Mat - 2.4177 Seminar on Case Studies in Operations Research

4. How to reduce CO2 emissions through better Supply Chain Management

Final Report

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Project for ROCE Partners

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2 Introduction

During the past decade, the significance of the green house gas emissions has increased with the growing knowledge of the climate change and global warming. Currently, governments are imposing regulations such as the EU emissions trading system to limit the externalities caused by CO2 emissions. Likely in the near future, these regulations, taxations and other actions required from companies are meant to be tightened. Additionally, companies are under pressure from environmentally conscious consumers and stock holders, who require detailed reports of caused emissions. The effects of the climate change and global warming on the world economy have been investigated and discussed widely[1]. Thus, the reduction of CO2 emissions is increasingly important factor in cost-effective supply chain planning in all companies. Tightened focus on emissions can lead to pro-environmental supply chain management.

Supply chain management (SCM) is the integration of key business processes from end user through original suppliers that provides products, services and information that add value for customers and other stakeholders (*Douglas M. Lambert*). Through successful supply chain management operations, a company can, among other things, hasten delivery times, and respond to quick changes in the market. SCM has grown to be one of the main competitive advantages for a manufacturing company in the world of increased expectations, and emission standards.

The purpose of this project was to examine supply chain planning in order to limit CO2 emissions. Our aim was to model and analyse the emissions caused by a unit of steel, using Swedish steel manufacturer SSAB as a case company. The work was carried out in collaboration with ROCE Partners, a supply chain consultancy company.

The project consists of three main parts: The literature review, the building of the supply chain model, and the scenario simulations of the model. The literature review was concentrated on providing the team appropriate information of the means to calculate CO2 emissions, and the supply chain modelling. With the holistic view of the research in the field, a relatively simple supply chain model, that captured desired elements related with CO2 emissions, was built. After this, the team proceeded to identification of different scenarios in order to investigate the amount of CO2 emissions throughout the supply chain. This was followed by scenario based simulations, i.e. utilization of the model, performed by using commercial simulation software. Finally, the results were analyzed.

[1] Stern, N. (2007). *Stern Review on The Economics of Climate Change. Executive Summary*. HM Treasury, London

This report is organized as follows. First, the results of the literature review are presented. This is followed by introducing the target industry in section Calculation of CO2 Emissions Caused by Steel Industry. In chapter Building the Model, the assumptions made for the simulation are described. The simulation scenarios and results are illustrated in the two last chapters Simulation Scenarios and Discussion of the Results of Simulation Based on Scenarios.

3 Literature Review

Since the focus of this study is in two rather specific fields, supply chain management and measuring emissions, a literature review was necessary. The aim of the literature review is two-fold:

1. Formulate a general understanding of the major concepts such as supply chains and CO2- and other greenhouse gas emissions in supply chains
2. Compile a list of factors to be taken into consideration when building and simulating the model

The literature review was carried out by searching for the latest research in the field of life-cycle assessment, green supply chain management and ecological indicator systems. Furthermore, articles on how environmental issues in the metal industries were studied to connect the themes involved to the case company. In addition to the articles give to us from ROCE Partners, articles were searched for by using Internet based scholarly search engines such as Google Scholar[2] and ISI Web of Knowledge[3]. Articles such as Seuring's and Sarkis's "Sustainability and supply chain management – An introduction to the special issue" [Seuring et al. 2008], that compile the results of the most important articles in the field of study were also used to detect the most relevant studies.

Three types of articles were found: (1) Articles covering supply chains and simulation in general, (2) studies of the methodologies to measure environmental impacts and (3) metal industry related articles. In general, we noticed that there is very little consensus on how to measure environmental impacts or how to formulate a supply chain model. Therefore the findings will be presented on a per article basis and conclusions will be drawn in the analysis of the literature review results.

3.1 Review of General Supply Chain Related Articles

3.1.1 "Development of a high-level supply chain simulation model" [Jain et al. 2001]

Jain and Workman describe an effort of developing a simulation model for evaluating business processes and inventory control parameters. A supply chain, according to Jain and Workman, "includes the transition

[2] scholar.google.com
[3] isiknowledge.com

and transportation of material from raw form through several stages of manufacturing, assembly and distribution to a finished product delivered to the end customer."

The article is a good overview of simulations in supply chains in general. According to the article, simulation has been identified as one of the best means to analyze supply chains. The study relates to key performance indicators of supply chains such as service levels, inventory turns and order to delivery lead times. The processes included order fulfilment, procurement and demand and supply planning.

Jain and Workman describe the steps of simulation. Abstractation is the process of determining what real-life process is modelled and on what detail. The performance measures should also be determined; what will the simulation measure? After determining the process and scope, the process model is developed. This is done by examining the process and gathering data. A good way to visualise the process is to draw flow charts. This static process model is then transitioned into a dynamic simulation model that can be used to forecast or estimate different scenarios.

The general supply chain simulations provide insight into the basic elements of a supply chain and the steps for the simulation. An in-depth study of general articles is, however, seen as irrelevant since this study is not concerned with typical supply chain performance criteria such as service levels and inventory turns.

3.1.1.1 "Supply chain planning under the European Union's GHG emission trading regime" [Roth 2004]

In his MBA management project report, Mathias Roth studies how to include potential effects of green house gases into typical supply chain models. His focus is on certain software, the i2 Technologies' Supply Chain Planner application. The software is used to optimise supply chains with decision support for production planning, revenue and profit optimisation, spend optimisation, logistics optimisation and fulfilment optimisation. His aim is to be able to incorporate the optimisation of green house emissions into a supply chain model and he discusses three possible approaches:

1. Resource
    - Emissions could be modelled as a resource that is used in the operations and constrained by the number of emission rights
    - Holds the assumption that further rights are not considered an option
    - Necessary to share the resource across all operations, which is unusual
2. Co-product
    - Emitting CO2 is treated as a co-product of the operations
    - Unusual to constrain the production of the main product due to a not desired by-product
3. Bill of Material

- Emission are modelled as a component for the production
- The component can be constrained or infinitely available, which is often modelled in supply chains

In his model, Roth decides to use the bill of materials approach due to its best fit to business cases, best modelling flexibility and the simplicity of the model. The method of incorporating emissions to previous models is out of the scope of this study, but it is valuable information to the party that gains our results of the sources of CO2 emissions.

3.1.1.2 "Investigating corporate social responsibility in supply chains: a SME perspective" [Ciliberti et al. 2008]

Ciliberti and Scozzi define CSR (corporate social responsibility) as "the voluntary integration, by companies, of social and environmental concerns in their commercial operations and in their relationships with interested parties." Companies must involve all firms in the supply chain to be effective in CSR terms. The study analyzes the practices of small and medium-sized enterprises (SME) to transfer socially responsible behaviours to suppliers that operate in developing countries. For our research the main finding is that when looking at the emissions of a company's product, you should look at the supply chain from cradle to the customers of the target company, since the company can only efficiently affect its suppliers; it has little power over its customers.

CSR in supply chains is also studied by Kovács [Kovács. 2008] who found that extending corporate social responsibility beyond corporate boundaries increases supply chain collaboration, increasing the role of supply chain management. She also found that environmental demand upstream in the supply chain can mediate environmental demand a to other industries (that are supplied by the same suppliers). Primary areas of supply chain environmentally-friendly practices are identified by Walton, Handfield and Melnyk [Walton et al. 1998]:

- Materials used in product design for the environment
- Product design processes
- Supplier process improvement
- Supplier evaluation
- Inbound logistics processes

3.2 Review of Methodology-Related Principles

3.2.1 Carbon Footprint

3.2.1.1 “A Definition of ‘Carbon Footprint’” [Wiedmann et al. 2007]

Wiedmann’s and Minx’s article “A Definition of ‘Carbon Footprint’” studies the ways of calculating the carbon footprint. The term “carbon footprint” has become very popular during the last decade with climate change becoming an ever-increasing concern. The term does not, however, have any commonly accepted definition. As Wiedmann and Minx write:

> *… the common baseline is that the carbon footprint stands for a certain amount of gaseous emissions that are relevant to climate change and associated with human production or consumption activities. But this is almost where the commonality ends. There is no consensus on how to measure or quantify a carbon footprint.*

Wiedmann and Minx highlight questions that are important for this study as well. For example, should the carbon footprint include just carbon dioxide emissions or should it incorporate other greenhouse gases as well such as N_20? Should it include all sources of emissions, not just those that are produced in the use of fossil fuels (such as CO_2 emissions from soil)? Should the carbon footprint figure be an absolute one indicating for example the amount of emissions, or a measure of impact on the environment? The most relevant question is whether the figure should include indirect emissions that are produced in upstream production processes or should it only include the emissions of the target organization or product. The different definitions found by Wiedmann and Minx are presented in table.

Table 1: Definitions of 'Carbon Footprint' [Wiedmann et al. 2007]

Source	Definition
BP (2007)	The carbon footprint is the amount of carbon dioxide emitted due to your daily activities – from washing a load of laundry to driving a carload of kids to school.
British Sky Broadcasting (2006)	The carbon footprint was calculated by “measuring the CO_2 equivalent emissions from its premises, company-owned vehicles, business travel and waste to landfill
Carbon Trust	“… a methodology to estimate the total emission of greenhouse gases in carbon equivalents from a product across its life cycle from the production of raw material used in its manufacture, to disposal of the finished product (excluding in-use emissions). “… a technique for identifying and measuring the individual greenhouse gas emission from each activity within a supply chain process step and the framework for attributing these to each output product will refer to this as the product’s carbon footprint.
Energetics	“… the full extent of direct and indirect CO_2 emissions caused by your business

(2007)	activities.”
ETAP (2007)	“… the ‘Carbon Footprint’ is a measure of the impact human activities have on the environment in terms of the amount of greenhouse gases produced, measured in tonnes of carbon dioxide.”
Global Footprint Network (2007)	“The demand on biocapacity required to sequester (through photosynthesis) the carbon dioxide (CO_2) emissions from fossil fuel combustion.”
Grub & Ellis (2007)	“A carbon footprint is a measure of the amount of carbon dioxide emitted through the combustion of fossil fuels. In the case of a business organization, it is the amount of CO_2 emitted either directly or indirectly as a result of its everyday operations. It also might reflect the fossil energy represented in a product or commodity reaching market.”
Hammond 2007	“The property that is often referred to as a carbon footprint is actually a ‘carbon weight’ of kilograms or tonnes per person or activity”
Haven 2007	The carbon footprint is described as a “life-cycle assessment which takes into account materials, manufacture, transport, use and disposal at every stage of development
Parliamentary Office of Science and Technology (POST 2006)	“A ‘carbon footprint’ is the total amount of CO_2 and other greenhouse gases, emitted over the full life cycle of a process or product. It is expressed as grams of CO_2 equivalent per kilowatt hour of generation (gCO_2eq/kWh), which accounts for the different global warming effects of other greenhouse gases.”

(Wiedmann and Minx mention that life-cycle thinking can be found in many definitions.) Finally, they suggest that a definition:

The carbon footprint is a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product.

The definition relates strongly to the methods in life cycle assessment that are also found in many of the other definitions. LCA will be assessed below.

According to Wiedmann and Minx, there are two different ways to calculate a carbon footprint: bottom-up, based on process analysis (PA) or top-down, based on environmental Input-Output analysis (EIO). Both methodologies are based on a full life-cycle assessment approach. The process analysis has been developed to understand environmental impacts of individual products from cradle to grave but suffers from a boundary problem, since only onsite and mostly first-order impacts are considered. The EIO analysis provides an alternative, where the input-output tables are economic accounts providing a picture of all economic activities. With environmental account data, they can be used to establish comprehensive and consistent environmental account data.

