UPTEC W09 019
Examensarbete 30 hp
Juli 2009

Impacts on natural resources and climate affecting emissions from landfill coverage in Stockholm

Sluttäckning av deponi i Stockholm: projektets påverkan på miljö och utsläpp av klimatgaser

Erik Adriansson

Abstract

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Land development causes stress on the surrounding environment. Natural resources that we cannot replace are utilized in the extensive development. Land development and transport cause a large part of emissions in Stockholm. By planning with sustainable development the negative impacts can be limited.

What impacts can landfill activities have on the environment? In 2008 a landfill southeast of Stockholm was covered as a part of the city's environmental program. The landfill was covered with approximately 113 500 metric tons of mixed aggregates. All aggregates were secondary materials originating from contemporary land development projects in Stockholm.

The landfill coverage was studied with respect to energy use and emissions. A hypothetical case was also created, in which all landfill aggregates were produced from virgin material. The study was hence separated into two systems: one with secondary aggregates, and one with virgin materials. Evaluation of environmental impacts in each system was conducted with life cycle assessment methodology.

Results showed that the City of Stockholm kept emissions of pollutants at lower levels by using secondary materials in the landfill coverage. Greenhouse gas emissions were reduced by 48% when secondary aggregates were used as compared to usage of virgin material. Production from virgin material resulted in high energy consumption and consequentially high emissions. Production of aggregates from virgin materials contributed with 25% total CO_2-emissions, and 44% of energy consumption.

Emissions were kept low through minimized vehicle kilometers. By utilizing secondary materials 69% of the energy consumption was spared. Valuable natural resources of virgin materials were conserved.

Keywords: landfill coverage, aggregates, transport, environmental impacts, life cycle assessment

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ISSN 1401-5765

Referat

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Markexploatering påverkar miljön omkring oss. Värdefulla naturresurser förbrukas och utvecklingen leder samtidigt till skadliga utsläpp. Växande infrastruktur generar årligen stora utsläpp av klimatrelaterade gaser. Om en hållbar utveckling antas kan skadorna hållas nere.

Vad kostar en sluttäckning av deponi i utsläpp och energiåtgång? Under 2008 slutfördes en övertäckning av Skrubbatippen sydost om Stockholm. Vid sluttäckningen användes 113 500 ton återanvänt fyllnadsmaterial. För att minska projektets klimatpåverkan hämtades material från samtida exploateringsobjekt i Stockholm.

Begränsningen i utsläpp och energiåtgång vid sluttäckningen har här studerats. Ett fiktivt fall där sluttäckningen gjordes med jungfruligt fyllnadsmaterial undersöktes som jämförelse. Endast dem steg där materialhanteringen i de två fallen skilde sig åt studerades. Kvantifiering av miljöpåverkan i de två fallen gjordes genom livscykelanalys.

Resultaten visade att utsläppen av växthusgaser var 48 % lägre då sekundära fyllnadsmassor användes, jämfört med om jungfruligt material använts. Sluttäckning med jungfruligt material resulterade i en högre energiåtgång och medföljande höga utsläpp. Då sekundärt material användes sparade fyllnadsarbetet 69 % av energiåtgången. Nyproduktion av krossat stenmaterial och grus stod för 25 % av koldioxidutsläppen och 44 % av energiåtgången i det fiktiva fallet. Naturmaterialen har ej värderats i studien men bör användas så sparsamt som möjligt. En hållbar utveckling bygger på begränsade transporter och intelligent resursanvändning.

Nyckelord: sluttäckning av deponi, fyllnadsmaterial, transporter, miljöpåverkan, livscykelanalys

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ISSN 1401-5765

Preface

This project was written for Tyréns AB and is the Master Thesis project for the degree of Master of Science in Aquatic and Environmental Engineering at Uppsala University. The thesis covers 30 ECTS credits.

In particular, I send my gratitude to Susanna Bruzell for initiating the study, and for continuous supervision. Subject reviewer for this thesis has been Joel P. Franklin, Ph.D., Assistant Professor at the Department of transport and Economics, Royal Institute of Technology.

I wish to thank the staff at the Environmental department at Tyréns for supporting my work and contributing with their professional reflections. Anna Fröberg Flerlage, though constantly busy, provided data needed in my study. Figures are used with permission from the Swedish Energy Agency and the Swedish Environmental Protection Agency.

A special shout-out to Sanna Berg: thank you for bearing with me throughout my busy times.

This study was commissioned by the city of Stockholm, Exploaterignskontoret.

Stockholm, July 2009

Erik Adriansson

UPTEC W 09 019, ISSN 1401-5765.
Printed at the Department of Earth Sciences, Geotryckeriet, Uppsala University, Uppsala, 2009.

Populärvetenskaplig sammanfattning

Sluttäckning av deponi i Stockholm: projektets påverkan på miljö och utsläpp av klimatgaser

Erik Adriansson

Sverige har stora tillgångar på naturligt berg-, sten, och grusmaterial. Dessa material har utnyttjats sedan landet började bebyggas. Materialen fyller viktiga funktioner även i naturen. Den svenska landskapsbilden utgörs bland annat av grus och sten i berg och åsar, av den anledningen finns bevarandet med bland dem 16 Svenska miljömålen. Sten- och grusmaterialen har även mer direkta värden. Grusmaterial filtrerar ständigt vatten på väg genom marken till grundvattnet. Dessa värden och funktioner försvinner om naturmaterialen bryts och används vid byggnation.

Stockholm är en region under kontinuerlig tillväxt. Nya områden står städigt inför eventuell exploatering. Expansionen kräver både material och ny mark för vidare utbredning. Många projekt kräver stora mängder jord- och bergmaterial endast för grundläggningen. Samtidigt finns det många exploateringsobjekt som generar stora mängder spillmaterial, även kallat sekundärt material. I många fall transporteras dessa massor direkt till deponier. Det finns dock stor potential att använda materialet på andra håll där fyllnadsmaterial saknas. Vad som krävs för en hållbar hantering av materialet är framför allt en god planering av regionens tillväxt. För att sekundära material ska användas måste de vara fria från föroreningar. Egenskaper i fråga om kornstorlek och densitet måste även överrensstämma med uppställda krav. Om det är möjligt att använda sekundära material som fyllnad kan utvinning av jungfruligt material undvikas.

Exploateringen omkring Stockholm hotar tillgången på naturmaterial. Exploateringen leder även till ökade transporter med tunga lastfordon. Fordonsflottan bakom Sveriges tunga trafik drivs i stort sett uteslutande på fossila bränslen. Under tidigt 2000-tal är fortfarande bensin och diesel dominerande drivmedel bland dessa fordon. Konsekvensen är höga utsläpp av föroreningar. Årligen släpper fordonen ut ämnen med stor miljöpåverkan, både klimatet, stadsmiljön samt människors hälsa påverkas. Utsläppen leder även till övergödning och försurning, samt påverkar hälsan hos levande varelser. Med kännedom om detta är det viktigt att transporterna begränsas. Även med alternativa bränslekällor ger trafiken skadliga effekter.

Stockholm har ett pågående arbete för att minska belastningen på miljön i området. Enligt beslut i staden ska förutsättningarna för en hållbar utveckling förbättras. Genom detta ska utsläppen av växthusgaser och andra skadliga partiklar minskas. Detta innebär att klimatpåverkan ska begränsas och förutsättningar för god hälsa gynnas.

Som ett steg i miljöarbetet har Stockholms stad instiftat *Miljömiljarden*, en fond avsatt till miljöförbättrande projekt. Ett av projekten var sluttäckningen av *Skrubbatippen* i Tyresö. Området hade ursprungligen använts som grustag för att sedan fungera som avfallstipp under 50 år. *Miljömiljarden* möjliggjorde en övertäckning av området för att begrava avfallet och skapa rekreationsområde. Övertäckningen gjordes med omkring 113 500 ton fyllnadsmaterial. Allt fyllnadsmaterial hämtades från samtida exploateringsprojekt inom Stockholm. Fyllnadsmaterialet testades för att inte utgöra en långsiktig fara för miljö och hälsa i Skrubba. Samtliga sex exploateringsobjekt som bidrog med fyllnadsmaterial var belägna inom Stockholms län.

I denna studie utvärderades sluttäckningen med hänsyn till materialanvändning och klimatpåverkan. Bedömningen genomfördes med livscykelanalys (LCA). Livscykelmetodiken innebär systemstudie *från vaggan till graven*. Alla inflöden till systemet spåras till uttag av råvaror och alla utflöden följs till utsläpp och miljöpåverkan. Kort sagt inventeras systemets alla flöden av material och energi.

Utvärderingen av Skrubbatippen utformades som en jämförelsestudie. Ett fiktivt sluttäckningsfall där all fyllnad kom från jungfruligt material skapades som jämförelse. Energiflöden och utsläpp utvärderades i båda fall. När sekundära material användes var masstransport den enda befintliga aktiviteten. Jungfruligt material skapade ytterligare processer: utvinning och kross av material och transport till Skrubba. Allt sekundärt material transporterades samtidigt till en deponi utanför Stockholm. Dessa aktiviteter krävde energi och genererade utsläpp.

Resultaten visade att utsläppen av växthusgaser var nästan hälften så stora då sekundära fyllnadsmassor användes, jämfört med om jungfruligt material använts. Sluttäckning med jungfruligt material resulterade i en mycket högre energiåtgång. Då sekundärt material användes sparades omkring 70 % av energiåtgången. Av de processer som behövdes för användning av jungfruligt material var transporter mest energikrävande. Nyproduktion av krossat stenmaterial och grus stod 25 % av koldioxidutsläppen och 44 % av energiåtgången i det fiktiva fallet. Hantering av jungfruligt material ledde till närmare 70’000 fler avlagda transportkilometrar.

Naturmaterialet värderades inte i studien. Det står dock klart att naturgrus är en resurs som bör sparas för framtiden. Viktiga funktioner samt egenvärde i miljön kan inte ersättas av mänskliga aktiviteter. För att minska klimatpåverkan och energiförbrukning i samhället bör transporter begränsas. Som studien visat kan transportkilometrar och följande utsläpp begränsas genom att exploatering planeras. Återanvändning av fyllnadsmaterial leder till en hållbar utveckling för Stockholms stad.

TABLE OF CONTENT

1 INTRODUCTION

Intensified global warming, polluted air, eutrophicated water systems and depletion of the ozone layer. These are all examples of impacts that threaten to change the climate, and our environment. All these impacts result from anthropogenic activities. The cars we drive, the industries we depend on and the energy we produce - all activities have impacts on environmental systems.

The majority of all cars still run on fossil fuels. The combustion of fossil fuels in the engines results in emissions of compounds with long lasting environmental effects. Climate mitigation is one major impact that is not reversible from one generation to the next.

Wear and tear on natural resources can never be undone. With this knowledge it is necessary to use resources as efficiently as possible. Along with development of more energy efficient techniques we need to adapt more restrictive energy consumption. Natural resources need to be conserved.

The policymakers in Stockholm have adopted an environmental program that aim at sustainable development. At present, this program states the city's strategies until 2011 (City of Stockholm, 2008). The program involves strategies to limit emissions of pollutants and climate affecting compounds. The program also set goals for sustainable use of energy, land and water. To reach the goals it is vital to look for synergies in the strategies.

The City of Stockholm is constantly surrounded by land development projects. Many of these sites produce large quantities of aggregates as by-products. Some of these aggregates are contaminated with heavy metals or residues of other contaminants. Some aggregates are clean and can be use at other construction sites that yield material. The reuse of secondary materials, possibly from industrial activities, has been suggested earlier (Stripple, 2008; Engström et al, 2005). If resources are re-used it is also possible to reduce the energy consumption. With reduced use of energy there will also be a consequent decrease in emissions. With decreased emissions the climate mitigation can be slowed down. With effective strategies healthier environments can be established.

In 2007 the Swedish Environmental Protection Agency proposed a guide for handling of fill in land development projects – *Kriterier för återvinning av avfall i anläggningsarbeten, Handbok 2007:xx med Naturvårdsverkets rekommendationer för återvinning av avfall i anläggningsarbeten.* The guide stated new criteria for use of residual products. Both industries and scientists immediately claimed that the new criteria would oppose re-use of residual products. This study originated in the context of the proposed guide.

