dominating one for total waste amounts. There is however variation regarding waste generation factors for the different waste fractions. Demolition creates a very large amount of the heavy fraction concrete and bricks, compared to the other activities, making this the main contributor to the total figures. Summarizing Equation 4 for all counties and building types, amounts and composition of C&D-waste for the entire country is found, using Equation 5

$$W_{frac,act,t} = \sum_{f,bt} W_{f,frac,act,bt,t} \quad \forall frac, act, t \tag{5}$$

The results are shown in Table 5 for construction, rehabilitation and demolition.

Table 5: Waste composition for different activities (%).

Composition	*Construction*	*Rehabilitation*	*Demolition*	*Total*
Asbestos	-	0,70	0,32	0,38
Hazardous waste	0,23	0,04	0,04	0,07
Concrete/Bricks	45,79	47,69	84,16	67,24
Gypsum	6,25	5,72	0,15	2,77
Glass	0,47	0,41	0,12	0,26
Insulation/EPS	1,87	0,51	0,07	0,49
Metal	1,32	3,59	4,33	3,63
Paper/Cardb/Plastics	4,50	0,89	0,27	1,14
Wood	13,67	30,31	6,42	14,58
Unknown composition	25,89	10,13	4,13	9,44

The major waste fraction is concrete and bricks, accounting for 2/3 of the total waste amount. For demolition the same number is 85%, which is much higher than the contribution for construction and rehabilitation. The second largest waste type is wood, with about 15% of the total, and as high as 30% of the waste from rehabilitation. The table further shows that about 10% of the total waste amount from the AEC-industry is of unknown composition, making it the third largest category. For construction, as much as 1/4 of the waste amounts are of unknown composition.

There is great variation between the amount of activity as well as waste generation related to each of them. Excluding the composition of the waste from Equation 5 gives the total waste distribution related to each activity, from Equation 6

$$W_{act,t} = \sum_{frac} W_{frac,act,t} \quad \forall act, t \tag{6}$$

These results are presented in Figure 2, showing the distribution of total C&D-waste amounts between the activities for all of Norway, while Table 6 displays the corresponding projection of waste amounts for 2002.

Table 6: Waste amounts 2002 (tons).

Construction	*Rehabilitation*	*Demolition*	*Total*
205.000	367.000	684.000	1.256.000

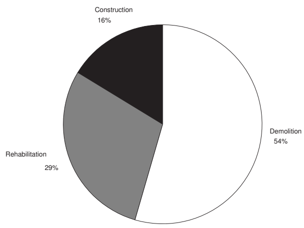

Fig. 2. Total C&D waste distribution in Norway (1998)

The amount from demolition activity is an adjusted value, since previous reports on C&D-waste from Statistics Norway have estimated too high waste production. More than 1.5 million tons were estimated in 1998, from Statistics Norway (1998). Poor registration of earlier waste production resulted in overestimation of this activity. In recent statistics the total amount is adjusted to less than 1 million tons, mainly from a reduction in demolition activity as described in Statistics Norway (2002). The waste production is here estimated to give a value between these two figures, giving an amount in accordance with the figure proposed by Ministry of the Environment (2000), and displayed in Table 6. Looking at this table, demolition clearly contributes the most, with more than half of all waste generated from this activity. Comparing this to the activity distribution in Figure 1, the ranking is reversed. Although demolition accounts for only 8% of the activity, this share results in a great contribution regarding waste generation, while the opposite is the case for construction. This demonstrates what is displayed with the waste factors in Table 4. Demolition is much more sensitive to changes in the activity level than construction, while the opposite is true for the waste factors.

5 National waste projections

Projections of waste amounts from AEC-activity is hard to forecast. This industry will be affected by fluctuations in the economy as well as the general population growth described earlier. Trends for some indicators related to welfare and living conditions in Norway are shown in Figure 3. The positive trend in GDP/Capita is reflected in an improvement in living conditions. Furthermore, area per capita of construction can be calculated from Statistics Norway (2003b), and is found to be growing by an average of about 4% annually for the recent decade for the nation as a whole. National numbers for rehabilitation and demolition are not available, but the trend for these activities are assumed to be the same in the projections. By varying the population growth

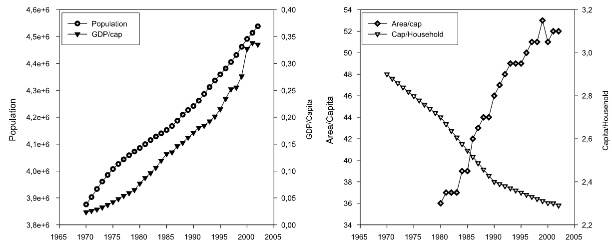

Fig. 3. Welfare and living conditions in Norway

and the growth in area per capita for each activity, 7 scenarios are developed to project the total national C&D waste amounts towards 2020. Table 7 shows the scenarios and their characteristics.

Table 7: National waste projection scenarios

Scenario	*Population growth*	*Growth area pr. capita*
I	0	4%
II	Low	4%
III	Medium	4%
IV	High	4%
V	0	4%-10%
VI	Medium	4%-10%
VII	Medium	0%

The population growth has four levels in the scenarios, including 0 growth. The others are based on projections for low, medium and high national growth, from Statistics Norway (2002). For Scenario I-IV, these are combined with a continuation of the current growth in activity per capita, displaying the influence of population growth. The activity growth vary from 0 to 10%. In Scenario V and VI, this growth increases from the recent trend of 4% in 2002 to an annual growth of 10% in 2020. Figure 4 shows total projected waste amounts for all scenarios from 2002 to 2020.

As can be seen from Figure 4, the increase in area per capita dominates the waste generation. The trend in construction activity per capita is the basis for

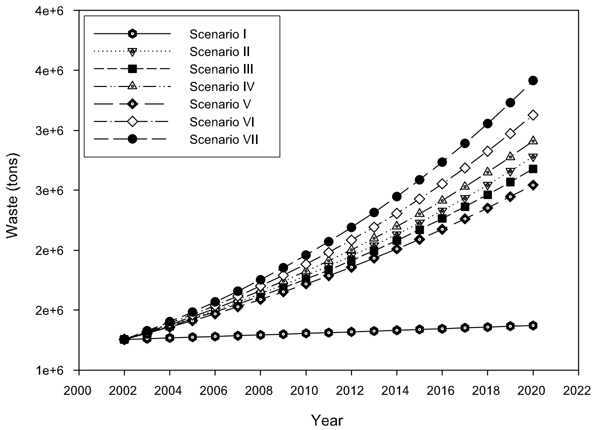

Fig. 4. Projected waste amounts

this parameter, and has a much higher growth rate compared to population growth. Varying population growth does not give dramatic changes in the waste projection. However, a continuation of the recent trend in activity results in a considerable increase. In 2020, waste generation will be nearly 2.5 times as large for Scenario VI compared to the lowest one, Scenario VII.