3.2.2 Life Cycle Assessment (LCA)

3.2.2.1 "Environmental supply chain management: using life cycle assessment to structure supply chains" [Hagelaar et al. 2002]

Hagelaar and van der Vorst's article assesses the use of life cycle assessment as a tool to analyse supply chains. They suggest that there are no guidelines as to how this should be done, and suggest that a distinction between different types of LCAs should be made.

An LCA is defined as an "instrument with which environmental effects of a product during its life cycle can be integrally assessed." The steps of making an LCA are:

1. Goal definition and determination of the scope
2. Inventory analysis
3. Impact assessment
4. Interpretation

The article suggests that there are three types of LCAs which are:

- Compliance oriented – Includes end of pipe data on emissions in order to show compliance with regulations
- Process-oriented – analysis aiming to measure the impact of a certain process, in order to achieve compliance with government rules and regulations and a better return
- Market oriented – A holistic approach that aims to measure the environmental burden caused by the design of the product. Here the LCA aims at achieving a competitive advantage.

Hagelaar and van der Vorst also review the different types of supplier co-operation structures that exist within a supply chain. The structures are identified based on their differences in complexity and how close the relationship between suppliers and their customers is. This analysis gives rise to four different types: a Multi-focus simple structure, a multi-focus network structure, a round table structure and a decomposed structure.

3.2.2.2 "An LCA study of a primary aluminium supply chain" [Tan et al. 2003]

Tan's and Khoo's article documents a study using a Life Cycle Assessment (LCA) approach for the production of aluminium billets. LCA is a systematic method for evaluating the environmental impacts of a certain product, process or activity, by identifying and quantifying energy and materials consumed and wastes released to the environment. A full LCA study includes the definition of goal and scope, life cycle inventory (data gathering), environmental impact assessment and interpretation. The research is implemented with a case study on aluminium production involving a refinery, a smelter, and a casting plant. The study focuses on the following major inputs and outputs:

- Main resources: bauxite and coal
- Bulk wastes: red mud from the refinery, solid wastes from the smelter, metal loss (scrap and dross) from the casting plant
- Carbon monoxide (CO), oxides of nitrogen (NO_x) and sulphur dioxide (SO_2) from bauxite mining
- CO_2, nitrous oxide (N_20), NO_x and oxides of sulphur (SO_x) from the refinery
- CO_2, N_20, NO_x, SO_x and hydrogen fluoride (HF) from the smelter
- CO_2, CO, methane (CH_4), N_2O, NO_x, non-methane volatile organic compounds (NMVOC), SO_x, and particulates from the power plant
- CO, NO_x, SO_2 and VOC from ship transportation
- CO, NO_x, particulates and VOC from truck transportation

Four different scenarios are tested with SimaPro LCA 5 software to calculate five different environmental impacts: (i) Global Warming Potential; (ii) acidification; (iii) human toxicity for air; (iv) resources; (v) bulk wastes. This is done by first characterizing the environmental impact categories according to their effect, then normalizing the results and finally weighting the normalized scores with a weighting factor representing the relative importance of the total environmental impact. The study states that the gases that contribute to global warming are mainly CO, CO_2, CH_4, and N_2O that are emitted directly from the refinery and smelter processes and indirectly from power plants. The total amount of emissions from transportations is not significant compared to the main processes.

The study was developed on a "cradle-to-gate" approach, although a full LCA study would incorporate a "cradle-to-grave" scheme. The authors also suggest to further look at "green trucks" or alternate modes of transportation from the bauxite mine to the refinery.

3.2.2.3 "Economic input-output models for environmental life-cycle assessment" [Hendrickson et al. 1998]

Hendirckson, Joshi and Lave study process and product models for performing LCAs. They present LCA as an important tool used in pollution prevention and green design efforts. LCA models assess the selection of product design, materials, processes, reuse or recycle strategies, and final disposal options. They present the SETAC-EPA LCA approach, determined by the Society of Environmental Toxicology and Chemistry (SETAC) and the Environmental Protection Agency of the United States (EPA). This approach focuses first on manufacturing processes. Factors included in the model consist of consumed fuels, other resources and the amount of each waste generated by the process. The most important upstream suppliers and downstream activities (recycling and disposal) are taken into the analysis. An example of a life cycle of a steel-reinforced concrete component is presented in **Error! Reference source not found.**. An analysis of this life-cycle etermines the required inputs, such as the amount of coal and iron ore, and environmental outputs.

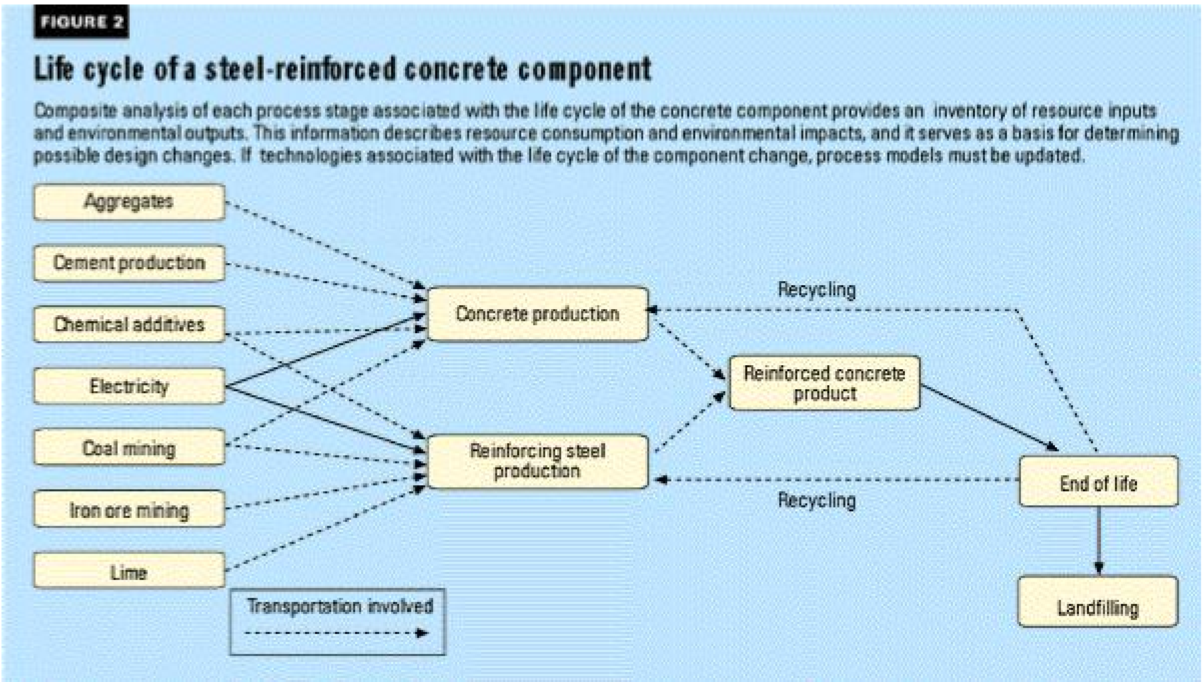

Figure 1: Life cycle of a steel-reinforced concrete component" [Hendrickson et al. 1998]

3.2.2.4 "Fuzzy outranking for environmental assessment. Case study: iron and steel making industry" [Geldermann et al. 1998]

Geldermann, Spengler and Rentz accept the LCA as an instrument for the environmental assessment of products. They determine the same four steps of LCA as in the article by Hagelaar et al. and explain that these steps have been harmonized in the ISO 14040 document. The article aims to ease the simultaneous decision making of economic, technical and ecological criteria. They use the concept of fuzzy sets to deal systematically with unsharp figures, which better represent the reality where human goals affect decision processes. The article introduces the concepts of Multi Criteria Decision Making (MCDM) as suitable means to implement Life Cycle Assessment into integrated decision processes. This article is valuable in integrating the different criteria, but since the scope of this study is to only assess emissions, the methodologies of this article were not studied further.

3.2.3 Eco-intensity

3.2.3.1 "A recursive ecological indicator system for the supply chain of a company" [Schmidt et al. 2008]

The article by Schmidt and Schwegler propose the concept of cumulative eco-intensity that relates environmental or sustainable indicators to the added value of economic activities. In contrast to the LCA, the eco-intensity process is applied to whole companies, not to individual products, by passing on the intensities from supplier to supplier.

Eco-efficiency was a concept that was developed in the beginning of the 1990s to address the need for an economic measure that is set against the value-adding of a desired output. The eco-efficiency of a company can be calculated:

Eco-efficiency = economic benefit / ecological expenditure,

Where ecological expenditure stands for pollution. There are also the concepts of environmental value added, sustainable value and sustainable value added, that evaluate eco-efficiency by relating different environmental impacts to the value added of a company. These figures help to compare the economic and ecological performance of companies but do not take into account the whole supply chain of the product (Schmidt and Schwegler). For example, Nokia can outsource its component manufacturing and claim to produce emission-free mobile phones.

Schmidt and Schwegler introduce eco-intensity as a solution to the disadvantages of eco-efficiency by taking into account the ecological expenditures from the whole supply chain. Eco-intensity can be calculated with the following formula:

Eco-intensity = ecological expenditure / economic benefit

In this model, however, the eco-intensity is cumulative. To understand this, we use the example from Schmidt and Schwegler's article. There are two companies 1 and 2. Company 2 receives a quantity M_1 of a pre-product from company 1 and produces a quantity M_2 of its own product. Company 2's emissions from its own production are E_2 and company 1's emissions are E_1. The prices of the two companies' products are P_1 and P_2 and the companies' eco-intensities are EI_1 and EI_2 respectively. Now company 1 can calculate its eco-intensity:

$$EI_1 = E_1/M_1P_1$$

Company 2 will take this eco-intensity into consideration when calculating its own:

$$EI_2 = (E_2 + EI_1M_1P_1) / (M_2P_2 - M_1P_1 + M_1P_1) = (E_2 + EI_1M_1P_1) / M_2P_2$$

In this way, company 2's environmental burden includes the emissions from the product from company 1 that they use to produce their own. By always calculating the eco-intensity in this way a cumulative eco-intensity can be obtained.

Schmidt and Schwegler argue that the main strength of eco-intensity is that it incorporates both direct and indirect environmental impacts of a company. In this way there is no problem related to insourcing and outsourcing. They also state that the data required is easy to obtain. This data includes turnover, costs of supplies and disposal services, prices and quantities of products produced and reducts reduced. Compared to LCA they state that a company doesn't have to look at the whole supply chain, provided that their suppliers pass on their cumulative eco-intensities.

In regard to this study we do not see eco-intensity as a feasible measure since contrary to Schmidt and Schwegler some of the data can be hard to obtain for our case company and their suppliers will not pass on their eco-intensity figures to make the calculations possible.

3.2.4 Others

3.2.4.1 "Performance measurement for green supply chain management" [Hervani et al. 2005]

Hervani and Helms (2005) review performance measurement and attempt to generate a framework for integrating supply chain management, environmental management and performance management. They define green supply chain management as the combination of green purchasing (i.e. certifying suppliers, purchasing environmentally sound products), green manufacturing/materials management, green distribution/marketing and reverse logistics (recycling, reuse, remanufacturing). They introduce a green supply chain management performance measurement system that evaluates environmental performance using a long list of measures, such as stack or point air emissions, releases to land on site, discharges to receiving streams and water bodies etc. They also suggest a framework for designing and implementing such as system, using ISO 14031 standard guidelines as a foundation. The key principle of building such as system is the Deming cycle of "plan-do-check-act". The article also discusses the use of a balanced score card to assess environmental performance by introducing quantifiable measures to each area in a typical corporate scorecard, i.e. Financial, customer, internal process and learning and growth areas. A balanced score card or performance measurement system are useful both for measuring the company's success internally and identifying key areas for improvement but also for communicating the company's environmental impact to regulatory bodies, NGOs, stockholders and other stakeholders, which are putting companies under increasing pressure to improve environmental performance.