To attain a sustainable development natural resources have to be conserved. At the same time other environmental impacts need to be minimized as well. Total emission of greenhouse gases in Sweden was 65.75 million tonnes in 2006 (Swedish Environmental Protection Agency, 2008b). This study will evaluate if certain environmental impacts are reduced when residual products are used.

1.1 AIM

The aim of this master thesis was to evaluate environmental impacts associated with the coverage of a landfill in Stockholm. The impacts were studied in relation to emissions and energy consumption. A comparative analysis was performed to study environmental impacts in two scenarios:

Case 1: The landfill was covered with secondary material

Case 2: Virgin material was used as fill in the coverage

1.2 LIMITATIONS

The study focused on emissions from material transport. Kicked-up particles that result from transport were not included in the study. Energy consumption and emissions associated with production of machinery and vehicles was not included.

1.3 DEFINITIONS

Below are definitions of certain expressions that were central in this study.

- Aggregates: Rock materials of various size, ranging from small clay particles to large rocks
- CO_2-equivalents: System with certain factors assigned to each greenhouse gas to denote their global warming potential in relation to carbon dioxide
- Deposition site: Area used as placement for disposed landfill materials
- Functional unit: Object of analysis in a life cycle assessment
- Greenhouse gases: the gaseous substances that constitute the atmosphere and affect infrared radiation. A greenhouse gas absorbs and emits radiation at specific wavelengths
- Landfill: Method to dispose of solid waste by which the refuse is buried under layers of uncontaminated soil
- Secondary material: Aggregates produced as by-products from land development
- Virgin material: Aggregates that are extracted from nature to be used in constructions

2 BACKGROUND

2.1 PREVIOUS STUDIES

Since the beginning of the 21st century a number of studies have been concluded in areas pertaining to waste handling, use of aggregates or disposal of such. In scientific contexts life cycle assessment studies have evaluated environmental impacts from transport. Impacts from landfill coverage were studied in the report *Coverage of landfills in a national perspective* (Engström and Ulwan, 2005). The study focused on the extended coverage of landfills in Sweden. In their results Engström and Ulwan forecasted a shortage of conventional aggregates around 2010. To minimize community expenses and reduce negative environmental effects it is important to use secondary materials (Engström and Ulwan, 2005).

Another study regarding aggregates in landfills was performed as a life cycle analysis by Håkan Stripple at IVL Swedish Environmental Research Institute in 2008. Stripple's life cycle analysis emphasised how negative environmental consequences could be reduced if industrial residues were re-used. In the study Stripple specifically studied possibilities of using by-products from copper excavations. The by-product, a fine grained aggregate, could effectively be used as fill in road constructions. Stress on natural resources was heavily reduced when industrial residues were re-used (Stripple, 2008). Empirically, Stripple's results displayed that both energy and resources can be conserved.

The Swedish counties are responsible for giving permission to regional fill material excavations. The Swedish county administrative boards maintain records of all such permits. When this study was conducted the county administrative board of Stockholm's most recent updated inventory of aggregate production was from 2000 (County Administrative Board of Stockholm, 2000). The County Administrative Board of Stockholm also communicated necessary environmental strategies. Namely, the board declared that it shall support increased recycling of natural resources such as gravel and rock. Reuse of secondary aggregates was also stressed. Aiming at sustainable development, the County Administrative Board of Stockholm also stated that shipping by boat or train should increase.

Although the Swedish counties gather statistical information on the aggregate resources, it is mainly the Swedish Geological Survey that publishes such surveys. Based on information from the Swedish Administrative boards the Swedish Geological Survey has produced annual reports, *Aggregates: Production and resources*, in cooperation with the Swedish Environmental Protection Agency. When this study was performed, the most recent report of the aggregate series was from 2008, stating the prevailing situation of the production year of 2007.

2.2 SWEDISH ENVIRONMENTAL POLICIES

2.2.1 National policies

In 1999 the Swedish Parliament adopted 15 national environmental quality objectives, initially proposed in the government bill *Proposition 1997/98:145, Svenska Miljömål: Miljöpolitik för ett hållbart Sverige*[1]. An additional objective was adopted by the Swedish government in late 2005. This 16th objective addressed biodiversity, as proposed in government bill *Proposition 2004/05:150 Svenska miljömål – ett gemensamt uppdrag* [2]. The result was a line of 16 objectives, seen in Table 2.1 below (Swedish Government Offices, internet). To promote an implementation of the objectives based on broad cooperation and consultation, the parliament established the Swedish Environmental Objectives Council in 2002. The council was set to bring together and represent central government agencies, county administrative boards, local authorities, non-governmental organizations as well as the business sector. Since the establishment of the council, it has submitted annual reports on the progress to the Government.

The long term purpose of the 16 objectives was to reduce the pressure of Sweden's population on the environment by 2020, with one exception: the objective *reduced climate impact* is set to be attained by 2050. As stated in an evaluation of the environmental objectives, the life cycle

[1] My translation: *Government Bill 1997/98:145 Swedish Environmental Quality Goals: An Environmental Policy for a Sustainable Sweden*

[2] My translation: *Government Bill 2004/05:150 Environmental Quality Objectives – A Shared Responsibility*

perspective was crucial for a successful accomplishment (Swedish Environmental Objectives Council, 2008). With an environmental program of such width, life cycle perspective had a clear application: what is once extracted from nature should be recycled as far as possible and finally disposed of in a resource-efficient manner (Swedish Environmental Objectives Council, 2008).

Table 2.1 The 16 Swedish environmental objectives declared by the Swedish parliament

Objective	Prognosis of achievement by 2020
Reduced climate impact	No
Clean air	No
Natural acidification only	No
A non-toxic environment	No
A protective ozone layer	Yes
A safe radiation environment	Possibly
Zero eutrophication	No
Flourishing lakes and streams	Possibly
Good quality groundwater	Possibly
A balanced marine environment	No
Thriving wetlands	Possibly
Sustainable forests	No
A varied agricultural landscape	Possibly
A magnificent mountain landscape	Possibly
A good built environment	No
A rich diversity of plant and animal life	No

The table above shows expected fulfilment of the Swedish environmental goals. In 2009 only one out of 16 Swedish environmental goals was expected to be achieved by 2020.

As a step towards attaining the goals, the Swedish parliament adopted three national action strategies, based on *Proposition 2000/01:130 Svenska miljömål – delmål och åtgärdsstrategier* [3] (Government Offices of Sweden, 2001), namely:

- Efficient transport and energy consumption
- Non-toxic and resource-efficient cyclical systems, including an integrated product policy
- Management of land, water, and the built environment

These strategies all support sustainable development on national level.

2.2.2 Regional – County Administrative Board of Stockholm

In the fall of 1998, the Swedish government delegated the extensive environmental goals program to the County Administrative boards of Sweden (County Administrative Board of Stockholm, 2006). As a result of this action, each one of Sweden's 21 counties was delegated responsibility for the regional strive towards each one of the environmental objectives. One of the more important tasks related to the objectives was the County Administrative boards' assignment to give permits and supervise under the *Swedish Environmental Code (1998:808) – Miljöbalken*. Other tasks were related to treatment of contaminated areas, protection of endangered species and valuable areas.

[3] My translation: *Government Bill 2000/01:130 Swedish Environmental Objectives – Interim Targets and Action Strategies*

The relation between regional environmental goals of the Stockholm County and national goals is shown in Figure 2.1.

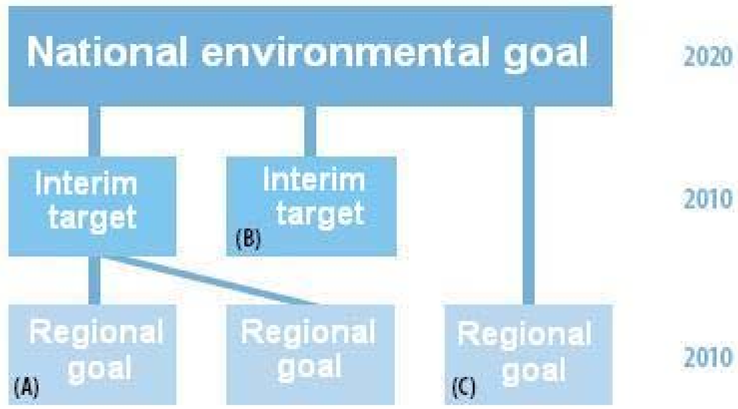

Figure 2.1 *Relation between Swedish national environmental goals and regional goals of the County of Stockholm (County Administrative Board of Stockholm, 2006).*

As displayed in the figure there is more than one relation between the environmental goals. Most regional goals were directly based on a national interim target (index *A* in Figure 2.1). One particular national interim target may also have set the base for more than one regional goal. Some regional goals were directly corresponding to a national environmental goal (index *C* in Figure 2.1). Some interim targets were not connected to a regional goal (index *B* in Figure 2.1). The goals of a *magnificent mountain landscape* and *a rich diversity of plant and animal life* were not regionalized.

2.2.3 Local – City of Stockholm

In the early 1990's greenhouse gas emissions were 5.3 tons per citizen and year in the Swedish capital (City of Stockholm, internet). In 1995 the City of Stockholm started its active work towards reduced emissions of greenhouse gases. After ten years, in 2005, emissions were down to 4.0 (City of Stockholm, internet). Climate change is not the only impact where the City of Stockholm In 2008 the City of Stockholm declared an environmental program consisting of six goals (City of Stockholm, 2008):

- Environmental efficient transport
- Goods and buildings free of dangerous substances
- Sustainable energy use
- Sustainable use of land and water
- Waste treatment with minimal environmental impact

- A healthy indoor environment

Four of these targets were directly aimed at sustainable development: environmental efficient transport, sustainable energy use, sustainable use of land and water and waste treatment with minimal environmental impact.

2.3 TRANSPORT AND CLIMATE AFFECTING EMISSIONS

In 2004, 26% of the world's energy use was amounted by the transport sector (Barker et al., 2007). This was brought to attention in the report *Mitigation of Climate Change* from the United Nations Intergovernmental Panel on Climate Change (IPCC). In *Sweden's National Inventory Report 2008* the Environmental Protection Agency declared that total emissions of greenhouse gases in Sweden was 65.75 million tonnes in 2006. Approximately 20.2 million tonnes – 31% – of the greenhouse gas emissions was amounted by the transport sector (Swedish Environmental Protection Agency, 2008b). With international transport included the total greenhouse gas emission in Sweden was approximately 76 million tonnes (Swedish Environmental Protection Agency, 2008a). Figure 2.2 show emissions from the Swedish transport sector per sub sector, and as total amount.

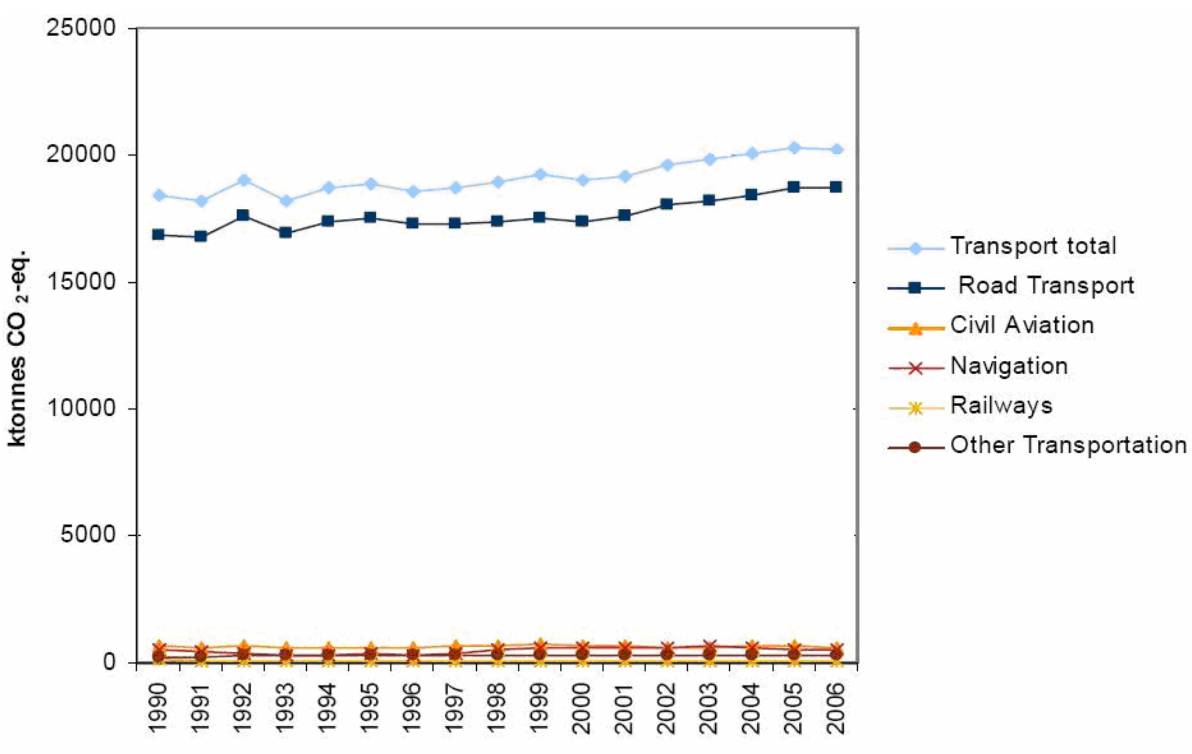

Figure 2.2 *Emissions from the Swedish transport sector (Swedish Environmental Protection Agency, 2008b).*

The graph shows an increase of total transport from 1990 emissions to 2006. The increase was principally traced to transport by heavy diesel vehicles (Swedish Environmental Protection Agency, 2008b). Within the County of Stockholm corporate transport constituted 20% of all vehicle kilometers in 2005 (Kommunförbundet i Stockholms län et al., 2005). The high emissions of greenhouse gases in Sweden are connected to the common use of fossil fuels. In the early 21st century gasoline and diesel still dominated the Swedish fuels market for transport. Figure 2.3 show proportion of fossil fuels in relation to total energy use in Sweden.