The projections are merely a forecast based on the recent trends, and do not take into consideration the dynamics of an ageing of the building stock, which will also lead to a further increase in waste amounts from demolition. Such effects will be discussed later, using Trondheim, Norways third largest city, as an example.

6 Waste projection Trondheim

Estimation of future waste amounts from construction, rehabilitation and demolition on a more local level would contain too high uncertainty if deducted from the national or regional level, since there is great variation related to AEC-activity for the different parts of Norway. Furthermore it does not include variations resulting from previous economic cycles, which affect the

AEC-activity and the building stock both in the past and for the years to come. More specific knowledge of building stock and activity is essential to estimate future activity and waste amounts for any local area under investigation. For the development of a method for this, the municipality and city of Trondheim is used as an example.

Information related to the building stock in Trondheim is obtained from the Norwegian Mapping Authority and their GAB-register (Ground property, Address and Building Register), which is a national register started in 1980, containing an inventory for existing buildings and their year of erection. This is the most detailed information available, and will serve as the foundation for activity- and waste projections. Data quality for projects of rehabilitation and demolition in this register, is however not satisfactory, leading to a need for calculation of this. These calculations will be based on expected average lifetime of the different building categories. Residential buildings are assumed to have a longer lifetime than the other two building categories, as displayed in Table 8. This is supported by the findings in Kotaji et al. (2003), which is a state-of-the-art report for Life-Cycle Assessment (LCA) in building and construction.

Table 8: Expected average time span until rehabilitation and demolition (years).

Activity	*Residential buildings*	*Large buildings*	*Other buildings*
1st rehabilitation	30	20	20
2nd rehabilitation	60	40	40
Demolition	90	60	60

Rehabilitation of buildings are assumed to be carried out every 30th year, as opposed to every 20th for the rest of the building stock. These lifetime expectancies and rehabilitation frequencies are important in this approach to estimate future waste amounts. Since the information on previous activity on rehabilitation and demolition is poor, future waste projections will be based on previous construction activity combined with life- and rehabilitation expectancies. Information on construction activity from the GAB-register includes all kinds of buildings, which are first grouped together by the premises set in Table 1. The total area constructed can be found for each year by using information on average size of buildings from Statistics Norway (1998). Average size of buildings have grown over the last century, and not very much detailed information on this is obtainable. From Myhre (1995), a general trend for this increase is calculated for residential housings the last 4 decades. Extending this trend backwards and applying it also to the other building categories, gives an approximation of the average size of buildings with time. By combining these numbers with the waste generation factors from Table 4 and the information in Table 8, future waste generation in Trondheim is projected according to Equation 7.

$$W_{act,bt,frac,t} = A(t-90)_{bt,t} \cdot FD_{bt,frac} + A(t-60)_{bt,t} \cdot FR_{bt,frac} \\ + A(t-30)_{bt,t} \cdot FR_{bt,frac} + A(t)_{bt,t} \cdot FC_{bt,frac} \quad \forall act, bt, frac, t \tag{7}$$

In Equation 7 A is the area constructed for a given year, while FD, FR and FC is the waste generation factors for demolition, rehabilitation and construction, respectively. The calculation is shown for residential buildings with a lifetime of 90 years. There are, however, some uncertainties related to different inputs in the calculations. The method of Monte Carlo simulation is therefore applied to reduce these uncertainties in the calculation of future waste amounts. Monte Carlo analysis involves conducting and then comparing repeated trials with inputs that sample the distributions of the system parameters. The normal distribution with standard deviation is used for the parameters, which are shown in Table 9. This simulation is a stochastic technique, meaning it is based on the use of random numbers and probability statistics to investigate the problem. For each trial, the calculation of waste amounts are carried out with random numbers for the parameters, although within the boundaries of the standard deviation, so as to produce a more robust result.

Table 9: Input parameters in Monte Carlo simulation of waste amounts.

Parameter	*St.Deviation*	*Conf.interval*
Number of buildings	10%	95%
Average area of buildings	10%	95%
Activity frequency	5 years	95%
Waste generation factors	10%	95%

Activity frequency in Table 9 means the periods between construction, rehabilitation and demolition. Figure 5 displays the results for projection of waste amounts, and their composition, in Trondheim for the next 15 years. Results for the recent years are included as well.

Waste amounts are increasing for all waste types due to increasing construction activity and size of buildings in the past. The change is especially dramatic for concrete/bricks which will increase more than four times during the

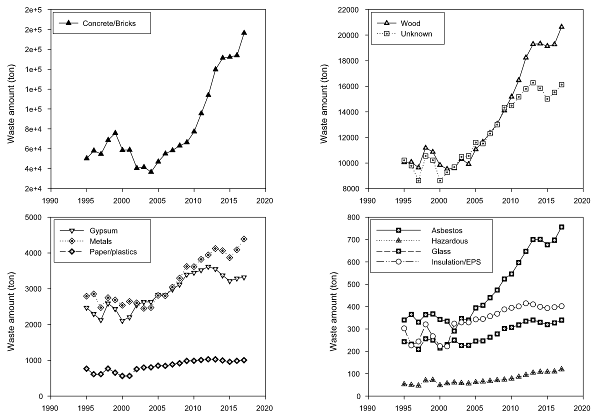

Fig. 5. Projected waste amounts in Trondheim.

period. The projections are based on previous construction activity and estimation of lifetime of buildings. From Table 8 the lifetime of buildings, except residential, is 60 years. For the waste projections, this brings us back to the middle of World War II, where construction activity was naturally low. Knowing also from Table 4 that demolition of "Large" and "Other" buildings are the activities generating the most concrete/bricks, this explains the very high increase for this waste fraction, as construction activity rose significantly in the post war period. A corresponding drop in waste amounts are shown for projections based on the pre war period. Wood, metals, asbestos and waste of unknown composition will also increase considerably, and the increase in asbestos amounts is worrying because of its potential for causing harm both to the environment and to humans. Waste of unknown composition constitutes a large share of the total waste amounts, and the considerable increase for this waste type calls for more attention and better tracking of this. The growth in waste generation for the minor waste types are much less dramatic, but still there is growth for these as well.