3.2.4.2 "A model for supply chains environmental performance analysis and decision making" [Tsoulfas et al. 2008]

Tsoulfas and Pappis recognise the increasing need to involve environmental criteria into decision problems. In their analysis they introduce a new approach to compare the environmental impacts of alternative supply chain scenarios. They propose six groups of environmental performance measurements:

1. Product/process design and production
2. Packaging
3. Transportation and collection
4. Recycling and disposal
5. Management practices that aim to greening the internal (company's personnel) and external (suppliers and customers) business environment
6. Other management issues that involve strategic policies that apply to the whole supply chain and affect the companies' environmental targets

To assess the different measures they use a multi-criteria decision problem, which takes into account the importance of the different measures. In the multi-criteria decision making technique they assume that there is no solution that optimises all criteria and therefore a decision-maker must find compromise solutions.

3.3 Review of Iron and Steel Industry Related Articles

3.3.1.1 "CO2 removal in the iron and steel industry" [Gielen. 2002]

Gielen analyses the prospects of CO_2 removal technology to be used at steel works. Using the Japanese steel industry as a case example, he shows that using technology already available, CO_2 capture could result in a reduction of over 6,5% of total Japanese CO_2 emissions. Globally, this could result in a 4% reduction in emissions, at a rather reasonable cost of $10.3-$18.8/ton of CO_2 (2002 prices). The option is still shadowed, however, by controversy related to the possible environmental impact of hydrating captured CO_2 deep in the ocean. The contribution of the article is a systematic analysis of how CO_2 capture would work within the steel industry, while earlier CO_2 capture related research had mostly focused on electricity plants. The article also suggests using new technologies, such as Selexol, and the use of a shift reactor, that have not been considered in previous research. Subsequently, using CO_2 capture technology at a blast furnace, used to making iron, would be even cheaper than using it at a coal power plant.

3.3.1.2 "CO2 in the iron and steel industry: an analysis of Japanese emission reduction potentials" [Gielen et al. 2002]

In another article, Gielen along with Moriguchi study emission reduction potentials in the Japanese steel industry at a more a general level. The article assesses a linear programming model called the "Steel Environmental strategy Assessment program". The model shows that Japanese steel related emissions will decrease dramatically as a result of declining production and increased recycling. It also assesses the effect of applying a tax (much like the EU emission barter system) and shows how this would both increase energy efficiency but also cause emission leakage, as in the industry moving abroad to pollute. It is suggested that using recycled steel as raw material reduces emissions significantly. The linear programming model is an LCA model for a whole industry whose scope is "cradle to grave", so it takes emissions into effect very broadly. The article's contribution is a comprehensive break-down of emission sources in the steel making process. This break down is presented in the analysis section. As possible remedies for CO2 emission reduction, the article suggests improving energy efficiency through the use of new technologies, switching fuels from coal to natural gas, charcoal or waste plastics, using electricity produced in a CO2 emission free way and increased recycling of steel

3.3.1.3 "International Comparison of CO2 emission trends in the iron and steel industry" [Kim et al. 2002]

Kim and Worrell studied CO2 emission trends in the global iron and steel industry by comparing seven major steel producing countries. Steel and iron production is one of the most energy intensive industries, and according to article, the steel and iron industry accounts for 7% of global CO2 emissions. They present a decomposition analysis showing which factors have affected the amount of emissions. Their findings show that emissions have grown during the last decades, but at the same time energy-efficiency has improved. There remain, however, significant differences in the energy efficiency levels of the different countries studied. Furthermore, the different ways these countries produce electricity have a significant effect on the steel and iron industry related CO2 emissions. Kim and Worrell's methodology is an extensive decomposition of CO2 emissions, which results in measure of CO2 intensity. This eases comparison between different countries which might have differing levels of technological development or different fuel mixes in electricity generation. The decomposition has been produced by measuring the use of different fuels in the manufacturing of a unit of steel, the emission intensity of the different fuel and summing them together. The key emission-reducing factors are, according to the article, using new technologies such as the basic oxygen furnace rather than the open hearth furnace, using more recycled steel scrap as raw material, and using less emission intensive ways of producing electricity. The article then presents a table summing up the best practice fuel usages of various processes, presented in the analysis section. This table clearly shows the effect of different fuels mixes and technologies on emission levels.

3.3.1.4 "Energy use and CO2 emissions in Mexico's iron and steel industry" [Ozawa et al. 2002]

Ozawa, Sheinbaum, Martin, Worrell and Price's article uses a similar decomposition analysis as in Kim and Worrell's international comparison article to further assess Mexico-specific emission trends in the iron and steel industry. Results show that while the Mexican steel industry's total energy consumption has risen by 211% between 1970 and 1996 due a large increase in production, energy efficiency and process changes have driven down energy usage by 51%. They conclude subsequently that CO2 emissions "are determined not only by activity, structural and energy efficiency changes, but also by the final fuel mix in the iron and steel industry and in the power generation". It is worth noting, that different fuels are better suited than others for different kinds of processes. For example in the Mexican steel industry, the use of lower carbon fuels such as natural gas increased due to growth in direct reduced iron (DRI) production which requires less energy in the steel making process. The article discusses measures that are cost effective in reducing CO2 emissions. These are:

- Various technological improvements , such as scrap preheating, recovering heat from BOF gas etc.
- Increasing the amount of scrap used as raw material

3.4 Analysis of Literature Review Results

3.4.1 Understanding of the Scope of the Project

As the goal of this project is to find out what a company can do to reduce the emissions of its supply chain, we decided to approach the problem using the life cycle analysis method (LCA). Based on literature, we identified several types of ways to perform an LCA. Our aim is to perform the analysis so that it enables the case company, SSAB, to measure the amount of CO2 emissions caused by a unit of its steel by the time the steel reaches its customer. This type of LCA is referred to as a ”cradle to gate” approach and is similar to Tan's and Khoo's article on an aluminium plant LCA.

The reason why we have chosen this extent is that we believe that a company is responsible for its environmental impact only until the point where it has the power to choose what is done with its product and how. Of course, intra-supply chain co-operation is very important, but we believe that the pressure to optimise must come from the downstream. In this sense, if SSAB wants low environmental impact to be a competitive advantage, it may put pressure on its suppliers and work together with them to optimise its supply chain and bring down emissions. In the same way, SSAB's customer could put pressure upstream on SSAB and its suppliers, but in this case, its processes would also have to be taken into consideration. This way of looking at environmental impacts relates to the concept of eco-intensity, where the eco-intensity of a company is calculated as a cumulative figure. Here, we assumed that were to gather data from SSAB and its upstream supply chain only.

Another distinction made between different types of LCAs is its purpose. LCAs can be used to measure whatever kind of environmental impact. In this study, only CO2 emissions are included. Other emissions to the atmosphere are not considered. This choice has been made due to the fact that CO2 emissions are the main cause of climate change and that CO2 emissions are directly linked to the amount of energy used. It can therefore be directly affected by optimising energy usage, choosing energy efficient technologies and by using low-carbon energy production methods. Other greenhouse gases result from different combustion methods which arise from the use of different technologies. As the team involved has no expertise on the technology used by the iron and steel industry, the technologies used to produce steel will not be an area of concentration. Hence the impact on non CO2 emissions is also limited.

The LCA performed is a market-based LCA, as distinguished by Hagelaar's study. The aim is therefore to be able to tell stakeholders what impact one unit of steel product has had on the environment, and not to focus on an individual process or measure compliance with certain regulations, for example.

In the articles, guidelines for what exactly an LCA should include were not found. Naturally, all directly value adding activities such as production process and transport related emissions are to be included in the LCA. Another question is whether company 'overhead emissions' should be included. These include, for example, the emissions caused by electricity used at the company's offices, emissions caused by employee commuting and company executive and sales force travel. This aspect was discussed with the client, after which it was decided that for simplicity's sake, overhead emissions would be left out of the analysis.

One way to possibly calculate these would be to use similar principles as in accounting and the splitting of overhead costs. What would have made it difficult, however, is that, as these emissions are caused throughout the supply chain, doing so would require extensive analysis into each of the suppliers and service providers involved.

3.4.2 Review of SSAB's Current Steel Production Process

SSAB claims that its products are environmentally more friendly than average steel because it focuses on very high-strength steels than enable lighter, high strength constructions that require less raw material to produce. The worldwide average use of recycled scrap metal in steel plants is 30%, according to the company.

The iron ore needed to produce steel comes to from LKAB's ore field in Norrbotten, from where it is transported to SSAB's steel plants in Luleå and Oxelösund. The other main raw material, coke, is made from coal which SSAB "imports from all around the world.

Transportation takes place mainly by railway, by ship and by truck. The raw materials are transported to the steel plants by train or boat. Transports of slabs between the production plants take place by rail. To model the supply chain, more information is needed on the distances and frequency of transport of various items.

Below is a description of SSAB's actual production process to give an idea why the steel industry is so energy intensive:

> *Steel production at SSAB takes place in blast furnaces and electric arc furnaces. In the Swedish operations, three blast furnaces are used in which iron ore is reduced to hot metal through the use of coal and coke. Before the hot metal becomes steel, its carbon content is reduced through the use of oxygen and a number of contaminants are reduced through the use of lime. This takes place in an oxygen converter and generates a heat surplus which is cooled down by adding scrap metal. This scrap metal mainly comes from the Company's own plants. In the North American operations, the scrap metal is smelted in four electric arc furnaces through the use of electrical power. This process uses scrap metal as the sole iron raw material, with most of the scrap metal being purchased on the market, among other things through IPSCO's own scrap metal collection companies. The liquid steel is refined and processed into alloys in various finishing stages, before being cast in the continuous casting machinery. The slabs that are manufactured in the continuous casting machinery are further processed in rolling mills into different types of steel. Apart from steel, the processes give rise to large quantities of heat, gas, slag and particulates, which to a large extent are utilized.*

4 Calculation of CO2 Emissions Caused by Steel Production

The most important CO2 emission producers were identified to be steel manufacturing process, electricity mix used to produce coal, mining of raw materials and the transportation related to the manufacturing process and supplying the final product.

4.1 The Steel Plant

The most significant emitter of CO2 in the steel supply chain was assumed to be the steel plant itself, where raw iron and scrap steel is transformed steel rolls and strips. An input-output model taken from SSAB's 2007 annual report is shown below. SSAB's own analysis of their processes shows that producing one ton of steel caused 0.96 tons CO2 emissions (2007). Energy consumption in 875KWh/ton, while at the same time 830KWh of electricity and heat are produced for other use.