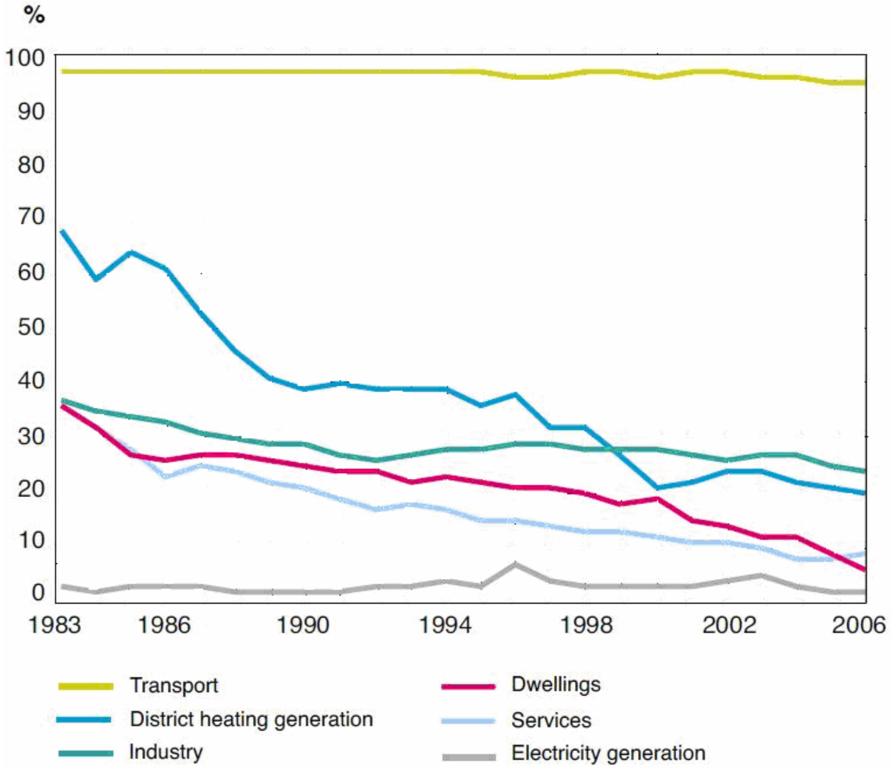

Figure 2.3 *Percentage of energy derived from fossil fuels in Sweden's most energy consuming sectors (Swedish Energy Agency, 2008).*

Close to 100% of all energy consumed in the transport sector came from fossil fuels, as the diagram above shows. Fossil fuels in the diagram included oil, coal, coke and gas. The wide use of fossil fuels in Swedish transport explains the high emissions of greenhouse gases.

With the heavy pollution and climate mitigation resulting from most transport, it is necessary to limit vehicle kilometers as much as possible.

3 METHOD

To evaluate environmental consequences of the studied landfill coverage following process was performed:

1. Create a model in Microsoft Excel to quantify emissions of pollutants from landfill coverage.
2. Run the model over data attained in the case study and evaluate emissions from the complete work of landfill coverage at Skrubbatippen.
3. Compare the case study to a hypothetical landfill coverage where all aggregates came from virgin material

This study was based on life cycle assessment methodology.

3.1 LIFE CYCLE ASSESSMENT

Life cycle assessment is a method applied in studies with the goal to gather information on environmental impacts from a given system. The life cycle strategy has proven useful in projects pertaining to fields as wide apart as construction of roads and development of milk cartons (Stripple, 1995; Bodö, 2009). A particular strength of the life cycle assessment method is the possibility to focus on any type of product and the function it performs. The product can be a physical object which will be evaluated with regard to its impact on the environment. The product can also be a service, which is studied with the purpose of mapping its environmental impact (Moberg et al, 1999). With no regard to whether the system performs a service or defines a product, the life cycle analysis is performed to assess the environmental impacts of the system. As the nomenclature advices, the system is studied with regard to its environmental impacts over a complete life cycle. In practice this means that impacts are assessed from the beginning of raw material extraction, through production, product utilization, re-usage and maintenance, recycling of materials and finally ending with disposal or decomposition (Stripple, 2001). A life cycle assessment is often used in evaluations of the environmental consequences as induced by the studied system. Examples of environmental impacts possible to study are eutrophication, heavy metal spreading or intensified global warming as resulting from greenhouse gas emissions.

At the end of the 20th century, principles and framework for the life cycle assessment method were developed by the International Organization for Standardization (ISO). The framework was organized in the ISO series 14040 (International Organization for Standardization, internet).

The life cycle assessment method has been applied in academic contexts since the 1990’s. Two recent reports in which the authors used the life cycle assessment methodology are Olsson (2008) and Stripple (2008). In these reports the authors evaluated the environmental effects from re-use of ashes, and re-use of residues from quarrelling, respectively. The authors used similar approaches to life cycle assessment and therefore served as a guide to the methodology used in this analysis. Coherent with practice of Olsson and Stripple, the life cycle assessment in this study consisted of four parts:

Scope definition. The primary step in a life cycle assessment is to state the goal and limitations of the study. This sets the detail level of the study.

Inventory analysis. As a second step of the analysis a complete collection of data is performed. After the scope and goals are defined all mass and energy flows are gathered in the inventory.

Impact assessment. When the inventory contains all data necessary for a complete study of the system calculations can begin. Data is analyzed and potential environmental consequences are evaluated. The impacts from each part of the system is evaluated. Environmental impacts caused by the system may be intensified greenhouse effect, acidification or altered concentrations of low level ozone, characteristics of the studied object.

Interpretation. As a final step the results of the analysis are evaluated. It is important to give examples of how the system may be improved to lessen the environmental impacts.

Each one of the above stated parts is described in individual sections below. Both form and function of each step is described.

3.1.1 Scope definition and goal

The first part of a life cycle assessment is to clarify the purpose of the analysis. When formulating the goal of the study it is also important to define the functional unit. The functional unit is chosen with respect to the study's purpose. The scope of the study is also defined. Scope definition includes system borders as well as limitations. The scope definition should include all system parts regarded in the study. It is important to clarify if any sub-components to the system are excluded. It is also necessary to consider other factors, such as:

- What type of environmental impacts will be studied
- Description and justification of the presumptions made in the study
- Description of the study's completeness. If any further aspects can be evaluated these should be clearly defined

3.1.2 Inventory analysis

The next step of the life cycle assessment includes forming of the life cycle inventory. In the inventory all data deemed necessary in the study is gathered. Data covering flows of energy or materials in or out of the system should be included in the inventory. The system may include transport, extraction from natural resources, and manufacturing of components or disposal of material used in system sub-parts. Each sub-part of the studied system includes specific inflows and generates certain outflows. Each sub-step inflow should be traced to the extraction of raw materials (Stripple, 2001). Consequently, each outflow should be traced to emissions to the environment (Stripple, 2001). A completed life cycle inventory should contain all information concerning in- and outflows from the system.

3.1.3 Impact assessment

The impact assessment is a summary of all the studied system's environmental impacts. System outflows that have similar impact on the environment can be grouped together. All impacts that are discussed should be described in relation to relevant environmental processes. Examples of impact categories that may be relevant in life cycle assessments have been suggested by Stripple (2001). Table 3.1 shows examples of common impact categories.

Table 3.1 Environmental impact categories that may be included in a life cycle assessment (Stripple, 2001)

Impact category	Impact
1. Resource consumption	1.1 Energy and material
	1.2 Land
	1.3 Water
2. Health effects	2.1 Toxic effects
(including working environment)	2.2 Physical effects
	2.3 Psychological effects
	2.4 Illnesses caused by biological organisms
3. Ecological effects	3.1 Global warming
	3.2 Ozone depletion
	3.3 Acidification
	3.4 Eutrophication of aquatic systems
	3.5 Eutrophication of terrestrial systems
	3.6 Formation of photochemical oxidants
	3.7 Ecological toxicity
	3.8 Effects on the biodiversity

The impact assessment should include characterisation and valuation of each impact category relevant to the studied system.

3.1.4 Interpretation

When impacts have been introduced and connected to impact categories they should be evaluated. Impacts can be evaluated in relation to both scientific and social contexts. There are several approaches to this part of the life cycle assessment. One option is to compare two or more impact categories. In a comparison of impact categories the aim should be to ascertain which category that holds the highest relevance. In this step it may be relevant to discuss impacts that have been evaluated with connection to moral factors (Stripple, 2001). The comparisons can be done both qualitatively and quantitatively. The final step of the evaluation should be suggestions of system improvements. Improvements should perform most efficient impact reductions.

4 ANALYSIS - LIFE CYCLE ASSESSMENT

4.1 GOAL AND SCOPE DEFINITIONS

The main target in this study was to evaluate greenhouse gas emissions connected to handling of aggregates in a landfill covering within the Stockholm region. The alternatives of re-using secondary material or virgin material were of specific interest.

The system analyzed in this study had two functions: aggregates produced through land development were to be taken care of, and a landfill had to be covered with aggregates. If the aggregates were used as landfill there was no need for production of aggregates. If the aggregates produced during land development were taken to deposition sites there was a consequent need for production from virgin material. The functional unit was defined as the mass needed in the studied landfill coverage. The mass equalled approximately 113 500 metric tonnes of aggregates. The material composition was roughly 53% crushed rock and 47% soil or sand aggregates. The study consisted of two cases:

Case 1: Secondary material was used for landfill covering. Land development sites provided aggregates suitable for landfill coverage.

Case 2: Secondary material was taken to deposition sites for definite storage. Aggregates extracted from virgin material in natural resources were used for landfill coverage.

Both cases were based on the functional unit. The only aspect separating the two cases was the material's origin.

4.1.1 Model structure

A life cycle analysis model was created to calculate emissions from the studied system. Microsoft Excel was used as platform for the model. The scope of the model is seen in Figure 4.1. As the flow chart shows, three sections constituted the model. One section described disposal of aggregates that were produced as secondary material at land development sites. In relation to this one section described the production process for virgin material suited for landfill. Another section described the process of using secondary material as landfill.