7 Conclusion

Knowledge of future waste generation is based on the activities of construction, rehabilitation and demolition. Through knowledge of waste production from these activities, future waste generation has been projected. Both national and local projections predict a considerable increase in waste amounts. This furthermore calls for more concern being paid to appropriate end of life treatment to reduce the potential stress on the environment due to AEC-activities. With the present development, both nationally and internationally, towards stronger regulation of the waste sector and heavier taxation on landfilling, there should also be strong economic incentives for more environmentally friendly solutions. The potential for better economic and environmental solutions is further discussed in a second paper, "Evaluating eco-efficiency based strategies for C&D waste recycling at the level of a city", by Bohne et al. (2004). Here, information on waste amounts in Trondheim from this paper is used to elaborate a consistent framework for the quantification and evaluation of Eco-Efficiency for different waste treatment scenarios of C&D waste.

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References

Bohne, R., Bergsdal, H., Brattebø, H., 2004. Evaluation of strategies for recycling of c&d-waste in trondheim, based on eco-efficiency. Tech. rep., Norwegian University of Science and Technology, Trondheim.

Kotaji, S., Schuurmans, A., Edwards, S., 2003. Life-cycle assessment in building and construction: A state of-the-art report, 2003. Tech. rep., Society of Environmental Toxicology and Chemistry (SETAC), Brussels.

Ministry of the Environment, 2000. The governments environmental policy and the state of the environment. Tech. rep., Ministry of the Environment, Oslo.

Myhre, L., 1995. Some environmental and economic aspects of energy saving measures in houses. Tech. rep., Norwegian University of Science and Technology, Trondheim.

Norwegian Mapping Authority, 2003. RiksGAB, instruction for registration of gab-data. Tech. rep., Norwegian Mapping Authority, Hønefoss.

Statistics Norway, 1998. Construction and demolition waste. Tech. rep., Statistics Norway, Oslo.

Statistics Norway, 2002. Population projections 1999-2050. Tech. rep., Statistics Norway, Oslo.

Statistics Norway, 2003a. Buildings statistics. Tech. rep., Statistics Norway, Oslo.

Statistics Norway, 2003b. Construction statistics. Tech. rep., Statistics Norway, Oslo.

Appendix D

Paper 2

Bohne, R., Brattebø, H. and Bergsdal, H., [2004], Evaluation of eco-efficiency based strategies for c&d waste recycling at the level of a city. Paper submitted the Journal of Industrial Ecology.

Evaluation of eco-efficiency based strategies for C&D waste recycling at the level of a city

Rolf André Bohne *, Helge Brattebø and Håvard Bergsdal

Norwegian University of Science & Technology, Department of Hydraulic and Environmental Engineering/Industrial Ecology Programme

Abstract

In this paper we have elaborated a consistent framework for the quantification and evaluation of eco-efficiency for different waste treatment scenarios of C&D waste. Such waste systems will play an increasingly important role in future, since there for many years has been, and still is, a significant net increase in stocks in the built environment. Consequently, one need to discuss future waste management strategies, both in terms of growing waste volumes, stricter regulation and sectorial recycling ambitions, as well as a trend for higher competition and need for professional and optimized operations within the C&D waste industry. It is within this framework we develop and analyze models, which we believe will be felt meaningful to the actors in the C&D industry.

We have outlined a way to quantify future C&D waste production, as well as developing realistic scenarios for waste handling, on the basis of today's actual practice. We then demonstrate how each scenario is examined with respect to specific and aggregated cost and environmental impact from different end-of-life treatment alternatives for major C&D waste fractions. From these results we have been able to suggest which fractions to prioritize in order to minimize cost and total environmental impact, as the most eco-efficient way to achieve an objective of overall system performance.

Key words: AEC-Industry, C&D-waste, Recycling, eco-efficiency

1 Introduction

The AEC-industry is a major contributor to the overall waste production in Norway. Much of this waste is technically recyclable (95%) [1], but is today not

* Corresponding author. Tel.; +47-73598946; Fax.; +47-73598943
Email address: rolf.bohne@ntnu.no (Rolf André Bohne).

recycled for various reasons. In this paper we investigate the environmental and economic performance of different waste handling options in a future C&D waste recycling system of Trondheim, Norway. The baseline for our system is today's practise.

Eco-Efficiency [2, 3, 4, 5, 6] is a tool, primary developed for production processes, where value added and environmental impact is rather straight forward to follow. When we are dealing with recycling systems, the picture gets more complicated, both for the estimation of value added and environmental influence, since these systems involve numerous companies, products and material fractions, as well as open loop recycling options where the variables are not easily determined and allocation problems may arise. This paper seeks to outline how to calculate eco-efficiency for recycling systems, and how eco-efficiency can be utilized as a tool in decision making processes.

2 Methods

2.1 Projection of future waste generation

In order to make qualified predictions about the future, it is necessary to know something about the past. In our previous paper, "Projection of Waste Amounts from the AEC-Industry in Norway" [7] we described a method for the projection of future generation of C&D waste i Trondheim, Norway. This was a difficult task due to the lack of availability of empirical data from the past, and the ever shifting requirements of both working and residential buildings. We have estimated the pattern of increasing amounts of various material fractions in the C&D waste during the next 15 years, for all sources of C&D waste, i.e. construction, renovation and/or demolition. All together the building are categorized into 161 types, which we have grouped into three categories; residential [1], large [2] and other [3] buildings [7]. A key issue here has been the expected service life of the actual construction and elements. There is now consensus in regard to the expected service life of buildings or building components in literature [8].

Another issue that has been difficult to incorporate in the projection is the shift in construction materials that has occurred during the last decades, due to the a lack of good statistical data. But our results clearly indicates that some fractions will increase more than others, Figure 1.

1 Single houses, Chained houses etc.
2 Office buildings, High houses etc.
3 Industrial-, Agricultural buildings etc.

Especially the concrete and brick fraction is believed to increase more than the average. There is mainly two reasons for this; The first is the high content of these material fractions and the shorter lifetimes of larger buildings and other buildings, as shown in Table 1. A second explanation is the rapid increase in the construction activity of such buildings after WWII, the 1950s and 1960s especially. A wave of demolishing of these buildings are now starting, creating rapidly increasing amounts of concrete, brick and wood. For the same reasons we can explain the sigmoidal shape of the curve, and that the curve seem to level of around 2020.

In order to have a reference to the scale of Figure 1; the population in Trondheim equals 150.000 persons in 2002, and the total building area is estimated to 46 million m^2.