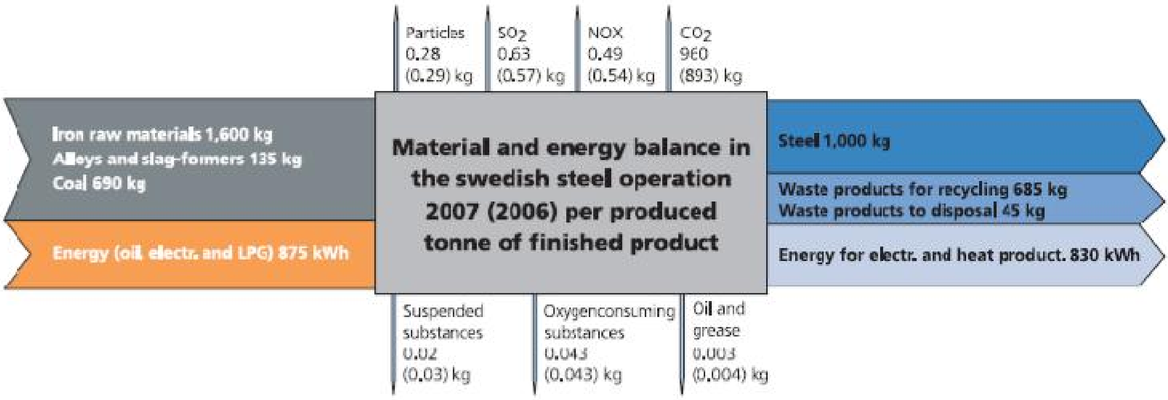

Figure 2: SSAB's input-output model of steel production

4.2 Iron Pellet Production

The iron supplier is set to be the LKAB which has two mines in Kiiruna, Sweden (Kiiruna mine and Svappavaara). According to LKAB, the CO2 emissions caused by iron ore mining and production have developed as follows:

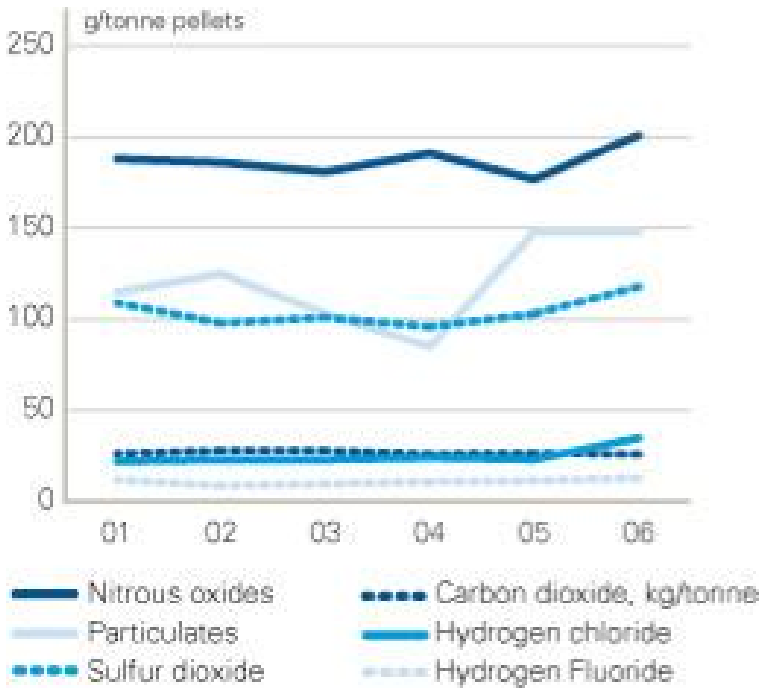

Figure 3 Mean values of emissions from the pelletizing plants in Kiruna, Svappavaara and Malmberget. The fluegas cleaning equipment in the pelletizing plants has reduced emissions of, above all, sulphur and particulates. http://www.lkab.com/?openform&id=D2F6

As we can see from the above picture, the iron ore pelletising plants cause about 0.025 tons CO_2/ton of pellets. According to SSAB annual reports, one ton of steel requires 1.6 tons of iron raw materials, causing about 40kg of CO_2 emissions. The iron pellets are transported from the mines to Lulea by train. From Lulea, it is possible to take either a ferry or continue by train to Oxelösund.

4.3 Coal Mining

The other important raw material for steel production is coal which is used to reduce iron ore. One ton of steel requires 0.69 tons of coal. SSAB states it buys the coal from all over the world. We simplified this by assuming two suppliers: one in Poland and the other in Kuzbass, South-West-Siberia. The Polish supplier is assumed to be the preferred one because it is closer to the Oxelösund factory. IPCC has estimated the Russian coal mining to emit 0.0557 tons of CO_2 per ton of coal and the Polish producer 0.0493, respectively. (IPCC)

4.4 Electricity Production

Sweden is a country with very low carbon electricity production. According to EU statistics, Sweden's electricity generation is almost completely independent of oil and coal, with the major electricity sources being nuclear and hydro electricity.

According to Vattenfall, Sweden's largest electricity producer, the production of one kilowatt hour of electricity causes 5,8g of CO_2 emissions. If we take, however, for comparison's sake neighbouring Finland's electricity mix as an example, we see that the electricity is a major source variation.

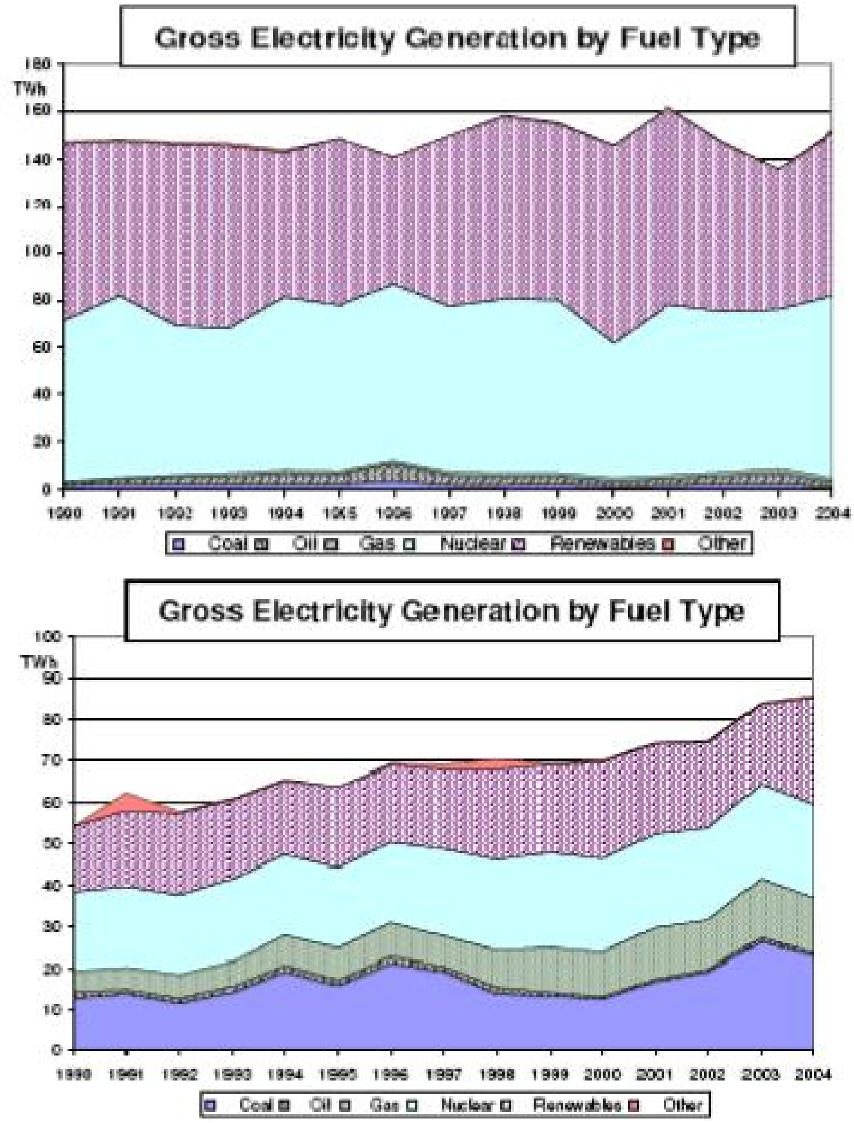

Figure 4 Comparison of Sweden and Finland's electricity mixes

As we can see, Finland is much more dependent on coal and gas for its electricity production than Sweden. In fact, Finland's average CO_2 emissions per kilowatt hour of electricity were 260 grams (2004). For a ton of steel, this would mean 227,5 kg of CO_2.

4.5 Transportation

Transportation forms essential part of the supply chain. McKinnon presents the following table for average values for CO_2 emissions for different cargo transportation methods. The emissions are expressed in grams.

Emissions per kilometre cargo ton	
Mode of transport	Emissions (G/tn*km)
Train	20
Inland ship	30
Long haul ship	15
Truck	120
Air (longhaul)	1900

Figure 5 Emissions per kilometre per cargo tonne. Values gathered from two sources. (EU statistics and McKinnon)

The transportation of raw materials is described on the following table:

Table 2: the transportation of the raw materials

Raw Material	From	To	Distance (km)	Mode of Transport
iron	Kiiruna	Lulea	300	train
	Lulea	Oxelösund	1000	train/ship
coal	Katowice	Gdansk	540	train
	Gdansk	Oxelösund	650	ship
coal	Novosibirsk	St. Petersburg	3000	train
	St. Petersburg	Oxelösund	1000	ship

4.6 Inventories

Companies have inventories in order to maintain continuous manufacturing processes, hedge themselves from unexpected supply breaks and to be able to react to sudden changes in the demand. Raw materials are stocked at the plant area before being used and end products before being delivered to the customers. The inventories may be significant polluters in some industries. For example in the food industry, the groceries have to be kept cold and delivered regularly to the retailers.

It turned out to be difficult to find exact information about steel plant inventories therefore we estimated the definite maximum for inventory emissions to be 10kg per ton of stock material. This number is intended to take into account the intra-factory logistics and possible warming expenses of the stocks, and it corresponds to 1.7MWh per ton and 83 km of truck drive for a ton of raw materials.

5 Building the Model

Our goal was to identify the key elements of the supply chain for the steel company and create a model for simulating the CO2 emissions throughout the chain. SSAB has provided some data, i.e. of customers and demands. In order to have appropriate level of abstraction and capture appropriate elements of the process, we have made few simplifications in the model. The model has been used to carry out simulations on a three different scenarios to evaluate the CO2 emissions.

5.1 LCA vs. Supply chain modelling

The LCA approach to modelling CO2 emissions in the supply chain is static, meaning that it is calculated for given input values at a given time. Even though this analysis allows for a detailed breakdown of CO2 components of the chain, its scope is limited in the sense that it doesn't take into account the dynamics of the process. As the literature review indicated, LCA models often do include a certain number of scenarios to vary the emissions by changing input parameters such as energy use, but we found this approach somewhat lacking in a medium-to-long term analysis. LCA cannot for example be used to assess the impact of demand fluctuation and the subsequent changes in production planning. On the other hand, traditional LCA would likely offer little new information for the company. Therefore, we felt the need to make the model more dynamic to introduce demand and other parameter scenarios implemented as a function of time.

Compared to LCA, on the other end of the spectrum of supply chain models (SCMs) are the "traditional" models, which are most often concerned with the *performance* or the cost-effectiveness of the chain. This usually involves minimizing the costs while keeping a required service level, which is achieved through inventory and production planning. The flows of materials and information through the chain can be described through a set of equations, giving rise to a dynamic system. This approach is tempting since it allows time-varying parameters to be included with a greater flexibility. However, the literature review found little evidence that it has been used for CO2 emissions modelling, as the purpose of these models has mostly been cost cutting.

As our goal was to give a detailed analysis of the CO2 emissions breakdown of the steel supply chain and we also wanted to incorporate the dynamic aspect of the chain in our model, we decided to propose a combined approach, building a (rather simplified) traditional SCM with an integrated LCA (Figure 6). This allows us to keep the advantages of the LCA but also actively introduce time-variant scenarios to the model and view the impacts on a timescale.