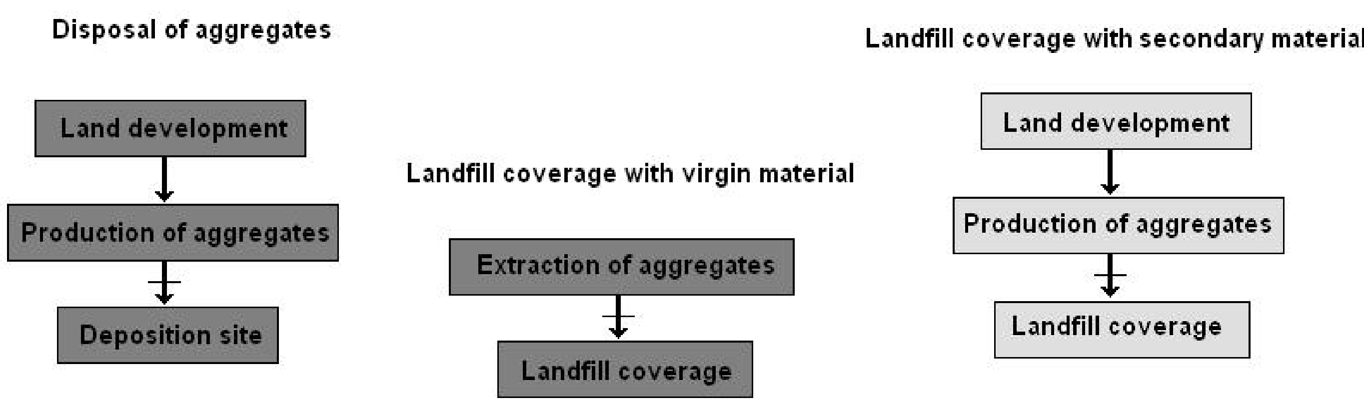

Figure 4.1 *Simplified flow chart showing sections that constituted the LCA-model: disposal of aggregates, landfill coverage with virgin and secondary material, respectively. The two colors indicate which scenario each section was connected to. The dark grey tone indicates components of Case 2 where secondary materials were disposed of, and virgin material excavated to function as landfill. The light grey tone indicates major sub-components of Case 1where the secondary materials available were utilized in landfill coverage. Arrows intersected by horizontal lines denotes transport.*

The two cases were based on the same functional unit – the quantity and quality of aggregates needed for landfill coverage at Skrubba. Use of energy in each case was also regarded in the study. The energy used in the system was exclusively fuel in the form of diesel. Diesel fuel was used in machines utilized for crushing aggregates in to smaller fractions. Diesel was also used in excavators and dump trucks that transported aggregates from production sites to end-use sites. At the end-use sites the aggregates was either used or disposed of.

A schematic flow chart of the life cycle model structure is shown in Figure 4.2. The two studied cases were separated in the model, as demonstrated in the figure. Each process in the model was accounted for in the life cycle inventory. Processes that were identical in the two cases were omitted in the analysis, the purpose was to compare differences between the scenarios.

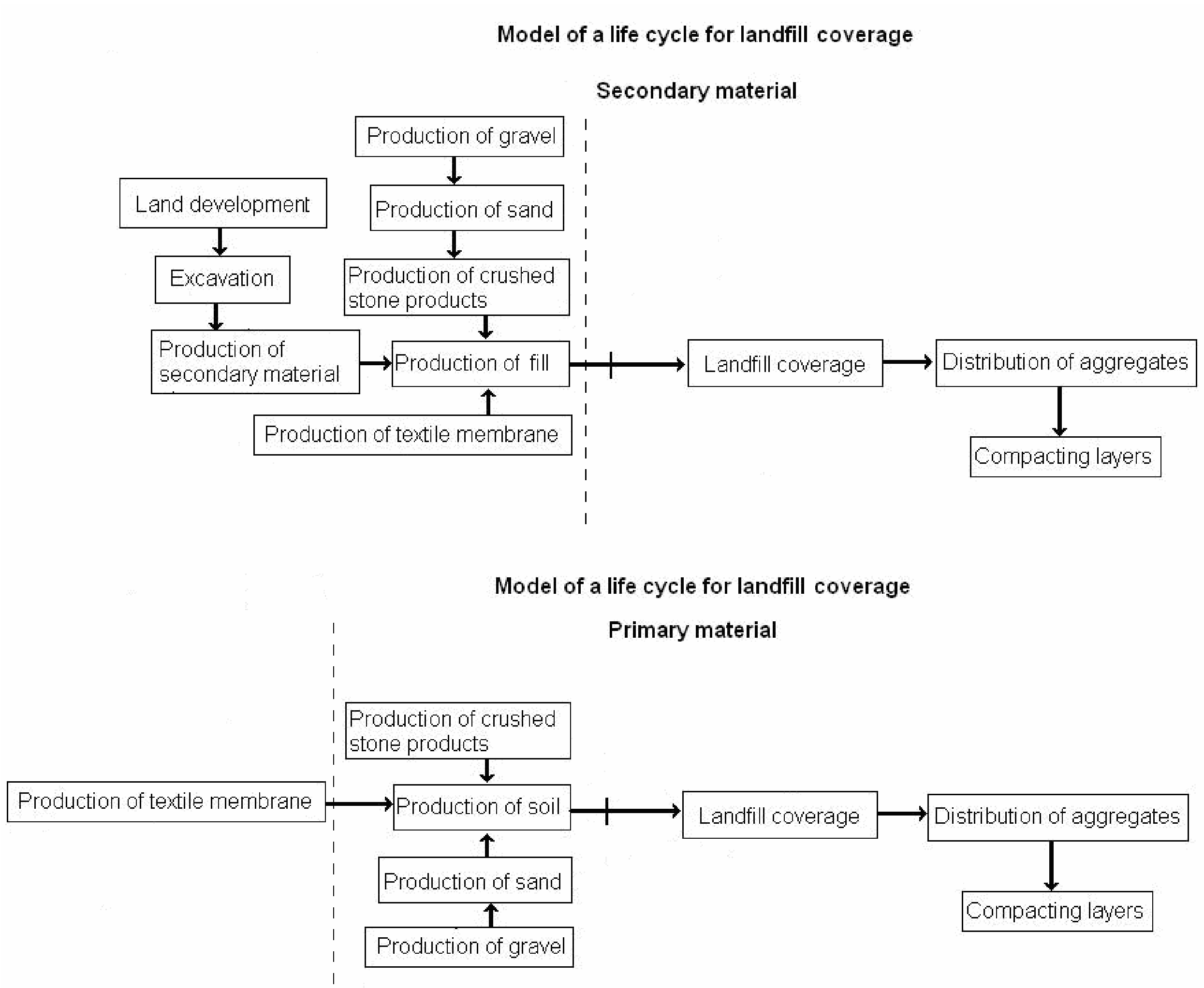

Figure 4.2 *Life cycle model structure for landfill coverage. Upper part represents Case 1, where secondary material was used. Lower section represents Case 2, in which virgin material was produced to function as fill. Intersected arrows indicate transport. Dotted lines show system borders.*

The two flow-charts in the figure above show simplified landfill processes. The inflow to the box labelled "landfill coverage" in upper section represents residues from processes outside the system border.

The boxes labelled “production of textile membrane” represent necessary a component in studied landfill coverage. As seen in the flow-charts above this component was present in both studied systems. The impact contribution from production and transport of textile membrane was equal in both systems and could thus be omitted in the actual life cycle assessment.

4.2 INVENTORY ANALYSIS

In the life cycle inventory all data necessary in the assessment is displayed. All data had a specific function when the LCA-model was arranged. Transport distances were based on road maps of the Stockholm area together with data on site locations from the landfill covering of Skrubba. The production of machinery such as crushing machines, dump trucks, excavators or wheel loaders was excluded in the life cycle assessment. Data from those processes was not part of the life cycle inventory. In this inventory all data necessary in the life cycle model is declared. The information given here was used in the assessment of environmental impacts from the landfill coverage in Skrubba, Stockholm.

4.2.1 Transport

Calculations of emissions from transport were executed with estimation of fuel consumption based on Stripple (2001, 2008). The vehicles used in the landfill coverage of Skrubbatippen were of two kinds: trucks able to carry a maximum load of 14 respectively 32 metric tonnes. The trucks were carrying full loads when distributing landfill to Skrubbatippen and empty when returning to pick up the next load. With such transport the average fuel consumption was approximately 0.34 l/vkm and 0.38 l/vkm, respectively (Stripple, 2001). Data on emissions from the diesel trucks that were used in the study are displayed in Table 4.1.

Table 4.1 Emissions and energy consumption for dump trucks carrying 14 and 32 metric tonnes, respectively, when fully loaded. Vkm representing *vehicle kilometre* (Stripple, 2001)

In or outflow	Unit	14 ton capacity truck Flow per MJ used diesel	32 ton capacity truck Flow per MJ used diesel	“Pre-combustion” - addition per MJ used diesel	14 ton capacity truck Total flow per vkm, full load, empty on return	32 ton capacity truck Total flow per vkm, full load, empty on return
Oil	MJ	1.0	1.0	0.1	13.1	14.7
CO_2	g	75	75	4	943	1050
SO_2	g	0.02	0.02	0.01	0.45	0.51
NO_x	g	0.5	0.6	0.004	6	8.06
Dust	g	0.01	0.01	0.0	0.1	0.14
CO	g	0.08	0.1	0.0	0.96	1.34
N_2O	g	0.002	0.002	0.0	0.02	0.02
CH_4	g	0.0	0.0	0.0	0.01	0.0

Carbon dioxide is the major constituent in emissions from dump trucks. From the table above it can also be noted that the larger capacity truck produces less emissions per mass load.

There were several routes of transport in the case study. In the landfill coverage of Skrubba secondary soil and sand materials were brought from land development projects at Annedal, Sabbatsberg, Snöflingan, Armborstet and Brovakten. Secondary crush products were brought from the infrastructure project Norra Länken north of Stockholm. Transport distances are displayed in Table 4.2. Production of vehicles was not incorporated in analysis.

Table 4.2 One-way transport distances that were covered in the life cycle model. Transport used in the model were those that 1: took material from development sites to disposal areas 2: took secondary material from land development sites to Skrubba, or 3: took virgin material material from production sites to Skrubba. Distances given in km.

Transport with truck one-way distances	1) Deposition of aggregates	2) Landfill with secondary material	3) Landfill with virgin material
From Annedal to Högbytorp	33.5	-	-
From Sabbatsberg Högbytorp	41.3	-	-
From Snöflingan to Högbytorp	38.0	-	-
From Armborstet to Högbytorp	50.0	-	
From Brovakten to Högbytorp	42.5	-	
From Annedal to Skrubba	-	31.0	-
From Sabbatsberg to Skrubba	-	21.0	-
From Snöflingan to Skrubba	-	23.0	-
From Armborstet to Skrubba	-	14.3	-
From Brovakten to Skrubba	-	21.3	-
From Norra Länken to Srkubba	-	21.0	-
From Sköndal to Skrubba	-	-	6.5
From Riksten to Skrubba	-	-	26.0

4.2.2 Production of aggregates

Productions of aggregates were done with bedrocks that were primarily blasted. The life cycle inventory of crushed aggregates was based on production at two specific sites. These sites held permits for aggregate production based on virgin materials. The production process started with rock material being blasted. Large aggregates were then transported with diesel driven trucks to crushing machines. Production of crushed aggregates here refers to the process in which a bed rock was broken down with the primary intent to produce aggregates. This process takes into account, blasting, transport of large aggregates to crushing machines, as well as the crushing process. Electrical energy used at the construction site was also accounted for in the emissions calculations. The vehicles that moved aggregates within production sites were standard diesel driven maintenance vehicles. An extended inventory over data on energy utilization connected to aggregate production sites was gathered from Stripple (2001). For inventory data concerning energy consumption related to aggregate production, see Table 4.3. The life cycle inventory for production of aggregates is displayed in table Table 4.4.

Table 4.3 Energy used in production of crushed aggregates (Stripple, 2001)

Energy source	Unit	Amount per tonne crushed aggregates produced
Diesel	litre	0.48
Diesel	MJ	17
Electricity	MJ	21.2

Table 4.4 Production of aggregates (Stripple, 2001)

Outflow	unit	Electricity used per tonne crushed aggregates produced	Total emissions per tonne crushed aggregates produced
CO_2	g	80.5	1420
CH_4	g	0.003	0.004
N_2O	g	0.01	0.036
SO_2	g	0.14	0.79
NO_x	g	0.2	0.12
CO	g	0.045	1.49
Dust	g	0.001	1.49
Oil	MJ	1.4	20
Biomass fuel	MJ	0.95	0.95
Peat	MJ	0.1	0.1
Coal	MJ	0.85	0.85

Extraction of gravel and sand from virgin material took place in typical pits. The sand and gravel aggregates were excavated by wheel loaders that had bucket holding capacities of 4.2-4.6 m^3, identified as *class 2* machinery. Life cycle inventory data related to production of sand and gravel is shown in Table 4.5.