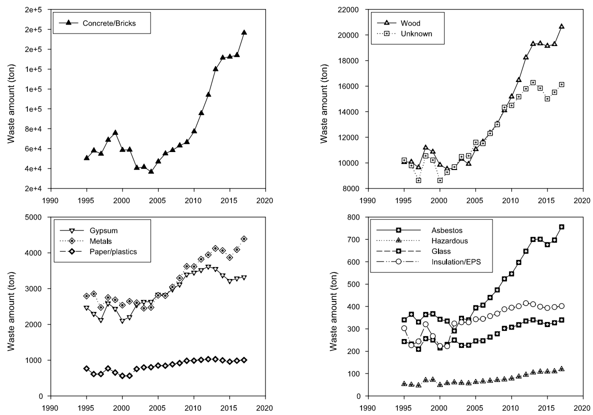

Fig. 1. Waste amount in Trondheim during 1995-2018, projected on the basis of history of existing buildings (from [7]).

Table 1: Expected lifetime and renovation need (years)[7].

Activity	*Residental*	*Large*	*Other*
Time until 1^{st} renovation	30	20	20
Time until 2^{nd} renovation	60	40	40
Time until demolition	90	60	60

2.2 System borders and allocation between co-products

In systems modelling, and modelling environmental impacts (LCA) in particular, co-production (the joint production of two or more products from the same process or system) has been seen as presenting a problem to the modelling, and the traditional solution has been co-product allocation (the partitioning and distribution of the environmental exchanges of the co-producing processes over its multiple products according to a chosen allocation key) in parallel to cost allocation [9, 10, 11].

Weidema and others [9, 10, 11] have demonstrated how co-product allocation always can be avoided by expanding the system to also include product system B: *"the co-producing process (and its exchanges) shall be ascribed fully (100%) to the determining co-product for this process (Product A)"* [9], Figure 2.

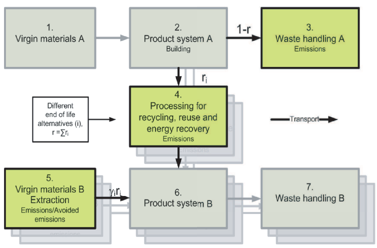

Fig. 2. System expansion (from A to A+B+ ...) for the allocation of influence among co-products, as input to the calculation of eco-efficiency in C&D waste recycling systems. Highlighted boxes and arrows denote system borders for this study. Arrows denote transport between processes. The layers beyond are further system expansions. r_i represents the ratio of a given waste fraction that enters an alternative end of life treatment, and γ_i is the factor for how much virgin materials that is replaced by r_i.

In the recycling system for C&D waste, it is the enterprize owner (of the construction or demolition project) or the entrepreneur in system A who in general determines where and what to do with the waste. However, the municipalities often seeks to influence these decisions through policies (the use of power).

This reopens for a discussion about allocation among co-products. In this paper we have chosen to follow Weidema's recommendation of system expansion[9], since our interest are in the overall system, and focus point is to maximize overall system performance.

2.3 Waste handling and environmental impact

The environmental impact of waste management options is a result of processing and disposal methods and transportation types and distances, for all disposal, recycling and reuse options in the system. Moreover, recycling and reuse should give positive downstream environmental benefits when recycling and reuse is applied, due to omitted emissions, and some of these benefits should also be allocated to the environmental performance of the initial C&D waste system. According to Bohne and Brattebø[12], different end of life treatments can be ranked in a general hierarchy according to their environmental impact, where direct reuse is ranked higher than recycling, which in turn is better than energy recovery, etc.

In practice some of these alternatives are either not wanted, not possible or too expensive to follow. Some of these processes demand facilities that are expensive to build and maintain. It is therefore of public interest to know as much as possible about the future waste generation and its possible corresponding environmental impact.

Data on environmental impact for the different alternatives for end of life treatment is calculated on the basis of data from many different sources using LCA methodology [13, 8]. A problem with these kind of calculations for recycling systems is that we deal with a wide range of products, of different age and from many different producers. Hence, it is a challenge to make use of appropriate system borders, cut-of rules and allocation rules when doing the analysis. Another issue to bear in mind is that it is the aggregated environmental impact that is of importance, and should be used as a design criteria, rather than aggregated volume or weight, parameters that often are used in industry's evaluations of system performance in the AEC sector.

Figure 1 shows that the brick and concrete by far will be the largest fraction, and also be the fastest growing fraction in the forthcoming years [7]. But this does not necessary mean that this is the most important fraction to deal with in order to reduce environmental impact. In order to examine this question we need to determine the aggregated total environmental impact (Ψ_j^*) for each waste fraction during the whole period we are studying, and then for the different waste fractions, including all transportation and end of life treatment activities, over the time period in question.

$$\Psi_j^* = \sum_t \psi_j w_{j,t} \quad (1)$$

where, ψ_j is the environmental impact per ton from the end of life treatment of each waste fraction (j) (transport included), $w_{j,t}$ the weight of the waste fraction in tons and t being the number of years studied.

For most waste fractions (j), there are several end of life alternatives (i) to consider. The total annual environmental impact of the waste fraction, Ψ_j, is thus the sum of the environmental impacts (ψ_i) from all these end of life treatments for each fraction, see Equation (2).

$$\Psi_j = \sum_i \psi_i r_i w_j \tag{2}$$

where, r_i is the share of a given waste fraction that is sendt to each end of life treatment alternatives (i) in question for each waste fraction (j), see Figure 2.

The aggregated total environmental impact, Ψ_j^*, is then calculated by summarizing Ψ_j over the years of interest, Equation (3);

$$\Psi_j^* = \sum_t \sum_i \psi_i r_{i,t} w_{j,t} \tag{3}$$

where, (t) is time period studied.

Calculating Ψ_j^* for all waste fractions will thus identify which fractions that should be of greatest concern in order to minimize environmental impact.

2.4 Economic data

Decisions can not be made from environmental data alone. A system owner would want to optimize his system for the best performance possible, in order to reduce pay-back-time for his investments as much as possible.

However, when dealing with reuse or recycling, which are in fact "de-production" systems in which you are dealing with a number of different stakeholders, the picture gets more diffuse. Due to the complexity of recycling systems with many stakeholders and products of different origin and age, economic efficiency is often difficult to measure.

For C&D waste, a typical recycle chain involves several stakeholders with different interests, whom each seeks to maximize its own profit, and is traditionally less driven by a wish to reduce environmental impact. The system owner is often the municipalities, whom also (in part) is responsible for the policies affecting the system.