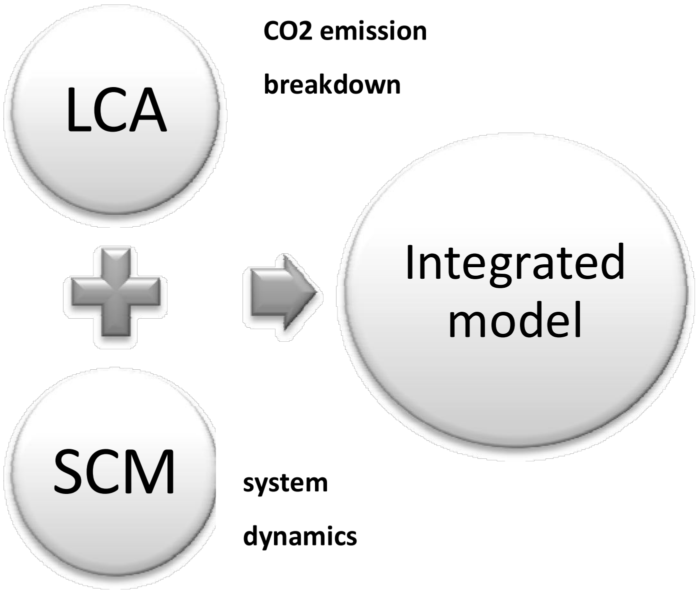

Figure 6. The model.

As a traditional SCM is mainly concerned with costs, applying an LCA raises the question of to what extent cost minimization and stock levels should remain an optimization target in the integrated model. The scope of this work has been limited to *modelling* the CO2 emissions with a scenario approach, as opposed to finding actual optimal heuristics for their reduction. Consequently, production planning in the model has to be based on stock or cost information, with the CO2 emissions as an output.

Although emissions trading has firmly linked CO2 emissions to the financial planning of energy-intensive industries, we have decided not to assess the actual costs involved with emissions and their reduction. This is partly due to the lack of availability of financial data, but also somewhat out of the focus of this work. However, the absence of cost analysis implies that any production heuristics in the SCM will be based on inventory optimization. These are discussed in more detail in the following sections.

5.2 Implementation

The model consists of the steel plant, which produces coke and steel, and makes use of the recycled steel. Raw materials are transported from two coal mines (located in Poland and Russia), and iron ore producer (located in Sweden). Other inputs for the production are customer demands and energy, i.e. electricity. Of course, the supply chain contains also the customers, who are located all around the world.

Numerical simulations were performed by using the commercial software packages, Simulink and Matlab. The Simulink model consists of systems and subsystems describing the steel plant, raw material producers, incoming orders and CO2 calculations. With the purpose-built m-file the user can vary parameters of the model and plot the results for the chosen scenario. The necessary computational loops and the model itself are discrete in time. As the production planning in the steel plant is not made continuously we can justify this approach.

The model is illustrated in Figure 7. There are five main components in the Simulink model. The steel plant (factory), holds the information about the production, stock level and outgoing orders. The customer relations, i.e. orders and deliveries are managed in its own subsystem, which uses the information provided by the *customers vector*. The raw materials are divided into two subsystems, where the information of raw material levels is, and future deliveries are handled. The CO2 counter gathers all the relevant components, and calculates the emissions. The full implementation is presented in Appendix A.

5.2.1 Stock Levels

The incoming orders, i.e. demand, can be considered as the original input for the model. The stock level links the information of the material flows and possible backlog. The change in stock level can be written as

$$\Delta stock\ level(k) = production(k - delay) - demand(k), \tag{1}$$

where k is the time step.

The main idea of the stock level is as in the beer game[4]. When the stock level is below zero, the steel plant has a certain amount of backlog, and all the orders should be satisfied in future. The original stock level ($stock_0$) can be varied in the beginning of the computational loop. This level represents the target level for the inventories, which is wished to be maintained during the scenario.

[4] J. Sterman , Modeling managerial behavior: misperceptions of feedback in a dynamic decision making experiment. *Management Science* **35** 3 (1989), pp. 321–339 March.

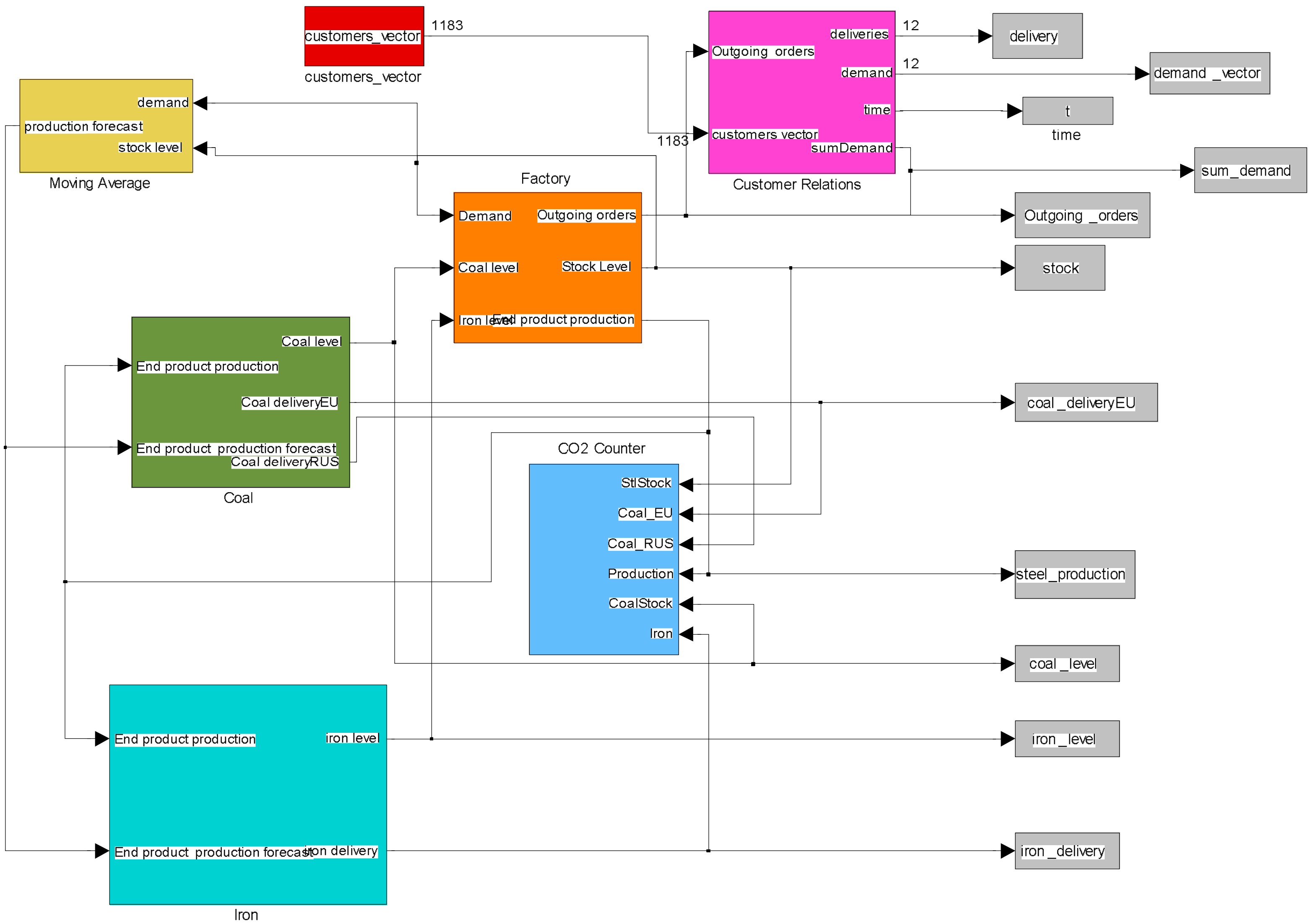

Figure 7: Supply chain simulation model

5.2.2 Steel Recycling

As discussed in the literature review, one major emission-reducing factor is the increased use of recycled steel scrap as raw material. In addition, recycling is economically advantageous compared to mining the iron ore and producing “new” steel. Reusing the steel scrap in the plant, one can save also energy along with reducing iron ore and coal consumption. In figures, recycling one ton of steel saves 1.1 tons of iron ore, and 0.63 tons of coal[5]. The share of the steel scrap in our case can be 30% at the most[6]. Thus, using the information presented in the Figure 2 the raw material consumption per one ton of steel can be expressed as

$$coal\ consumption\ [kg] = 690 - 630\alpha \tag{2}$$

$$iron\ consumption[kg] = 1600 - 1100\alpha, \tag{3}$$

where $\alpha(< 0.3)$ is the share of the steel recycling. One can easily see the decrease of the raw material consumption as α increases. For simplicity, we have assumed that all the required recycled steel is always available during the simulation.

5.2.3 Controlling the Production

Limitations of the production are assumed to be as follows: the steel plant has its maximum capacity, i.e. amount of steel that can be produced during one step. This maximum capacity we have estimated making use of the total amount of steel produced in SSAB in 2007. We have assumed, that the two main raw materials, coal and iron ore, limit the production so that the biggest possible percentage of the desired production is executed in the steel plant. On the other hand, if either the raw materials run out, the production of the steel plant drops to zero. In addition, we assume that the required energy is always available. The mathematical formulation of the production is presented below.

$$production(k) = capmax * production\ switch \tag{4}$$

$$production\ switch = \min(RMPF, FPCO) \tag{5}$$

[5] http://en.wikipedia.org/wiki/Steel
[6] Coal & Steel Facts 2007 World Coal Institute worldcoal.org

$$FPCO = \min\big(1, \min\big(0{,}5; PI(stock_0, stock)\big)\big) \tag{6}$$

$$RMPF = \min\left(\frac{coal\ level}{capmax * FPCO * \alpha_1}, \frac{iron\ level}{capmax * FPCO * \alpha_3}\right), \tag{7}$$

where $capmax$ is the maximum capacity of the steel plant, $stock_0$ is desired stock level, *FPCO* is the filtered production control output, *RMPF* is the raw material production factor, $PI(stock_0, stock)$ is the output from the PI-controller, and material consumption constants (per one ton of steel) are given by the following expressions $\frac{coal}{steel} = \alpha_1, \frac{coal}{elecricity} = \alpha_2, \frac{iron}{steel} = \alpha_3$.

The desired production is dictated by the stock level and demand. The wanted stock level is maintained by a conventional discrete PI-controller, whose parameters have been carefully chosen empirically. The current error term is written as $error = \ stock_0 - stock\ level$. The output of the controller is first limited between [0.5, 1], as we have assumed the controlling of the steel plant cannot be performed arbitrarily during the simulation. Secondly, the output of the controller is smoothed with an exponential filter in order to have a more stable and thus a more realistic production control. This approach may be somewhat unconventional, but the group noted that the factory performs better with this kind approach. In the end, the production is a percentage of the maximum capacity, restricted by the raw material levels and the desired production.

5.2.4 Outgoing Orders

The outgoing orders depend on the demand and the stock level. As mentioned earlier, all the orders should be satisfied. Thus, managing the deliveries should take into account the current stock level, current demand, and production. In the model this is managed through a purpose-built Matlab function, whose inputs are demand, stock level and production:

$$\begin{aligned} &outgoing\ orders \\ &= delivery\ decision\ function(demand, stock, production), \end{aligned} \tag{8}$$

where the script of the *delivery decision function* can be found from Appendix A.