Table 4.5 Extraction of gravel and sand from pits (Stripple, 2001)

In or outflow	Unit	Electricity production per tonne gravel/sand produced	Wheel loader operation, excavation class 2, per tonne gravel/sand produced	Total extraction, per tonne gravel/sand produced
Pit-run gravel/sand	g			1 000 000
Biomass fuel	MJ	0.11		0.11
Oil	MJ	0.15		1.04
Peat	MJ	0.01	0.89	0.011
Coal	MJ	0.10		0.096
Natural gas	MJ	0.02		0.022
Uranium	MJ	3.8		3.84
hydropower	MJ	1.1		1.13
CO2	g	9.1		72.8
SO2	g	0.016	63.6	0.047
NOx	g	0.022	0.031	0.6
Dust	g	0.000	0.58	0.023
CO	g	0.005	0.023	0.074
Radioactive discharge	manSv	0.0	0.069	0.0
Ashes	g	0.17		0.17
Radioactive waste:				
Highly active	cm3	0.003		0.003
Medium and low active	cm3	0.036		0.036
Demolition waste	cm3	0.036		0.036
N2O	g	0.001		0.002
VOC	g	0.003	0.001	0.044
CH4	g	0.000	0.041	0.0
Oil (aq)	g		0.0	0.0
Phenol (aq)	g		0.0	0.0
COD	g		0.0	0.001
Tot-N (aq)	g		0.001	0.0

As with the production of crushed rock materials the vehicle production was not included in this inventory over production of pit-run sand and gravel.

4.2.3 Wheel loader

In the study it was unclear as to which model of wheel loader that was used in the studied case. To build the life cycle model the inventory here includes data on a Volvo BM L180 wheel loader, commonly used for excavations. Data in Table 4.6 refers to a wheel loader with average capacity of 420 m^3/hr and shows fuel consumption and energy use. Table 4.7 shows emissions in relation to energy use for the Volvo BM L180 wheel loader.

Table 4.6 Production data for a wheel loader (Stripple, 2001)

Average production	Fuel consumption	Fuel consumption by material volume produced	Added energy by material volume produced
410 (m^3/h)	35 (litre/h)	0.085 (litre/m^3)	3.00 (MJ/m^3)

Table 4.7 Energy and emissions from wheel loader, model Volvo BM L180 with capacity of approximately 420 m^3/hr

Outflow	Unit	Total per MJ used diesel	Total per production volume (m^3)
Diesel	MJ	1.100	3.3
CO_2	g	79	237
SO_2	g	0.038	0.11
NO_x	g	0.71	2.14
Dust	g	0.028	0.085
CO	g	0.085	0.26
N_2O	g	0.002	0.005
CH_4	g	0.051	0.15
Oil (aq)	g	0.0	0.0
Phenol (aq)	g	0.0	0.001
COD	g	0.001	0.002
Tot-N (aq)	g	0.001	0.004

4.2.4 Excavators

The excavators were used when aggregates was loaded on to dump trucks for transport. The excavator type that the data corresponds to is an Åkerman model EC620. Data on emissions from the Åkerman is seen in Table 4.8. The data corresponds to loading activity with medium intensity and medium excavator capacity. Data on energy consumption and corresponding emissions on the Åkerman EC620 was gathered from Stripple (2001).

Table 4.8 Data over Åkerman EC620 excavator with average production of 360 m^3/h when loading a dump truck (Stripple, 2001)

Average production (m^3/h)	Fuel consumption (liter/h)	Fuel consumption per production volume (litre/m^3)	Added energy per production volume (MJ/m^3)
360	34	0.094	3.32

Inventory data concerning emissions and energy consumption related to the Åkerman EC620 excavator are displayed in Table 4.9.

Table 4.9 Data on energy consumption and emissions per volume handled by Åkerman EC620 excavator (Stripple, 2001)

In or outflow	Unit	Total per MJ used diesel	Total per production volume (m^3)
Diesel	MJ	1.1	3.65
CO_2	g	79	262
SO_2	g	0.038	0.126
NO_x	g	0.71	2.37
Dust	g	0.028	0.094
CO	g	0.085	0.28
N_2O	g	0.002	0.005
CH_4	g	0.0	0.0
Oil (aq)	g	0.0	0.001
Phenol (aq)	g	0.001	0.002
COD	g	0.001	0.004
Tot-N (aq)	g	0.0	0.001

4.2.5 Deposition of landfill

The deposition process started with the reception of aggregates at deposition sites. Excavators then distributed the materials on sight. The life cycle inventory includes all energy and emissions connected with the full caretaking of aggregates at deposition sites. Transport of material to the deposition sites was excluded. Aggregates that were taken to the sites were dumped upon arrival and then relocated for placement at designated areas within the deposition site. Aggregates dealt with in this study did not hold high enough levels of contaminants to be decontaminated. The aggregates were thus deposited without treatment. Table 4.10 shows data on energy consumption and emissions associated with deposition of landfill material. Emissions and energy use were based on data from wheel loader and excavators, see sections 4.2.3 and 4.2.4, respectively.

Table 4.10 Emissions and energy use for deposition of aggregates, includes use of excavator and wheel loader

Outflow	Unit	Total per MJ used diesel	Total per deposited volume (m^3)
Diesel	MJ	2.2	6.95
CO_2	g	158	499
SO_2	g	0.076	0.24
NO_x	g	1.42	4.51
Dust	g	0.056	0.18
CO	g	0.17	0.54
N_2O	g	0.003	0.01
CH_4	g	0.0	0.0

4.2.6 Aggregate densities

Landfill material composed of various aggregates that possess individual densities. Table 4.11 show densities for common landfill materials. The table separates densities for compacted and loose material.

Table 4.11 Material densities (Stripple, 2001)

Material	Compacted volume kg/m^3	Loose volume kg/m^3
Clay		
Dry	1640	1170
Damp	2100	1500
Dry with gravel	1660	1424
Wet with gravel	1840	1540
Compact	2017	1660
Soil		
Dry	1100	960
Damp	2100	1680
Sand/gravel mixed	1660	1420
Stone mixed (25 % stone)	1960	1570
Sand		
Dry	1600	1420
Damp	2070	1840
Dry with gravel	1930	1720
Wet with gravel	2230	2020
Gravel		
Dry	1470	1330
Wet	2340	2130
Rock		
Granite	2970	1980
Limestone	2640	1590
Sandstone	2400	1440
Stone, crushed	2670	1620
Plaster, solid	2580	1980

Materials used in the studied landfill covering had a mixed composition. The average density of the aggregates was approximately 1800 kg/m^3.

4.3 IMPACT ASSESSMENT

Emissions and energy consumption in the study was quantified with a life cycle analysis model. The model, created in Microsoft Excel, calculated total emissions in each of the two studied scenarios. Model results were exported as data on emissions and energy usage. In this section the impact assessment of each scenario is displayed as graphs that show amounted emissions.

4.3.1 Energy use

The energy used in the studied scenarios was mainly extracted from crude oil in the form of diesel fuel. Calculations were based on the amount of energy used for the delivery of approximately 113 500 tonnes of aggregates to the landfill covering in each case. Total amount of energy used in each case is shown in Figure 4.3.

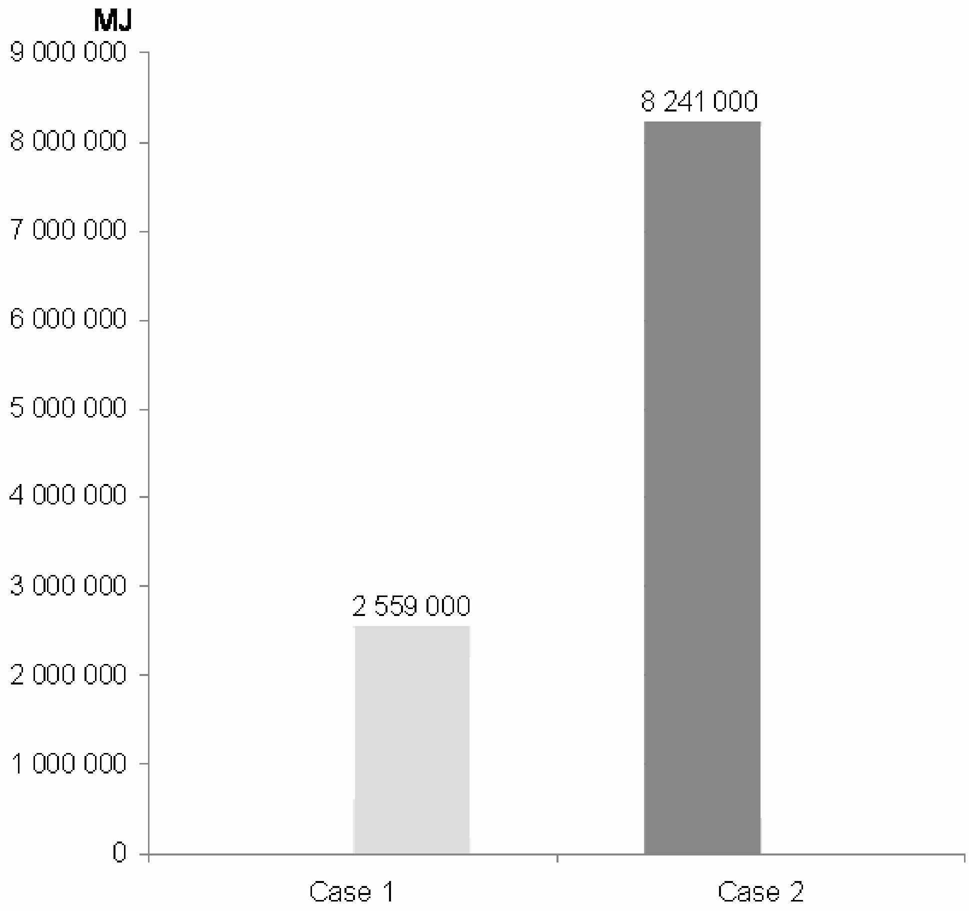

Figure 4.3 *Amounted energy use in Case 1 and Case 2.*

In *Case 1*, energy was only used for transport of secondary aggregates from land development sites. In *Case 2*, however, two different activities were necessary in addition to transport of aggregates: deposition of secondary material and production of virgin material. The latter category was further divided in production of crushed rocks and production of sand and gravel. Energy amounted by each activity in *Case 2* are shown in Figure 4.4.

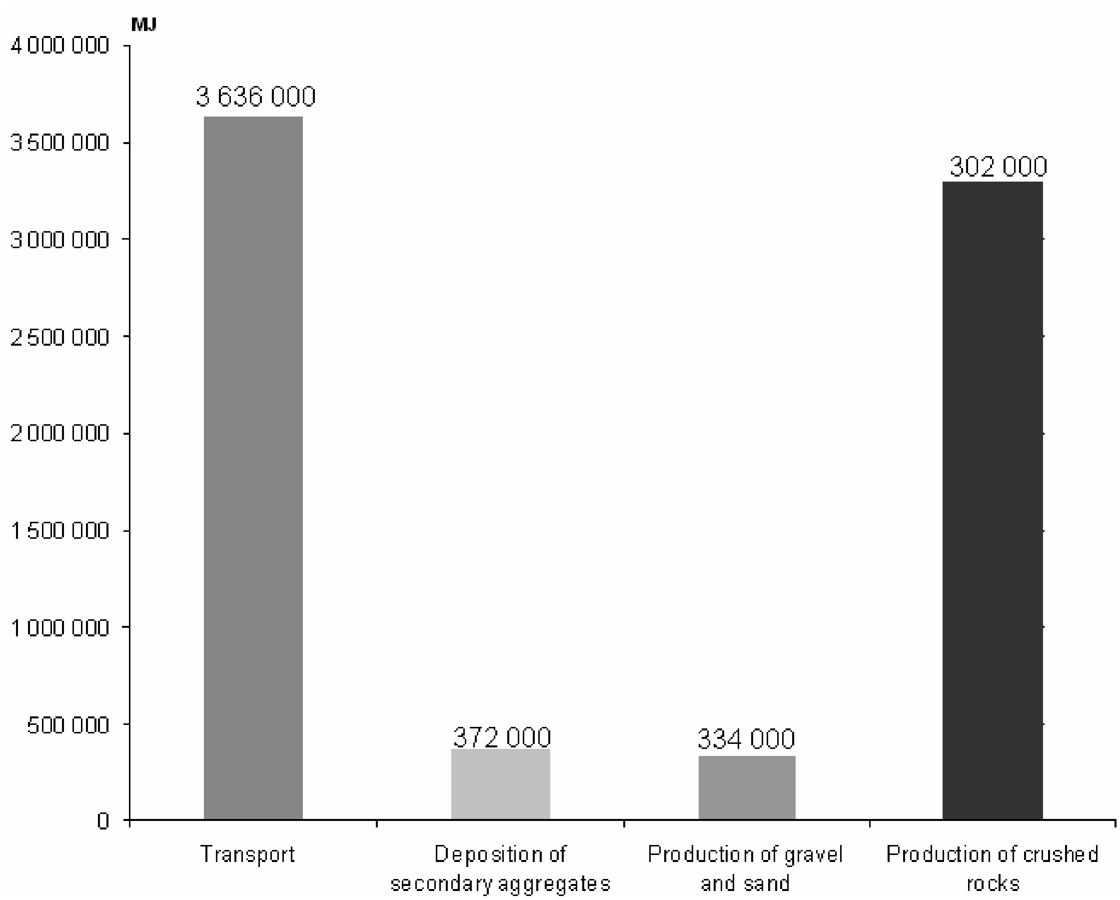

Figure 4.4 *Energy use separated by activity in Case 2.*

In *Case 2* transport of aggregates was the activity that used most energy. Both transport and production of crushed rock aggregates individually used approximately ten times as much energy as remaining activities. If transport distances had been slightly reduced in *Case 2* the production of crushed rock aggregates would have been the most energy demanding activity.