Given these restrains, we can categorize the economic data in three categories, Table 2, according to the source, type and availability of data.

Table 2: Availability and source of economic data

Category	1	2	3
Source	Public taxes	Price lists	Pers.com and/or best estimates
Availability	Very Good	Very good/ good	Good to unavaileable
Type of data	Static	Dynamic	Rapidly changing
Data quality	Very good	Very good/ good	Good to fair

It is most often the values on process expenses that are unavailable due to competition (cat 3), but also prices on transportation and waste delivery for large deliveries have been found to be lower than the official prices (and therefore shift from cat 1 to cat 2). Hence for the same reason such data would be hard to get.

It is also a problem that some economic values have a considerable dynamic variation. E.g. the price on transportation, which shifts with fuel prices. We have therefore used historically observed data and corrected those data according to the corresponding statistical index [14].

By using cost as the economic indicator (se below) we have managed to limit our data sources to category 1 and 2.

2.5 Sensitivity analysis

For these calculations to be useful in the actual decision making processes, the uncertainty and sensitivity of the data must be known.

The economic data, costs, are well known, and only need to be corrected for dynamic variations. In our case, transportation costs are the most relevant with respect to such variations.

On the other hand, the sensitivity questions are indeed important for environmental impact data. We base our impact data on Life Cycle Inventory data, with a combination of data from commercial LCI databases and our own empirical data, and it should be stated that inaccuracy is not widely published with LCI data. A commonly used convention is to use data quality indicators [13] to divide the LCI data into three categories. These three categories are often expressed with the corresponding uncertainties, Table 3;

Table 3: Uncertainty of LCI data

Data uncertainty	Low	Medium	High
2σ	0.1	0.2	0.3

From literature [8, 13] its generally known that CO_2-emissions are well studied, and therefore has lower uncertainties, while toxic emission, dust and noise are less studied, and therefore possess greater uncertainties.

We therefore choose a single standard error range of ±5%for the LCI data used in our calculations, which is an accepted approach to uncertainty of LCI data [15].

The maximum error can be solved analytically, but this will give an unlikely high number (±20%). Although we find a maximum error of ±20% acceptable for these kind of calculations, we have run a Monte Carlo simulation to find a more probable standard deviation for our expression, which gives a uncertainty of $\pm 5 - 10\%$. The Monte Carlo method is a method to solve a mathematical problem by an experiment with random number. Thus in our case we have done 100 000 runs where the standard errors have been independent and uniformly distributed. The uncertainty is then calculated from the results.

2.6 Eco-Efficiency in recycling systems

eco-efficiency [2, 3, 4, 5, 6] was first mentioned by Sturm and Shaltegger in 1989; *"The aim of environmentally sound management is increased eco-efficiency by reducing the environmental impact while increasing the value of an enterprize"* [2]. Later the Business Council (now the World Business Council) for Sustainable Development described how to achieve eco-efficiency, in a report released just prior to the 1992 Earth Summit in Rio de Janeiro. The term can be expressed mathematically as [4];

$$\mathsf{eco} - \mathsf{efficiency} = \frac{\text{product or service value}}{\text{environmental influence}} \qquad (4)$$

WBCSD [3, 4, 5, 6] and the UNCTAD [16] advocates for using internationally standardized economic indicators when calculating eco-efficiency. Value added is proposed as the indicator of choice for product or service value. Since eco-efficiency primarily was designed for measuring efficiency improvements in production systems, within a company, both value added and environmental influence should be known, at least for internal purposes.

But when we are looking at recycling systems, we can not use the term value added in the same way as at the firm level. And with a system of many stakeholders who seek to make profit along the way, this picture gets more complicated. Even so, some of this profit does not necessarily increase the value of the material in question, but arises from the stakeholders' performing services such as collection, transportation, sorting and processing. Processing activities in recycling systems, in fact, despite a lift of value for the material, normally lead to a considerable downcycling of the material, at the same time as the stakeholder makes profit. However, the alternative of no processing would of course be worse, since this gives even less value in the marked.

We have therefore rewritten the formulae (Equation (5))to include all economic transactions (for the extended system);

$$Eco - efficiency = \frac{\sum_i \text{costs}}{\sum_i \text{environmental impact}} \tag{5}$$

We use the term *costs* to denote all economic transactions when the material is transferred from one process to another. Equation (5) can be expressed mathematically as;

$$\varepsilon_j = \frac{\kappa_j}{\psi_j} = \frac{\sum_i \kappa_{i,j}}{\sum_i \psi_{i,j}} \tag{6}$$

where;

ε_j = eco-efficiency of a given waste fraction on a per ton basis,
$\kappa_{i,j}$ = process costs of a given waste fraction and end of life process alternative on a per ton basis,
$\psi_{i,j}$ = environmental impact of a givenaste fraction and end of life process alternative on a per ton basis,
i = the different end of life processing alternatives
j = the different waste fractions

Figure 2 shows that we include all processes in the overall system when calculating κ_j and ψ_j in Equation (6). Hence we will avoid the difficulktie of allocation.

However, for eco-efficiency to have any meaning as a tool for decision making, we need to measure the change in eco-efficiency between different end of life treatment options, or waste handling scenarios, for each of the different waste fractions[17, 18, 12]. Thus what we want to measure is the relative change in eco-efficiency (ε') of a proposed alternative end of life treatment option, or set of options (b) compared to the current practise (a);

$$\varepsilon_j' = \frac{\kappa_j'}{\psi_j'} = \frac{\sum_b \kappa_{b,j} - \sum_a \kappa_{a,j}}{\sum_b \psi_{b,j} - \sum_a \psi_{a,j}} \tag{7}$$

where;

a = a given mix of end-of-life process alternatives that are made use of in the current (reference) system, and
b = a given mix of end-of-life process alternatives that are made use of in the proposed alternative system.

However eco-efficiency, is a one dimensional number (Euro/Pt.) on a per ton basis that hides valuable information away from decision makers, especially when more than one alternative process is to be considered. Another issue is that the value of eco-efficiency will increase if the cost increases. Hence we will have to rearrange this parameter in order to better communicate information the way we prefer.

We will therefore follow Huisman[18] in his attempt to visualize the change in eco-efficiency by the BASF method[17]. In the BASF method, eco-efficiency is visualized by plotting the numerator ($\kappa_j{}'$) and denominator ($\psi_j{}'$) for a given waste fraction (j) in an XY-plot like Figure 3, where a positive value for the numerator expresses increased economic value (the Y-axis), and a negative value for the denominator expresses less environmental impact (the X-axis). By comparing several alternative end-of-life process alternatives this way, decision makers can make more qualified decisions on what solution to follow.