5.2.5 End Production Forecast

The order amounts of the raw materials make use of the end production forecast. This forecast (in the eqs. $\widehat{PF}$) is evaluated simply using the weighted moving average (MA-process) of a factor *PF* that is saturated with the maximum capacity of the steel plant. The factor takes into account the total demand and change in the desired stock level, so that the steel plant would satisfy all the incoming orders. The weighting is made with three last values with equal weights.

$$PF(k) = total\ demand(k) + (stock_0 - stock(k)) \tag{9}$$

$$\widehat{PF}(k) = \theta_1 PF_{k-1} + \theta_2 PF_{k-2} + \theta_3 PF_k\ , k > 2, \theta_1 = \theta_2 = \theta_3 = \frac{1}{3} \tag{10}$$

5.2.6 Delays

In a real world steel plant there are numerous different delays during the whole production process. In our simplified model we have built in only few of them. One assumption is that all the incoming orders reach the steel plant without a delay, this is reasonable if we assume that the information flows e.g. via e-mail. The model includes production delay, as the raw iron and coke are transformed steel rolls and strips. In every computational step, required amount of raw materials are ordered, but the materials reach the steel plant after a specific delay for the different materials. These delays include the production delay and are estimated (and rounded to weekly scale) using the distance between the steel plant and the mines. The changes in raw material levels can be expressed as

$$\Delta coal\ level(k + delay_{coal}) = coal\ delivery\ EU(\widehat{PF}) + coal\ delivery\ RUS(\widehat{PF}) - (\alpha_1 + \alpha_2) * \text{production(k)} \tag{11}$$

$$\Delta iron\ level(k + delay_{iron}) = iron\ delivery(\widehat{PF}) - \alpha_3 * production(k), \tag{12}$$

here the $coal\ delivery\ EU(\widehat{PF})$, $coal\ delivery\ RUS(\widehat{PF})$, and $iron\ delivery(\widehat{PF})$ are functions built in the model, as they make use of the production forecasts $\widehat{PF}$.

5.3 Implementation Issues

One of the difficulties encountered during building the simulation model was that Simulink is not able to treat complex data types inside it. Complex type in this context means a collection of data of a different shape and representation. This caused us some problems, as the customers database within our model is described by a cell of *structs* containing e.g. the name of the customer, its location, its transportation means etc. Building the database in such way and coding it into a *struct* seemed for us to be the only way to handle multiple information related to a same subject.

However, in order to be able to use that information, we had to be able to encode the *struct* into a vector in a specific way. With this kind of approach Simulink would accept the now purely numeric data given as its input and treat it in an appropriate way. Naturally, in order to use and display the data we had to decode the vector. All this was carried out by a (slightly personalised) package called *Simulink Structures* found on *Matlab Central*[7].

As noted before, the implemented model is essentially discrete by nature. Nonetheless, by default Simulink uses a continuous solver to numerically solve the system prescribed in it. This option can be changed, but setting the simulation step to one (as a basic measure of a week) causes some curious behaviour in the system. As now all the calculation is done by discrete steps of a week's length and also the demand coming from the customers is considered as a weekly one, the settling time of the system (notably the steel factory) is very long if measured in weeks. This is due to a fundamental limitation in sampling: if a signal contains no frequencies higher than some limit *L*, it is completely determined as a sampled one if the sampling takes place at frequency higher than 2*L*. This is a well-known *Nyquist-Shannon sampling theorem*.

Consequently, in our model we would have been forced to use a sampling step smaller than ½ (weeks) in order to be able to react appropriately to weekly changes in demand. This would have had an impact on the performance of the factory, if a measure of performance is thought to be factor's ability to stabilise itself as quickly as possible when changes in its demand occur. However, this would have blurred the interpretation of the system as a whole, while it is assumed that the agents in the system make decisions only on a weekly scale, not any faster. This assumption (as discussed above) is neither too restrictive nor unrealistic. In the light of this, the behaviour of e.g. the factory's production is a feature caused by limitations in numerical calculation, not a defect in its control: it cannot possibly be any faster than what the specified time step induces.

6 Simulation Scenarios

The model which our team built provides various opportunities to study the behaviour of the supply chain under different circumstances. Further these sets of circumstances shall be called scenarios.

Because of the nature of the model described by external customer demand driving the production, a natural choice of study is to look at the effect of demand shocks on the whole chain and its emissions. This is the principal task ROCE suggested us to explore. For this, we identified four possible demand scenarios:

[7] The source code can be found on http://www.mathworks.com/matlabcentral/fileexchange/2546

- Constant deterministic demand coming from the customers database with no variation whatsoever
- Stochastic demand with a constant customer demand expectation value but a weekly demand variation
- Constantly increasing demand (a ramp) similar to stochastic demand but with drift, based on for instance a boom in economy
- Stochastic step demand due to a change in for instance construction regulations or a marketing campaign

The goal of these simulations should be to find out what are the most important CO_2 emitters in the supply chain, what kind of effects different demand patterns have and if there could be some easy ways to reduce the emissions of the chain.

Furthermore, our approach for modelling the customers of the producer provides also a possibility to look at changes in customer locations and their transportation means. One could identify if there is a significant effect on the transportation emissions if, for instance, the customers change their locations to a more remote place. Choosing the transportation means tackles the same problem: is it important to think about the means of transport given the scale of transportation emissions in terms of total emissions.

As suppliers play a significant role in the supply chain, our model gives the user a possibility to test scenarios based on the behaviour of suppliers of the factory: it could be interesting to see for example whether there is an impact on emissions caused by a supplier changing its business in some way – in our model this possibility is boiled down to a change in the quality (in terms of CO_2 effect) of raw material procured by the supplier.

A very engrossing possibility is to inspect the adaption of use of recycled steel in the fabrication process. The effect of this to the total emissions is indeed clear by intuition; however its magnitude could be quite difficult to estimate without any use of simulation tools. The model can be used to estimate this effect: it uses some assumptions regarding the fabrication process and with this information estimates how much the use of a certain amount of recycled steel reduces the emissions.

There are several other parameters in the model that could be adjusted to create different scenarios, such as the CO_2 intensities of different parts of the supply chain. However, since the novelty of our model lies in the combination of a traditional SCM and a LCA, we decided to focus on the addition that SCM simulation brings to the life cycle analysis, i.e. a fluctuating demand.

Based on the discussion above, the final scenarios chosen by the team are the following:

1. Constant demand
2. Step demand with variation
3. Use of recycled steel worth of 30% of the production
4. Customer relocation to Asia

6.1 Demand and customers

The production of the steel plant is directly driven by demand coming from its customers. The customers are implemented as a list of different agents wanting to buy steel, with varying location and transportation means. The total demand leading to possible production – if there is not enough steel in the stock – is calculated by summing up all the individual demands of the customers in the list. After this, as will be seen later in the section describing scenarios, we normally add some randomness to the deterministic aggregate demand formed by real SSAB customer data. This result is then passed to the factory as an exogenous input.

7 Discussion of the results of simulation based on scenarios

7.1 Scenario 1:

In the first scenario the demand for steel produced by the factory is constant and well under the maximum capacity of possible production. The two raw material levels – coal and iron – start evolving from an arbitrarily chosen initial condition. What we see here is that as there is no variation of the demand, the production of the steel stabilizes to the level indicated by the demand after some fluctuation caused by inappropriate levels of raw materials at the beginning. Thus also the stock remains constant after the transient phase.

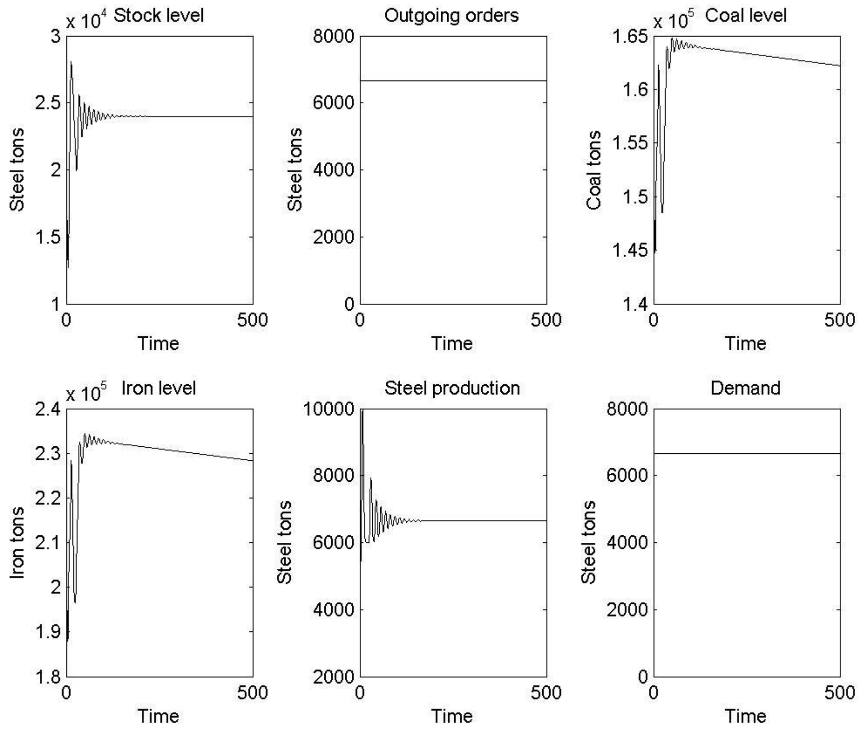

Figure 8. The steel factory in scenario 1

The same reasoning can be applied to the figures Figure 9, Figure 10 and Figure 11: after a transient phase in the steel production, also all the different greenhouse gas (further GHG) emission levels settle to the stationary values. Thus there hardly is anything surprising here: the most of the emissions of the supply chain are caused by the production process.

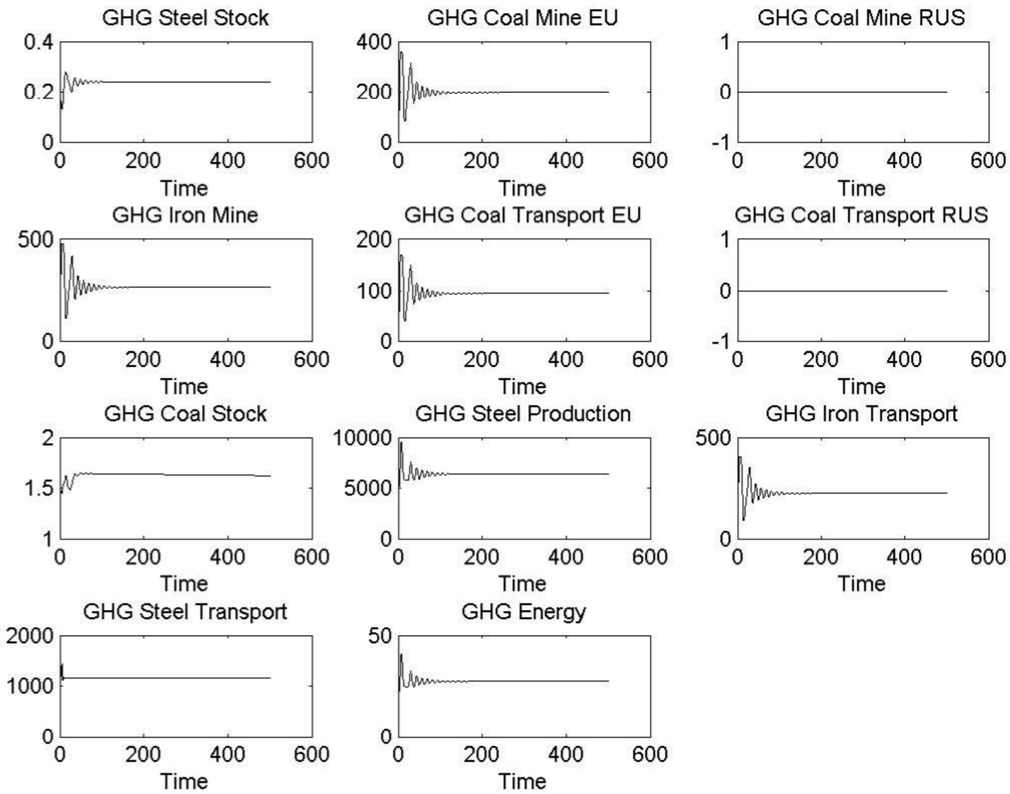

Figure 9. GHG emissions by source in scenario 1 (CO2 tons).