4.3.2 Transport distance

The two scenarios had a large variation of vehicle kilometers, as seen in Table 4.1.2. In *case 2*, where all aggregates were of virgin material, the calculations were based on transport distances from two production sites. These two sites delivered crushed aggregates as well as sand and gravel. In *Case 1* the secondary aggregates were gathered from six land development projects.

Table 4.12 Result output from model regarding transport distances

	Bogey [vkm]	Trailer [vkm]	Total [vkm]
Case 1	38 800	139 500	178 300
Case 2	0	247 300	247 300

Case 2 resulted in almost 39% more vehicle kilometers than *Case 1*. Transport was carried out with both trailers holding 35 tonnes and bogey transport holding 12 tonnes. Figure 4.5 shows vehicle kilometers by trailer and bogey, respectively, in each case.

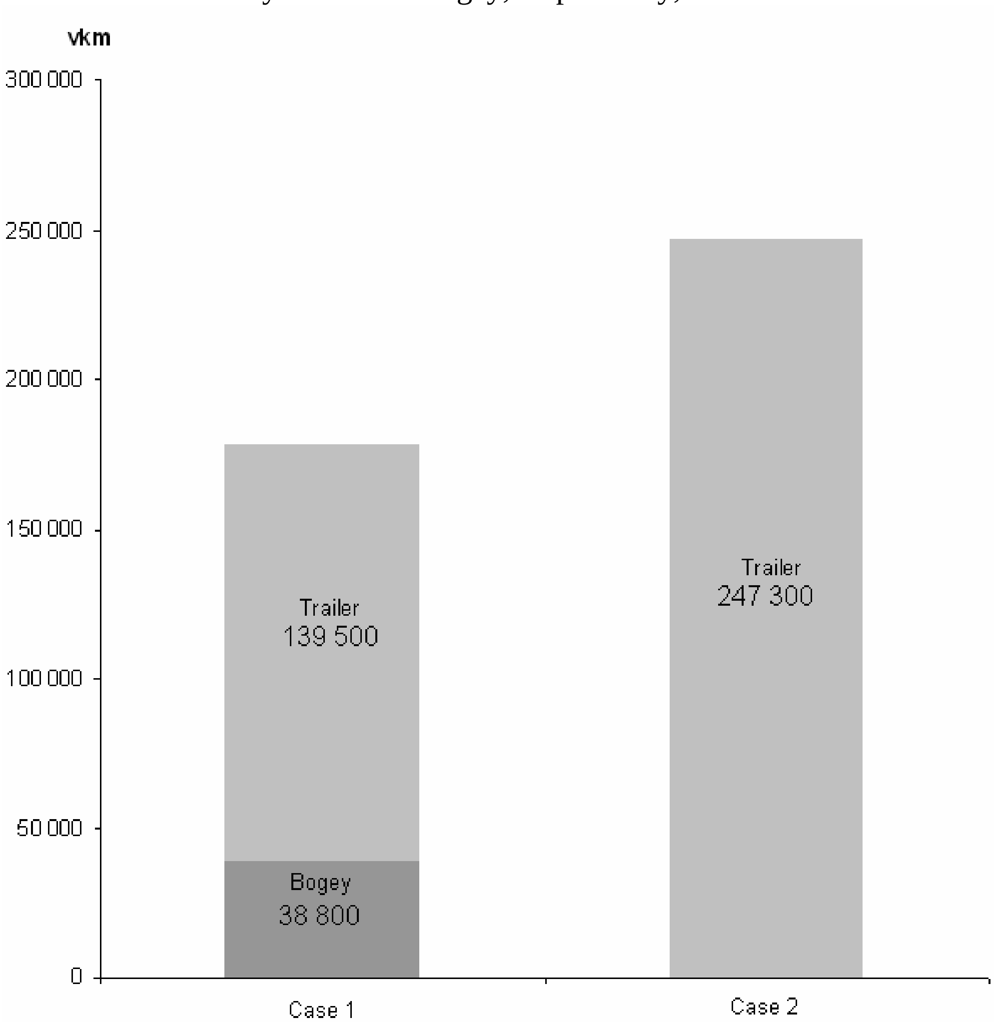

Figure 4. 5 *Transport distances in each studied case with distinction between vehicle kilometers by bogey and trailer transport.*

In *Case 1* all transport carried aggregates from land development sites to Skrubba where the landfill covering took place. *Case 2* included two types of transport activities: transport of aggregates from land development sites to deposition areas, and transport of virgin material from production sites to landfill coverage. Contribution from each transport activity is shown in Figure 4.6.

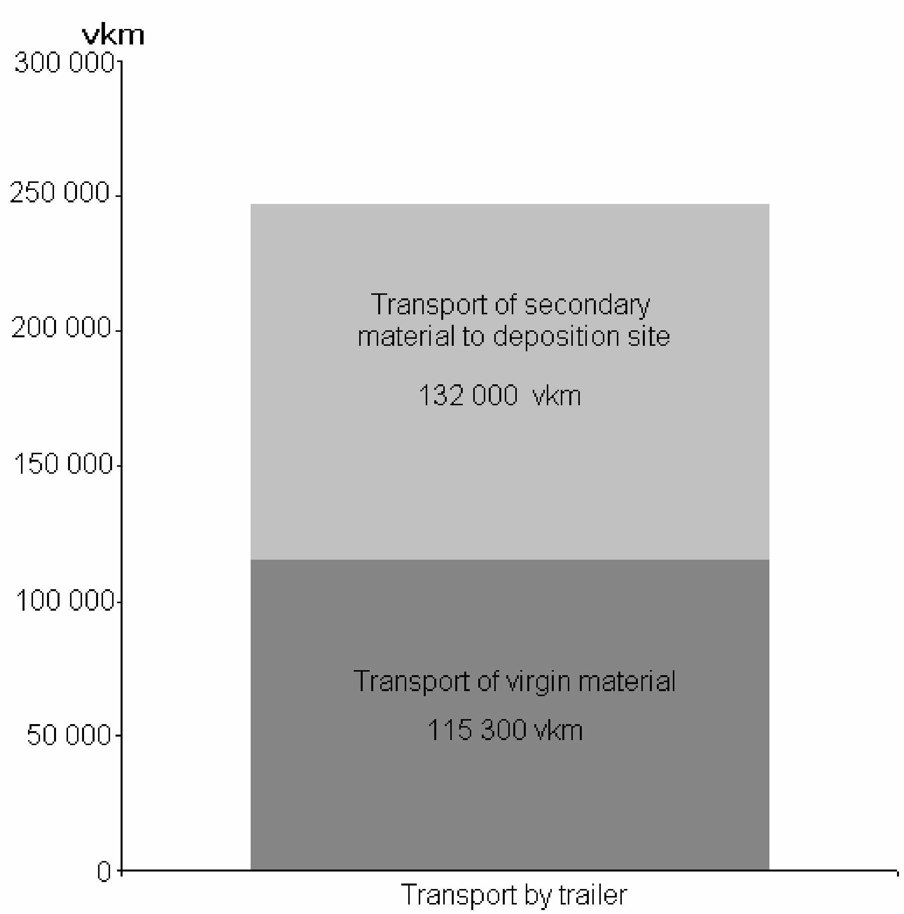

Figure 4.6 *Contribution to total amount of vehicle kilometers from transport of discarded aggregates and virgin material, respectively, in Case 2.*

In *Case 2* there was nearly as many vehicle kilometers spent on transport of virgin materials as on secondary materials. The amount of materials was the same, only destinations varied. All virgin material was transported to the landfill coverage and all secondary material was transported to depositions sites.

4.3.3 Emissions

The emissions produced in the studied scenarios were mainly caused by transport. The inflow of aggregates to the system formed in *Case 1* originated as waste produced by other land development activities. No secondary materials were used in *Case 2*. This demanded production of aggregates from virgin material. As a result of this *Case 2* included additional activities to road transport. All of these activities contributed with further emissions. Emissions accumulated in the studied cases are seen in Table 4.13.

Table 4.13 Total emissions [kg]

	Case 1	Case 2
CO_2	183088	351270
SO_2	88.3	188
NO_x	1358	2274
Dust	23	74
CO	224	453
N_2O	3.7	8.1
CH_4	0.12	0.43
Oil (aq)	0.93	1.8
Phenol(aq)	1.3	2.5
COD	2.8	5.2
Tot-N (aq)	0.44	0.83

In both cases CO_2 accumulated the largest quantity emissions. Total emissions of CO_2 were approximately one hundred times higher than emissions of NOx, which was the second quantitatively largest emitted compound in each case.

4.3.3.1 Emissions of carbon dioxide

Emission of carbon dioxide was the major pollutant in the landfill covering. Figure 4.7 shows emissions of carbon dioxide in each simulated case. *Case* 2 was the hypothetical case in which no secondary material was used. The consequent need for virgin material resulted in production of crushed aggregates and pit-run gravel and sand. These activities increased total emissions of CO_2 in comparison to *Case 1* where only secondary material was utilized.

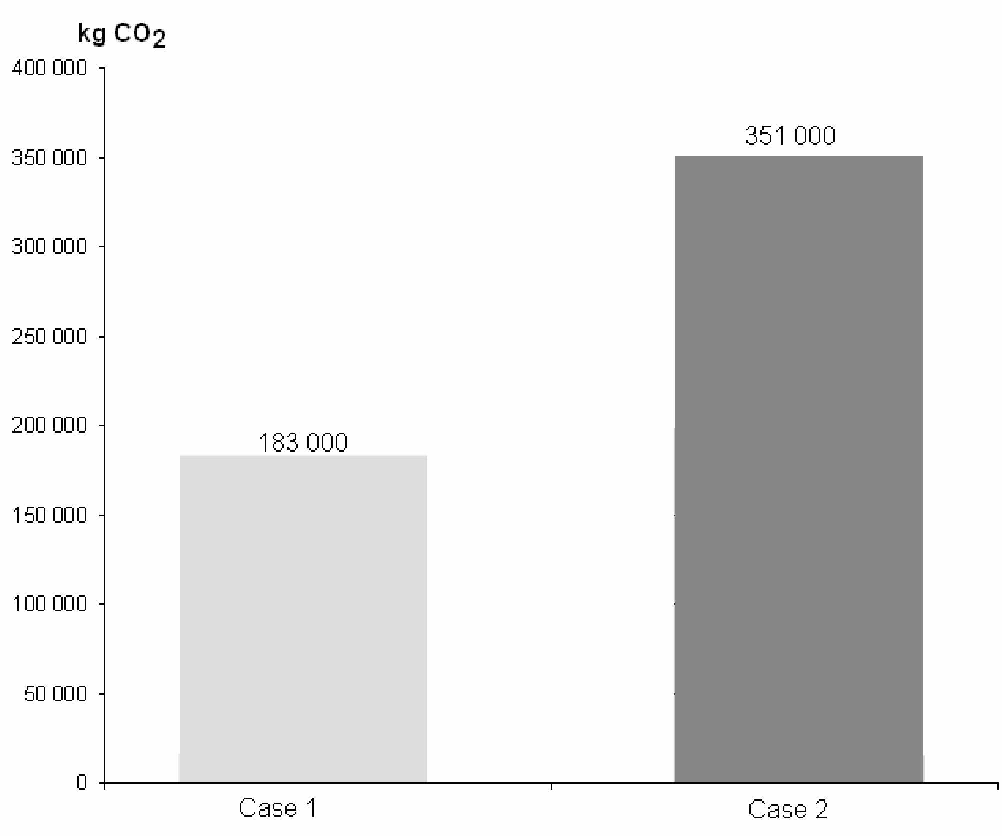

Figure 4.7 *Absolute emissions of CO_2 in each studied case.*

Case 2 amounted emissions of nearly twice as much carbon dioxide as *Case 1*. To display the individual contribution of carbon dioxide emissions from each process within C*ase 2* differentiated emissions are shown in Figure 4.8.