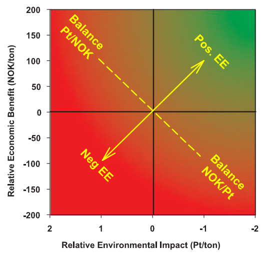

Fig. 3. Principal sketch of eco-efficiency (after [17, 18]), where Origo represents the baseline scenarion

Another interesting feature of this two dimensional figure, is that policy makers here can test how different policies will affect the eco-efficiency of the different end-of-life treatments within the system. [4]

[4] be aware of that Origo of the plot also changes (relatively) by introducing new policies.

3 Results

In order to examine the eco-efficiency of C&D waste systems at the local level, such as at the level of a city, we have estimated future waste projections for the city of Trondheim. Trondheim is the third largest city of Norway, with a population of 150.000 inhabitants, and a building structure which is characterized by many small wooden family houses covering a large area, together with larger residential and office buildings of concrete in the center and some clusters around the center of the city.

The projections of local C&D waste fractions for Trondheim, as given Figure 1, are accumulated for the whole period 2003-2018, and the aggregated amounts are shown in Figure 4. One can clearly see the dominant role of the concrete and brick fraction, in addition to wood wastes, even for a city with a large share of buildings made of wood.

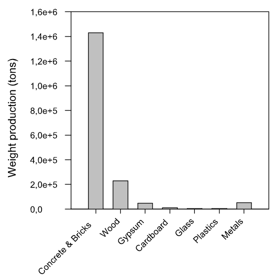

Fig. 4. Cumulative weight of selected C&D waste fractions for the city of Trondheim from 2003 to 2018.

The next step is to identify scenarios for the distribution of C&D waste fractions between various end-of-life treatment options. Table 4 shows the distributions for two scenarios, where "Scenario 0" assumes the continuation of the current end-of-life process alternatives practice during the whole period, while "Scenario NAP" assumes that waste fractions are being directed more towards recycling and reuse options as one can see in Table 4 for the whole period. [5]

[5] Scenario 0 is the reference point for our examination, since it is equal to the current practice. Hence this scenario will be represented by κ_a and ψ_a in Equation 7, and the origo location in the eco-efficiency plot. Likewise, the Scenario NAP will be represented by κ_b and ψ_b in Equation 7, and located away from origo in the plot.

Table 4: Distribution of C&D waste fractions (on a mass basis) between different end-of-life treatment options in Trondheim

C&D Waste	Scenario 0				Scenario NAP			
Fract.	Landf.	Rec.	En.	Reuse	Landf.	Rec.	En.	Reuse
Concrete & brick	0.70	0.30	0.00	0.00	0.20	0.80	0.00	0.00
Wood	0.60	0.00	0.39	0.01	0.20	0.00	0.70	0.10
Gypsum	0.95	0.05	0.00	0.00	1.00	0.00	0.00	0.00
Cardboard	0.50	0.30	0.20	0.00	0.20	0.70	0.10	0.00
Glass	0.80	0.20	0.00	0.00	0.20	0.80	0.00	0.00
Plastics	0.40	0.20	0.40	0.00	0.10	0.80	0.10	0.00
Metals	0.10	0.90	0.00	0.00	0.10	0.90	0.00	0.00

The distribution of waste fractions demonstrates that there must be realized an ambitious shift away from landfill towards recycling for concrete/brick, gypsum, cardboard and plastics, if the current end-of-life practice (Scenario 0) is to be replaced by Scenario NAP. Likewise, wood waste will have to be redirected from landfilling towards energy recovery and direct reuse.

On the basis of data in Figure 4 and Table 4 it is now possible to calculate the Net Present Value (Euro) and environmental impacts (Pt.) for each waste fraction during the 2003-2018 period. Cost data are achieved directly from the actors in the system, and environmental impact data are achieved from LCA software [13] by using the Eco-Indicator 99 valuation method.

For the calculations of Net Present Value, we have used the interest from Norwegian State Obligations (4% for obligations with 10 years running time) as the costing interest in order to estimate the present value of future costs.

The results are given in Figure 5 and 6, where 5A and 6A shows Net Present Value (Euro) and (Pt.) for each waste fraction in Trondheim during the next 15 years, according to Scenario 0. Similarly, 5 and 6 B shows the results if Scenario NAP is applied for the whole period, and finally 5C and 6C shows the net difference between the two scenarios.

We want to remind the reader that these are calculations for the extended system, and as such not representative for the individual stakeholders, but for the system as a whole, see Figure 2.

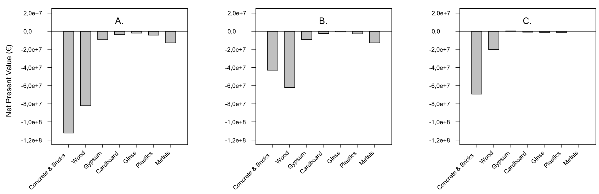

Fig. 5. Net Present Value (Euro) of C&D waste handling in the city of Trondheim from 2003 to 2018
A: Scenario 0
B. Scenario NAP
C. Relative difference A-B.

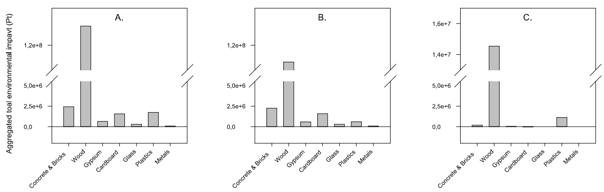

Fig. 6. Aggregated environmental impacts in Ecopoints (Pt.) of C&D waste handling in the city of Trondheim from 2003 to 2018
A: Scenario 0
B. Scenario NAP
C. Relative difference A-B.

As we can see, the concrete & brick fraction is dominating, by far, the material composition of the C&D waste (Figure 4). This is also reflected in the system costs Figure 5A, while its corresponding environmental impact is less obvious (Figure 6A).

If we look at Figure 6A alone, we would suggest that the wood is the fraction worth focusing on from an environmental point of view.

As can be seen from Figure 6C, the picture is somewhat different from the picture in Figure 6A. From Figure 6C; wood and to some extent plastics, is the only fractions worth focusing on from an environmental point of view. This does also correspond well with how developed the recycling systems for these fractions are. Monte Carlo simulations have shown that the standard deviations for the calculations are ≤ 10 %, which is very good given the input sources of data. The results are therefore believed to give a representative view of the eco-efficiency, given that the trend for waste production in Figure 1 are correct.