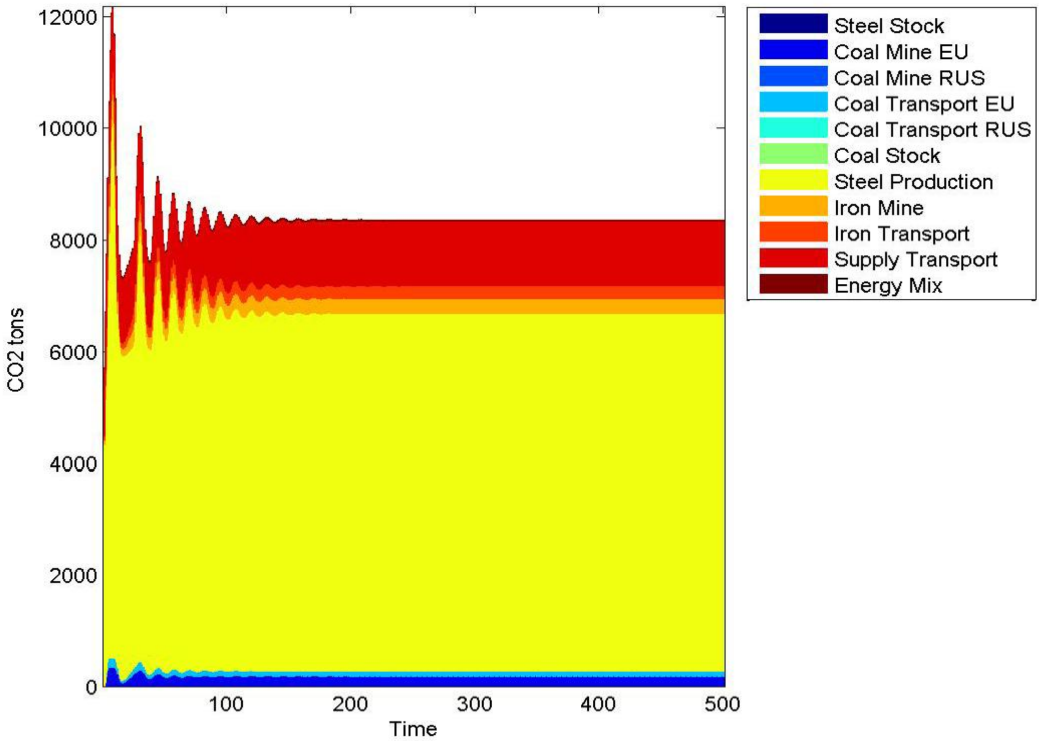

Figure 10: Total GHG emissions in scenario 1

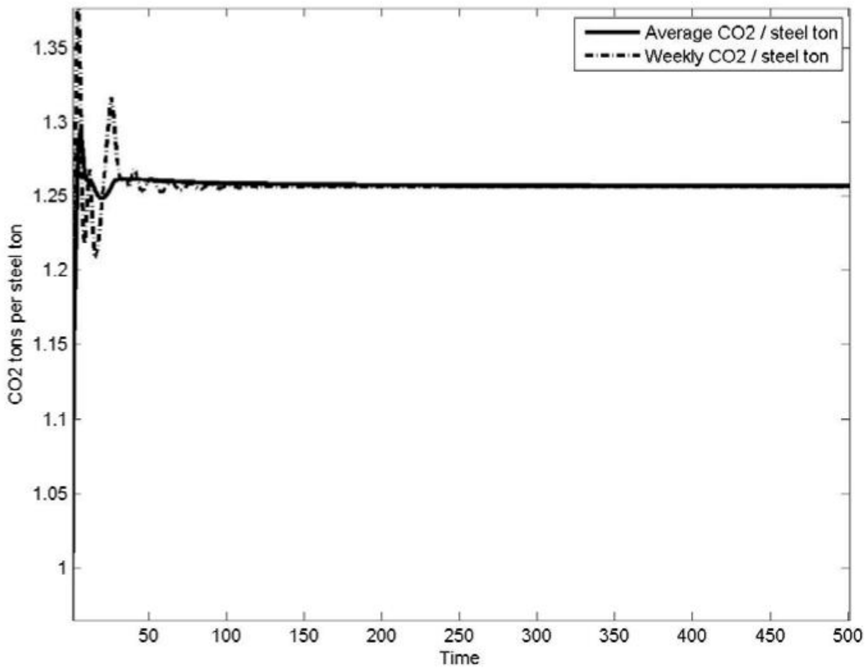

Figure 11. Cumulative GHG emissions per cumulative steel tons in scenario 1

7.2 Scenario 2:

In the scenario number 2 we have a stochastically fluctuating demand, whose level arises at time 200. What can be seen from the Figure 12 is that the step in demand is accordingly transferred to the level of production and also to the emissions of the chain. When the step occurs, there is a drastic (and almost equal to the step) increase in the emissions as the chain has to adapt itself to the new situation: more demand induces more production, more raw material supply, more transport etc. However, the ratio between the emissions and the production remains approximately constant (Figure 15). What is also to be noted is that the ratio is the same as in scenario 1, even if the total amount of emissions (and production) is larger, as noted.

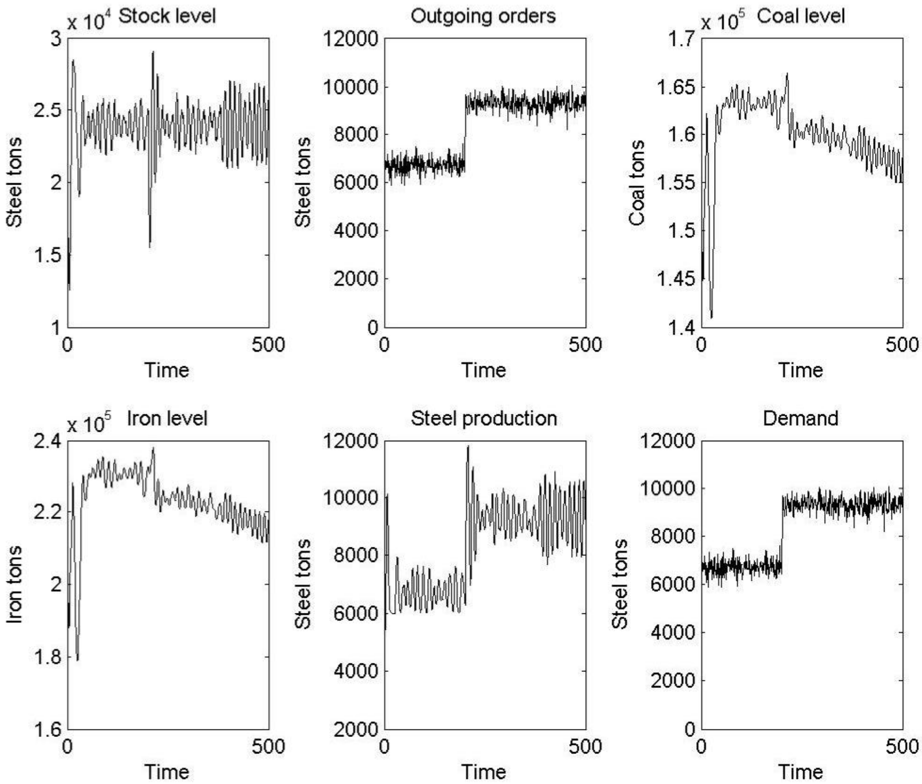

Figure 12. The steel factory in scenario 2

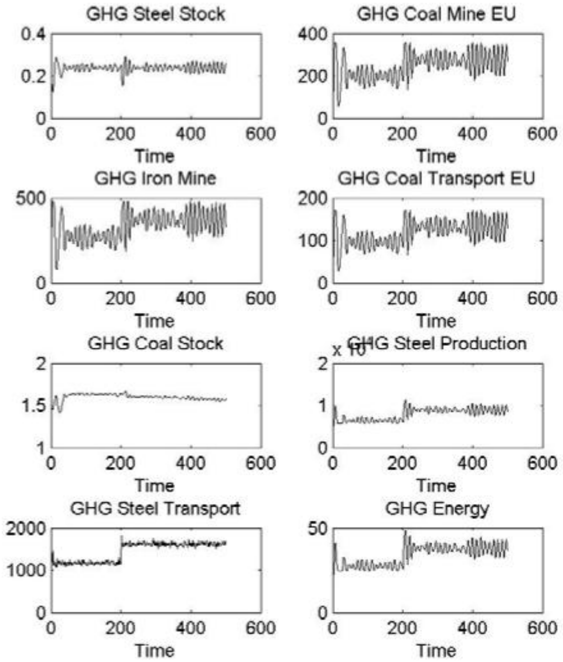

Figure 13. GHG emissions by source in scenario 2 (CO2 tons).