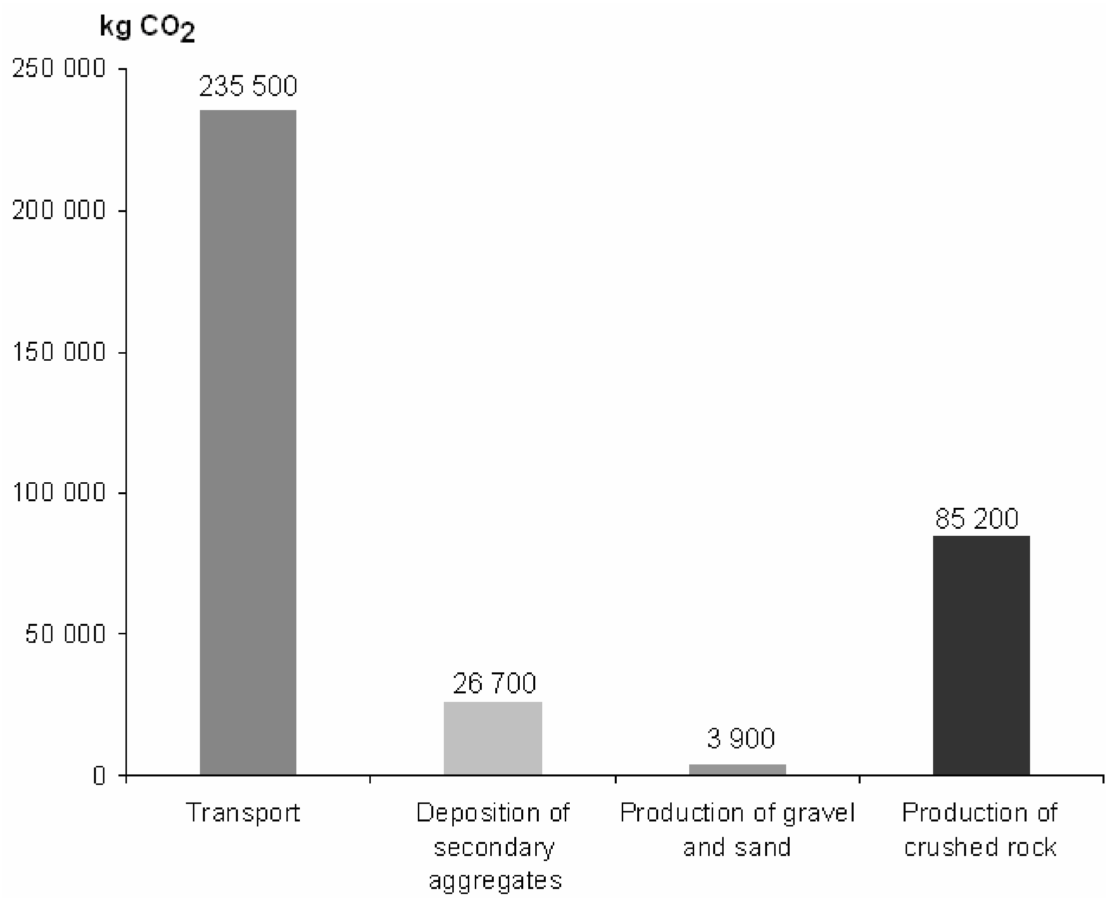

Figure 4.8 *Emissions of CO_2 from each process in the Case 2, where only virgin materials were used.*

Since *Case 2* called for extended transport of aggregates this process contributed with most of the carbon dioxide emitted.

4.3.3.2 Emissions of compounds other than carbon dioxide

Life cycle model results included emissions of a number of compounds other than carbon dioxide: SO_2, NO_x, CO, N_2O and CH_4. The results also included emissions of dust, oil, phenol and total nitrogen. Total emissions of studied compounds, as produced in each case, are shown in Figure 4.9.

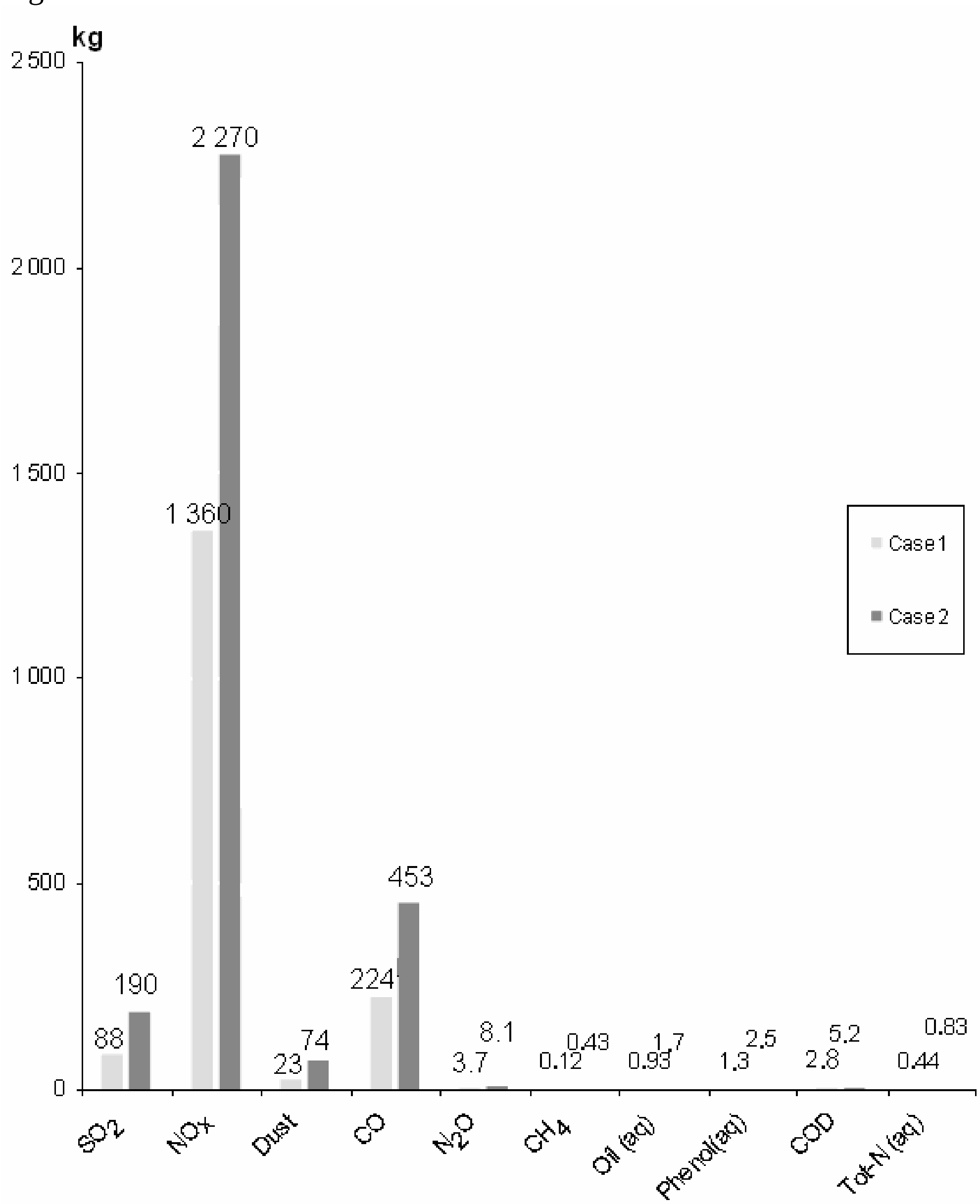

Figure. 4.9 *Absolute emissions of compounds other than CO_2 shown respectively for each case.*

The figure shows quantified emissions of all compounds other than CO_2 in each case. As the graph shows, all compound emissions were significantly smaller in Case 1 than in Case 2.

Emissions of oil, phenol, chemical oxygen demand (COD) and total nitrogen were also reported in the calculation model. These compounds were all emitted through combustion in the diesel engines used by transport and excavation vehicles. These emissions show greatest environmental impacts when spread to the hydrosphere. In aqueous environments such compounds inflict stress on ecosystems. However, as the emission data showed, neither case in this study generated considerable amounts.

4.3.3.2.1 Emissions of N_2O

Nitrous oxide is a greenhouse gas with high global warming potential. The compound is mainly produced through reactions in combustion engines. In *Case 1* the emissions of N_2O was 3.71 kg, as compared to 8.10 kg in *Case* 2. Transport of aggregates was the only activity that created N_2O-emissions in *Case 1*. In *Case 2* each one of the four activities contributed with N_2O-emissions, as seen in Figure 4.10.

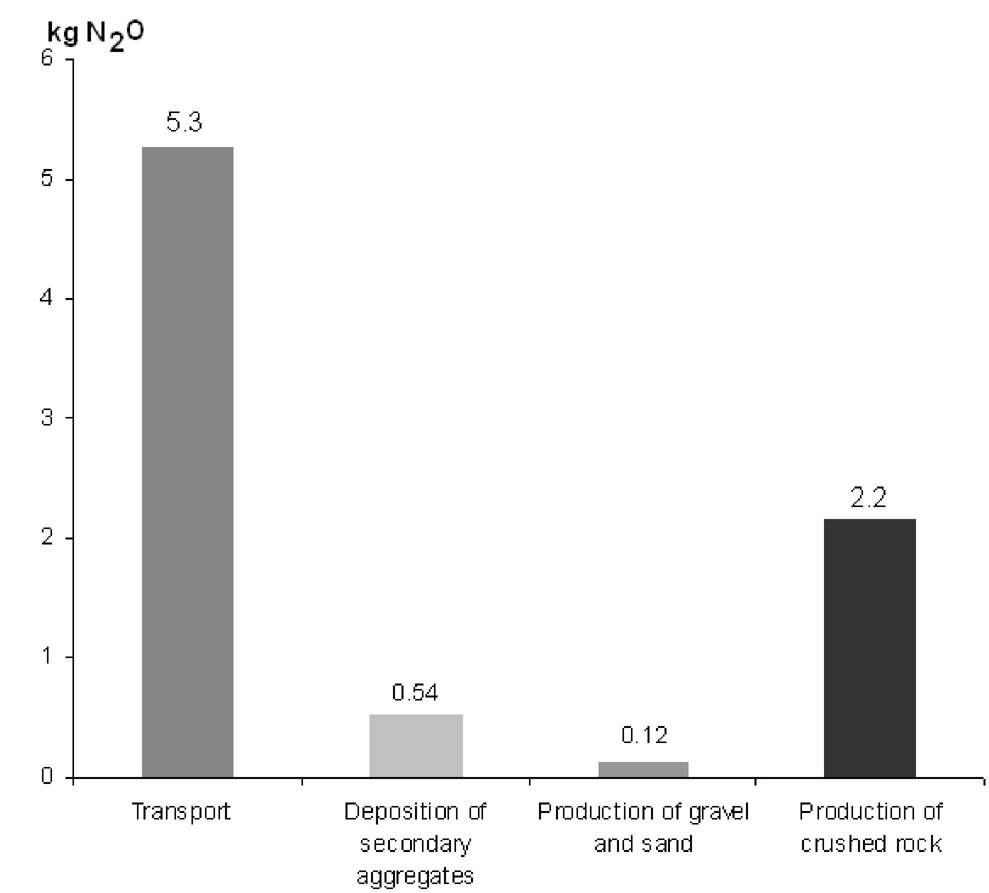

Figure 4.10 *Emissions of N_2O in Case 2.*

As the graph shows, transport of aggregates contributed with more than half of the amounted N_2O-emissions in *Case 2*. Approximately one fourth of the N_2O-emissions in *Case 2* were amounted through production of crushed rock products.