Most of the C&D waste (by weight) is handled by different material companies within Trondheim, but some of the fractions have to be handled long distances outside the city if they shall be recycled. Table 5 shows the nearest recycling facilities for these fractions, and the transport methods and distances for each fraction. We have used these transport distances in our calculations even though waste fractions may be sent to other more far distant places also.

Table 5: Distances to the nearest recycling facilities for waste fractions that are not being recycled in Trondheim

Recycling of:	Where	Distance	Who	By
Gypsum	Drammen	539 km	Gyproch	Truck
Cardboard	Skogn	73 km	Norske Skog AS	Truck
Glass	Stjørdal	33 km	Glava AS	Truck
Plastics	Folldal	197 km	Plastretur	Truck
Metals	Mo i Rana	482 km	Fundia Armeringsstål AS	Truck (train)

In order to make qualified decisions on what to do with the different waste fraction, we need to compare the eco-efficiency for the different end of life options for each fractions against each other. This will then be a basis for further qualified decisions in the overall C&D waste management system.

Figure 7 shows two-dimensional relative plots of the eco-efficiency parameters according to the BASF method. We have provided plots for each of the waste fractions, and the data show how different end-of-life treatment options position themselves relative to the current treatment practice (as we find it in Scenario 0), which always is represented by the Origo. The difference in environmental impact, between a given treatment option or scenario and the current treatment scheme, is given along the x-axis, where reduced impact gives a position to the right of Origo. The difference in cost is expressed as net economic benefit, on the y-axis, so that a reduced cost gives these are relative numbers, end of life options that are part of both current situation and the suggested Scenario NAP will be placed on a straight line, since the numbers are interconnected. In order to compare on a straight forward method, the results are presented on a per ton basis, i.e. Euro/ton and Pt./ton (by using the Eco-indicator 99 method). The better treatment options will always position themselves in the upper right corner of the plot.

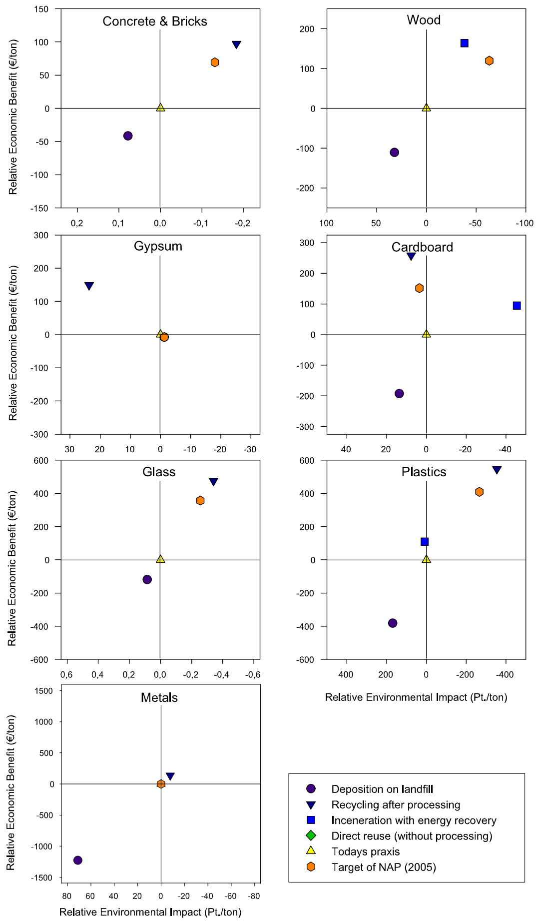

Fig. 7. Relative change in eco-efficiency for the different end of life treatments for selected fractions of C&D waste in Trondheim, Norway. Be aware of the large variations of scale between the different waste fractions in the figure

4 Discussion

The results shown in Figure 4, 5, 6 and 7, reveal some interesting issues.

Let us first take a look at the results from Figure 4, 5 and 6. Although the concrete & brick fraction, by far is dominating the waste production and the cost of waste handling, it does not have a corresponding high impact on the environment. A second interesting finding is that the figures show that wood has the largest environmental impact of all fractions, and it is also the fraction that has the largest possibilities for further environmental savings. Third, there is a general trend that for the waste fractions where a recycling system is up and running (to some extent) the costs for recycling are lower (one can even make profit) and the environmental impact relative to the current practice has a negative value. There is however one important exception to this - the concrete & brick fraction. This is most likely due to the fact that this recycling represents crushing these materials into aggregate that is used as a substitute for gravel. Hence, the materials are "downcycled", and most of the energy (actually exergy) once put into the materials are lost.

For the same reason there is an interesting potential for plastics, if one manages to shift from energy recovery to recycling.

It is worth mentioning here that in theory it is possible to increase environmental savings even more for the wood fractions, if wood is reused instead of being sent to recycling or energy recovering. Such a shift will also be more profitable for stakeholders. However, this is difficult due to altered construction practices, and the required handling of materials for reuse. If such a system should be implemented at a large scale, and not as of today be a work training facility, the costs would also increase beyond what we have used in our calculations, and as a result the corresponding eco-efficiency would decrease.

Figure 7 shows some interesting results, and we will discuss fraction for fraction.

Concrete & bricks

The figure reflects the current situation of 30% recycling. There is a clear economic and environmental benefit of recycling. If recycling still is not done, then other issues must be of higher economic importance to the decision maker.

Wood

One of the more interesting results, due to the fact that this is one of the fractions with renewable material, and that is possibility of all end of life solutions. As mentioned above there is a great potential for better environmental performance, if more wood is reused, recycled or energy recovered. As for concrete & bricks, other factors dominates the decision processes for stakeholders, since not more wood is actually being delivered to i.e. energy recovery.

Gypsum

Not all recycling is environmental friendly. This figure shows that landfilling is the most environmental friendly option, while recycling is the most economical solution for stakeholders located in Trondheim. This is due to the fact that the only two recycling facilities for gypsum in Norway is located in Drammen and Fredrikstad, and that the transport is polluting more than recycling saves the environment. When some gypsum still is recycled, this is due to the economic benefits, plus the general "truth" that recycling is environmental friendly. The NAP (2005)[1] has acknowledged this fact, and only suggests that gypsum is recycled from the more densely populated regions near to the recycling facility. Policy makers in Trondheim should use this information to lower the landfilling fee for gypsum (or impose a fee for recycling) so that landfilling is the economic choice in the region, or consider to build a recycling plant locally.