4.3.3.2.2 Emissions of NO_x

Nitrogen oxides are mainly spread to environmental systems through internal combustion engines. The compound contributes to both eutrophication and depletion of the ozone layer. In *Case 1* the total amount of emitted NO_x was nearly 1400 kg. Total emission of NO_x in *Case 2* was almost 2300 kg. When compared, emissions of NO_x in *Case 2* were approximately 67% more than in *Case 1*. Emissions of NO_x were mainly produced through combustion of diesel fuel. Figure 4.11 displays emissions from each process in *Case* 2.

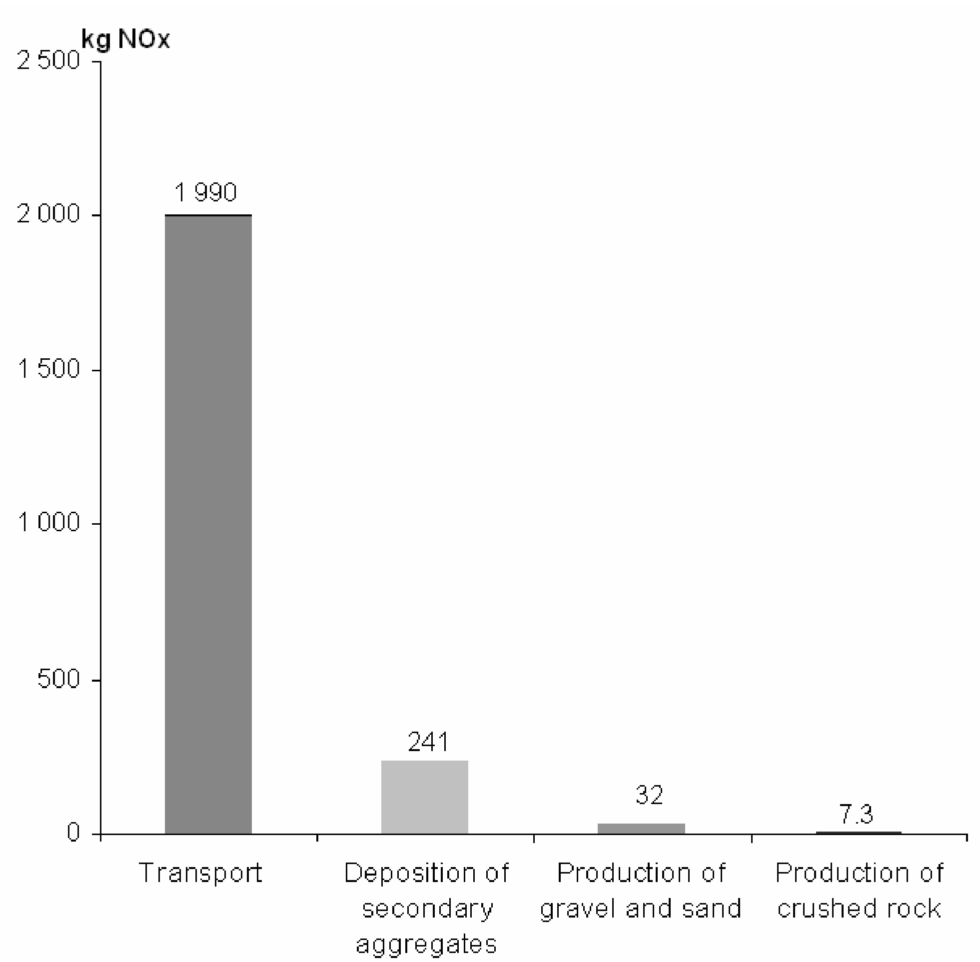

Figure 4.11 *Emissions of NO_x as contributed by each process in Case 2.*

Nearly all of the NO_x-emissions in *Case 2* resulted from transport. Transport amounted 87% of the emissions from studied processes.

4.3.3.2.1 Carbon dioxide equivalents

The principal greenhouse gases, carbon dioxide (CO_2), carbon monoxide (CO), nitrous oxide (N_2O) and methane (CH_4), can be expressed as carbon dioxide equivalents according to their individual global warming potentials (IPCC, internet). The global warming potential of each gas is related to the global warming potential of CO_2. The global warming potentials are weighted with respect to their decreasing effect over time. In Figure 4.12 the amounted emissions of principal greenhouse gases from each case is expressed in carbon dioxide equivalents (CO_2-eq.).

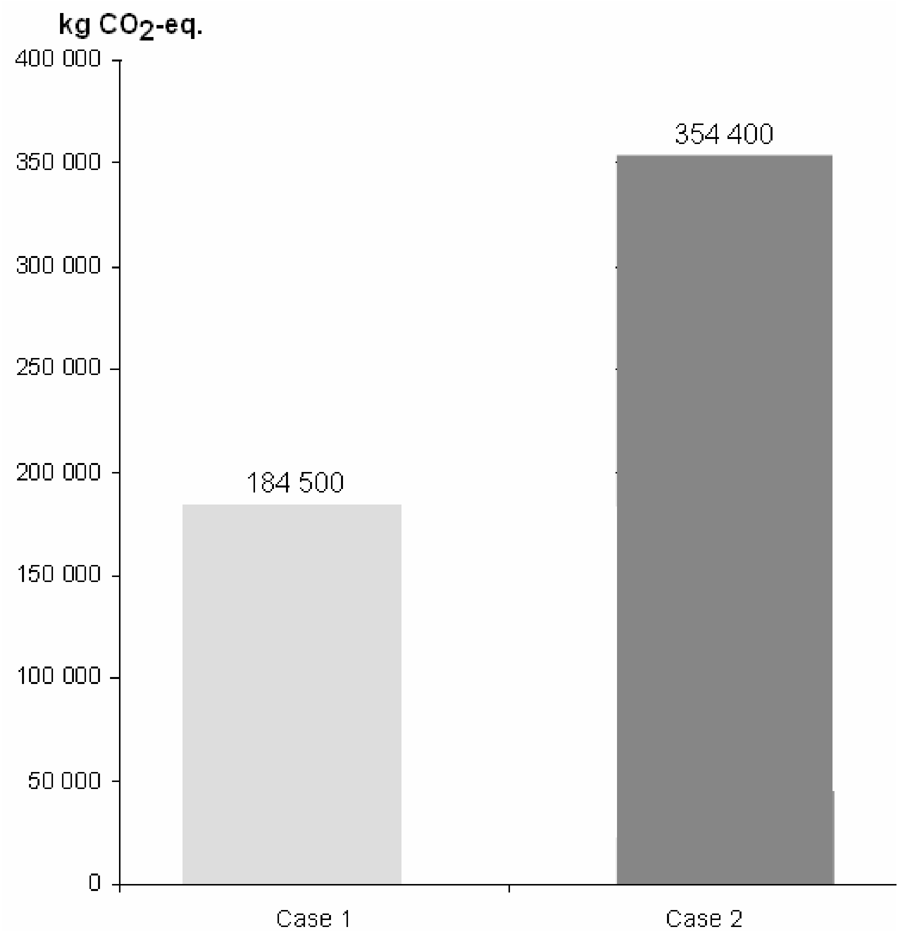

Figure 4.12 *Total emissions of greenhouse gases in the studied cases. Emissions are presented in carbon dioxide equivalents.*

The graph above shows that *Case 1* produced nearly half as much greenhouse gas emissions as *Case 2*. Together with Figure 4.8 this shows that CO_2 was the main contributor to the total greenhouse gas emissions in both cases.

4.3.4 Natural resources

The natural resources used in this system were all non-renewable. Aggregates that were excavated will not be replaced in nature over a short time period. Natural rock and gravel aggregates fill a specific function in the Swedish environment. Aggregates of various fractions filter precipitated water that later become ground water. Much of the Swedish fresh water supply comes from ground or surface water that has been filtered through these natural filter systems.

In this study both cases used the same amount of aggregates in the landfill coverage. In *Case 1* all material was produced as by-products from other land development sites. It was only in *Case 2* that excavation of virgin materials was necessary.

4.4 RESULTS

When virgin materials were used all secondary materials had to be transported to a deposition site. The deposition was necessary to complete the second system function – removal of aggregates from land development projects. Landfill coverage with virgin material hence necessitated additional vehicle kilometers. Transport increased with 39% more vehicle kilometers when virgin material was utilized. The extended transport consumed more energy and generated large emissions. In the activities here studied, emission of CO_2 increased with 29% due to transport of both primary and secondary materials.

Production of aggregates from virgin material also demanded large amounts of energy. Most energy used in aggregate production was derived from fossil fuels. Production of aggregates increased CO_2-emissions by 49% between the studied activities in *Case 1* and *Case 2*.

The total increase of emission from studied activities was approximately 92%, when emissions where measured in CO_2-equivalents. Emission of NO_x and N_2O also increased when virgin material was used as fill.

In the landfill activities that were studied, total use of energy increased by 122% from *Case 1* to *Case 2*. Transport was the overall most energy demanding activity. Transport used 44% of total energy consumed in the studied activities.

5 CONCLUSIONS AND DISCUSSIONS

The results here demonstrate that a landfill covering has less environmental impacts when residual products are used as fill. This was shown when two simulated landfill coverings were compared. The landfills were identical with the difference that residual products were used as fill in one case. The other landfill was covered with fill produced from virgin material. This slight difference in material origin resulted in synergies which affected environmental impacts. Transport distances were kept at a minimum when residual products were used. Virgin material resulted in other outcomes. These included increased environmental impacts. Mainly, virgin material resulted in greater transport distance. Transport of virgin fill hence produced large greenhouse gas emissions when compared to the option of residual fill.

Average emission from the studied activities in the landfill covering with recycled material was approximately 1.6 kg CO_2/ton used fill. The emissions were roughly 3.1 kg CO_2/ton when virgin material was used as fill.

These results indicate that stress on the environment can be reduced during land development projects. With the emission ratios presented above it is evident that absolute emission from a landfill covering is reduced as more residual products are used. Total CO_2-emission from studied activities was 48% lower when recycled material was used as fill. Further on, the total CO_2 emission would have been reduced by one fourth if primary and secondary materials were used in ratio of 1:1. Whenever there is a need for fill all options should therefore be considered.

Emission of greenhouse gases are but one of the consequences from transport in land development projects. In present study almost 3000 more trailer loads were used when secondary material was not utilized as fill. This excessive transport causes high pressure on roads and safety. Lined up on a road in a single file these trailers would stretch over 21 km.

If the circumstances allow, much of the future land development can be planned so that positive synergies are induced. Such planning can effectively lead to sustainable development. To apply sustainable development on projects that handle fill several steps should be followed. Primarily, the planning should aim to conserve natural resources. An early step in the planning process should therefore be to survey contemporary land development in the project’s vicinity. Within the region there might be several possibilities to trade fill. Residual products produced at one site might be requested at another. As fill is often an unwanted byproduct from land development it may create beneficial situations for all involved parts. The producer may avoid expensive transport to deposition sites as well as costs connected to refuse handling. Residual products are also less expensive than fill produced from virgin material, which should motivate eventual buyers.

A second step in the planning of land development projects that handle fill should be to evaluate transport routes. This should be done after surveying contemporary land development in the area. If fill is produced in the area it may be possible to avoid transport from production sites far from the prospected site. Besides environmental benefits, reduced transport is most likely linked to reduced cost. Possibilities of using residual products rely on both fill quality and quantity. This is why thoroughness is of highest importance in the primary survey. Residual products should only be used when there is no risk of spreading contaminants in harmful concentrations. Health aspects must always be considered.

Future research in this field should include additional simulated scenarios. The examples presented in this study are specific for the area around Stockholm. Deposition sites are far from the city where many land development sites are located. Fill production sites in Stockholm are also located far from the sites where fill is needed. Additional scenarios should therefore include shorter distance from land development site to deposition areas. Together with this study such simulations would be applicable on more general cases. According to emission ratios discussed above, it can also be of value to simulate landfill covering with fill mixed from both secondary and primary material.

Although transport distance may vary from one case to the next, these results indicate how environmental stress can be reduced through planned land development. Sustainable development necessitates reduced transport and restrictive excavation from natural resources.

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