Cardboard

A classic situation where energy recovery competes with recycling. Here contamination and convenience determines what end of life options to follow. The figure reflects a functioning recycling system not yet optimized. Recycling is the favorable economic choice. It should however, from our results, be considered to alter both the national target and the economic incitements of current policy so that incineration becomes more economical interesting for stakeholders, in order to enhance overall system performance.

Glass

The figure shows a recycling system in its early stage, with a lot of unrealised potential. The figure also indicates an lack of local recycling facilities.

Plastics

As for cardboard, a situation where energy recovery competes with recycling, but with one important difference. We are here dealing with a non renewable resource, and although the economic potential are in the same order, there is a magnitude of difference in environmental potential. The environmental impact for the system indicates that recycling should be favored, the opposite conclusion of that with cardboard. Policymakers should therefore alter the incitements such that recycling becomes more favored than energy recovery.

Metals

The image of an mature recycling system driven by the economic value of the material. Almost all the environmental potential is therefore realized. It is also the only waste fraction where one gets paid when delivering waste.

5 Conclusion

There is a need for municipalities and governments to make more qualified decisions on environmental issues, with regard to the long term management of waste handling systems and natural resources.

We have shown that long term models combined with environmental and economic information can make an powerful tool in such regard. Total environmental impact and eco-efficiency calculations can be used by system owner and stakeholders to evaluate their options and their system performance, as well as as which waste fractions to focus on, and what end of life alternative to give priority to.

Of special interest to waste handling systems are the possibility for the effect of different policies as well as alternative end of life solutions within each policy. Important to decision makers will be how different system alternatives meet given policy targets. Our model is able to simulate such issues.

However, even though we have demonstrated that recycling and/or reuse often are the most eco-efficient choices in most systems, we know that this is many times not followed in practise, for different reasons. We assume that this is often due to the fact that other economic processes overrun the environmental issues in waste handling decisions. Time penalties for delays in construction or demolition projects is an obvious example to this. These issues need more investigations.

Our reflection on this research method is that the approach looks very promising. Our way of presenting specific and aggregated results on eco-efficiency in C&D waste systems is intuitive and attractive with respect to communication towards stakeholders as a basis for decision making. However, there are two aspects that needs improvement. First, one needs to refine the dynamic model estimating future waste generation. This model should be based on more detailed examination and data of the building stock including its material composition and lifetime distribution. This would give much more robust projections for waste generation.

Second, we need more precise data on important processes in the C&D waste system, including environmental and economic parameters. Only then it would be possible to offer models that would be meaningful to the industry in decision making.

This sector is so important in term of its waste amount, that such research work should be given high priority.

Notations

$Euro$ = Euro (currency).
$Pt.$ = Eco Point, environmental performance indicator after the Eco indicator 99 method.
$NAP(2005)$ = The National Action Plan for recycling of C&D waste. Overall target of 70% recycling within 2005.
ε = eco-efficiency (Euro/Pt.),
ε' = Relative eco-efficiency (Euro/Pt.),
Ψ^* = Aggregated total environmental impact (Pt.),
Ψ = Annual total environmental impact (Pt.),
ψ = Environmental impact (Pt./ton),
ψ' = Relative environmental impact (Pt./ton),
κ = Costs (Euro/ton),
κ' = Relative Costs (Euro/ton),
w = Waste generation (tons),
r = Recycling ratio,
t = Time (years),
j = Waste fraction,
i = End of life treatment alternative,
a = Processes of product system A,
b = Processes of product system B.

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References

[1] Økobygg. Nasjonal handlingsplan for bygg- og anleggsavfall. Technical report, Økobygg/GRIP, Oslo, 2001.

[2] A. Sturm and S. Shaltegger. Ökologieinduzierte Entscheidungsinstrumente des Managements, 1989.

[3] BSCD. Getting eco-efficient. Technical report, Report of the Business Council for Sustaineable Development, First Antwep Eco-Effiency Workshop, Geneva, November 1993.

[4] C. Keffer, R. Shimp, and M. Lehni. Eco-efficiency Indicators & Reporting. Technical report, WBCSD, Geneva, April 1999.

[5] H.A. Verfaille and R. Bidwell. Measuring eco-efficiency. A guide to reporting company performance. Technical report, WBCSD, June 2000.

[6] S. Schmidheiny. Eco-efficiency. Creating more value with less impact. Technical report, WBCSD, August 2000.

[7] H. Bergsdal, R.A. Bohne, and H. Brattebø. Projection of waste amounts from the AEC-industry in Norway. 2004.

[8] K. Shpresa, A. Shuurmans, and S. Edwards. Life-cycle assessment in building and construction. State of the art report, SETAC, 2003.

[9] B. Weidema. Avoiding co-product allocation in life-cycle asssessment. *Journal of Industrial Ecology*, 4(3):11–34, 2000.

[10] B. Weidema and G.A. Norris. Avoiding co-product allocation in the metals sector. In *Presentation for the ICMM International Workshop on Life Cycle Assessment and Metals*, Montreal, Canada, April 15th-17th. 2002.

[11] H.A.U. de Haes. Industrial ecology an dlife cycle assessment. In R.U Ayres and L.W. Ayres, editors, *Handbook of industrial ecology*, chapter 12, pages 138–148. Edward Wlgar Publishing, 2002.

[12] R.A. Bohne and H. Brattebø. Eco-efficiency in Norwegian C&D waste recycling systems. In *ILCEDES*, Kuopio, Finland, 1st - 3rd Desember 2003.

[13] PRé Consultants. *SimaPro 5 User Manual*. PRé Consultants, 2002.

[14] Statistics Norway. Cost index for road goods transport, march 2004. www.ssb.no, March 2004.

[15] M.A.J. Huijbregts, G.A. Norris, R. Bretz, A. Ciroth, B. maurice, N. Mahasenan, B. von Bahr, and B.P Weidema. *A framework for evaluating data uncertainty in life cycle inventories*, pages 113–121. SETAC, 2003.

[16] UNCTAD. A Manual for the Preparers and Users of Eco-efficiency Indicators. Technical report, UNCTAD, 2003.

[17] P. Saling, A. Kicherer, B. Dittrich-Krämmer, R. Wittlinger, W. Zombik, I. Schmidt, W. Schrott, and S. Schimdt. Eco-efficiency Analysis by BASF: The Method. *Int J LCA*, 7(4):203–218, 2002.

[18] J. Huisman. *The QWERTY/EE concept.* PhD thesis, TU Delft, Delft, June 2003.