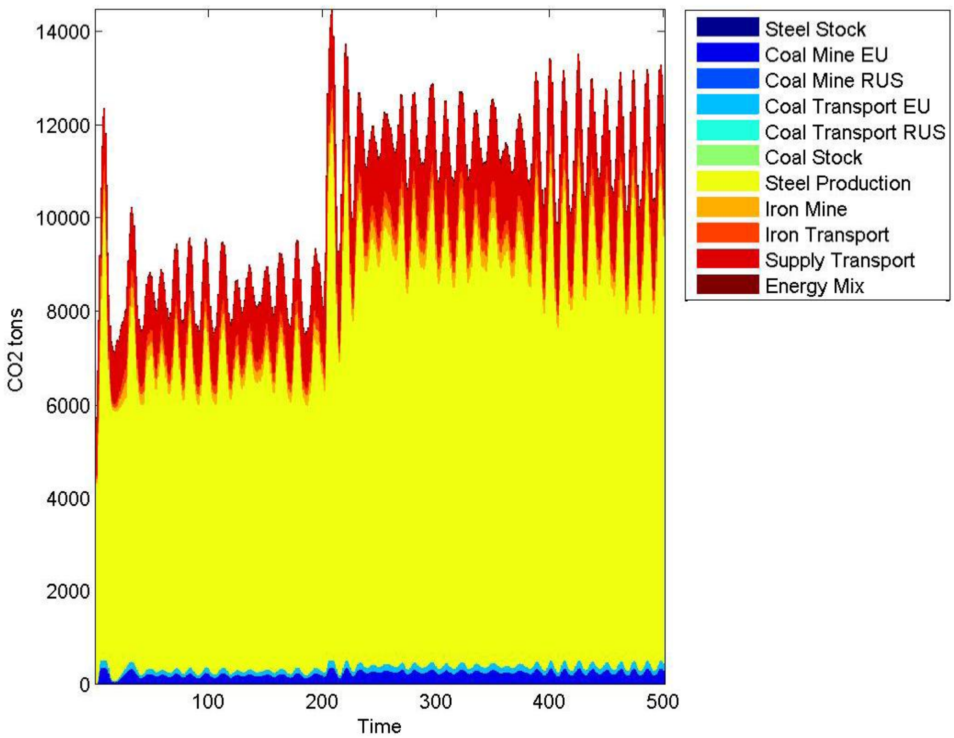

Figure 14. Total GHG emissions in scenario 2

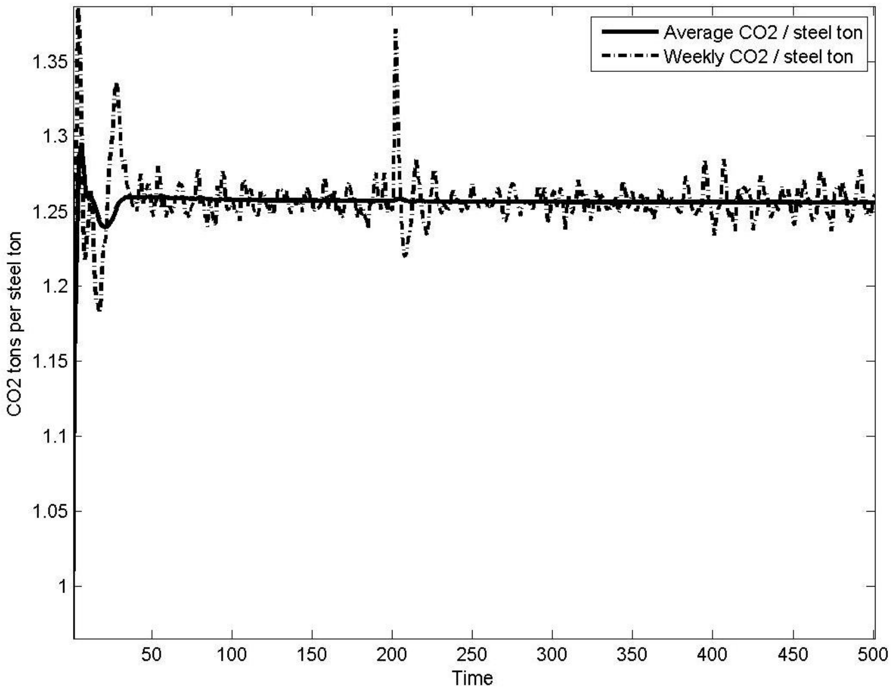

Figure 15 Cumulative GHG emissions per cumulative steel tons in scenario 2

7.3 Scenario 3:

Here we have a situation where the demand for steel is stochastically constant and where the industry learns gradually to use recycled steel more efficiently in its production process. This evolution (which starts at time 150) reduces the total emissions of the chain, as also affects the ratio between emissions and produced steel tons. The effect is actually quite large: by the 30 % use of recycled steel the emissions per produced tons are reduced by approximately 25%. This can be seen on Figure 19.

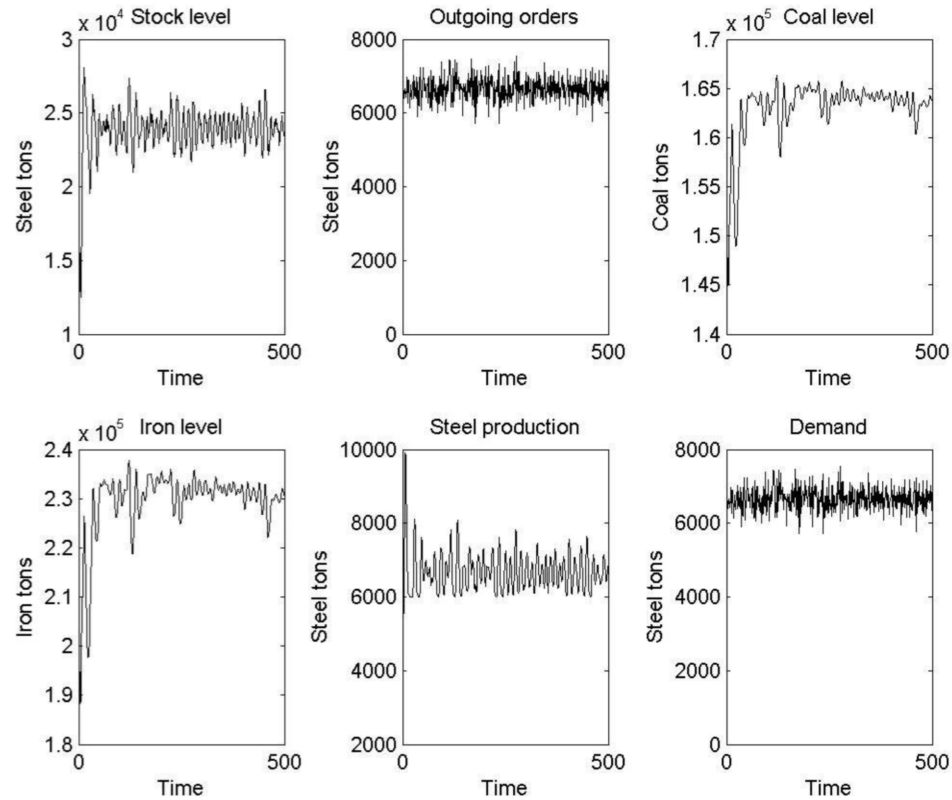

Figure 16. The steel factory in scenario 3

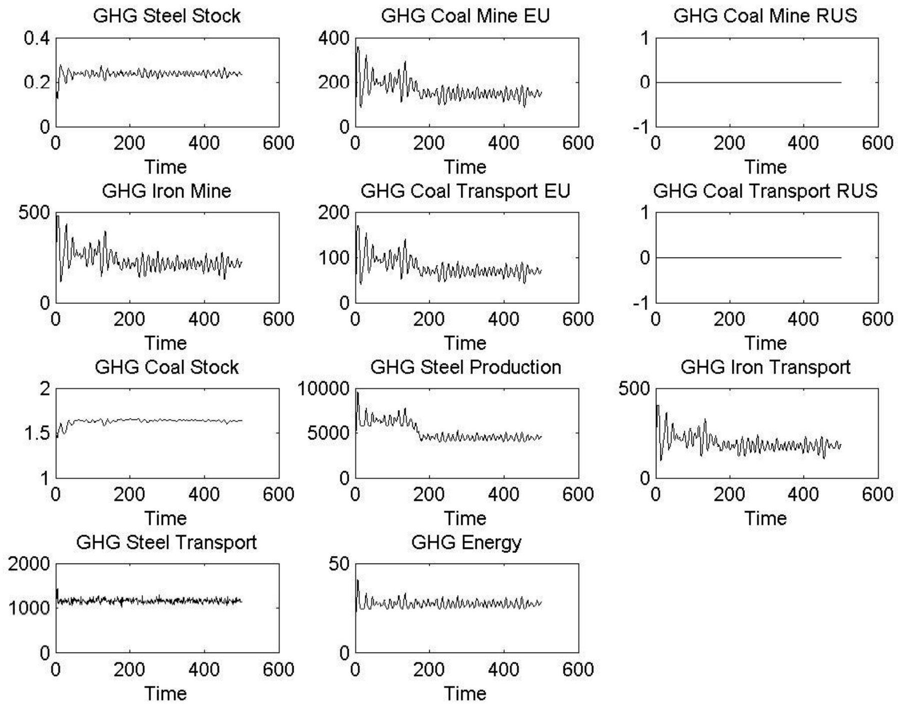

Figure 17. GHG emissions by source in scenario 3 (CO2 tons).

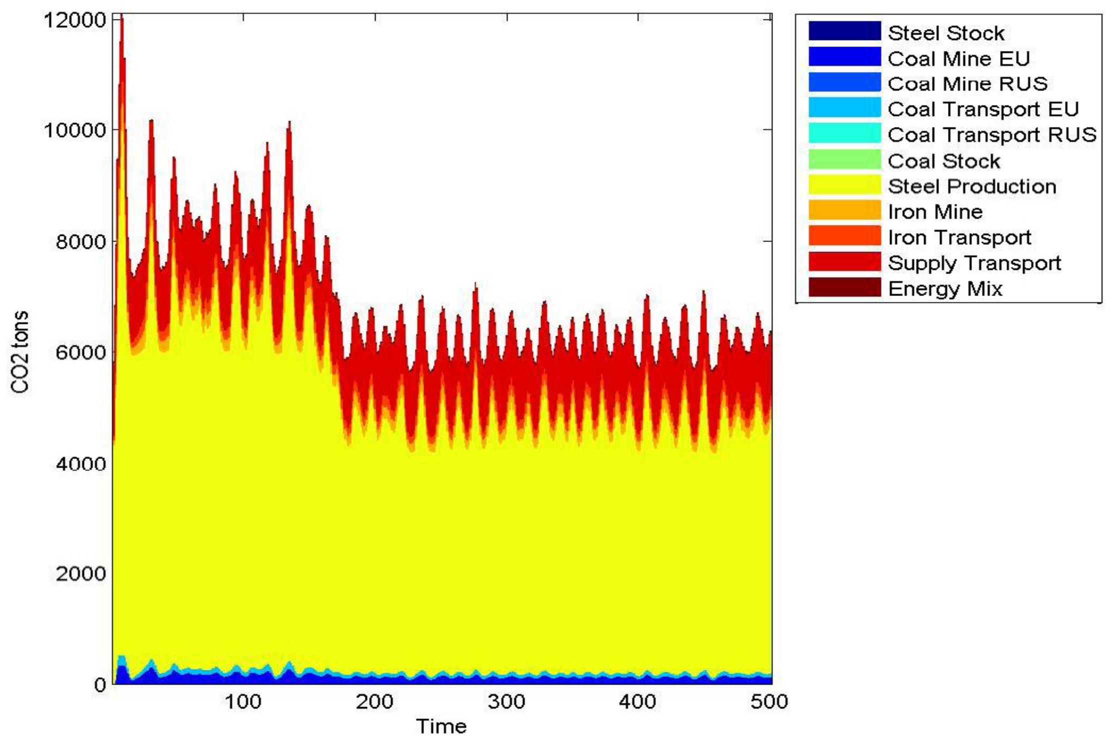

Figure 18. Total GHG emissions in scenario 3

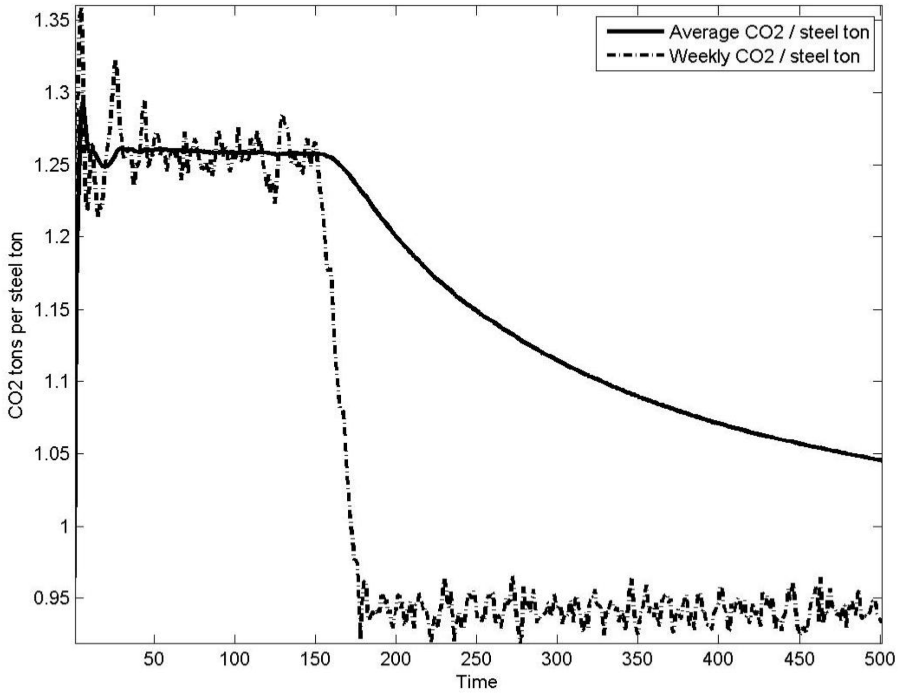

Figure 19. Cumulative GHG emissions per cumulative steel tons in scenario 3

7.4 Scenario 4:

In this last scenario the customers of the steel producers are different from the scenarios above: they are all located in a remote location in Asia. For this reason one can easily see that keeping other things constant, the location of the customers plays a role – if not a hugely significant one – in the emissions of the supply chain system. The ratio of emissions per production, as compared to scenarios 1 and 2, is indeed bigger.

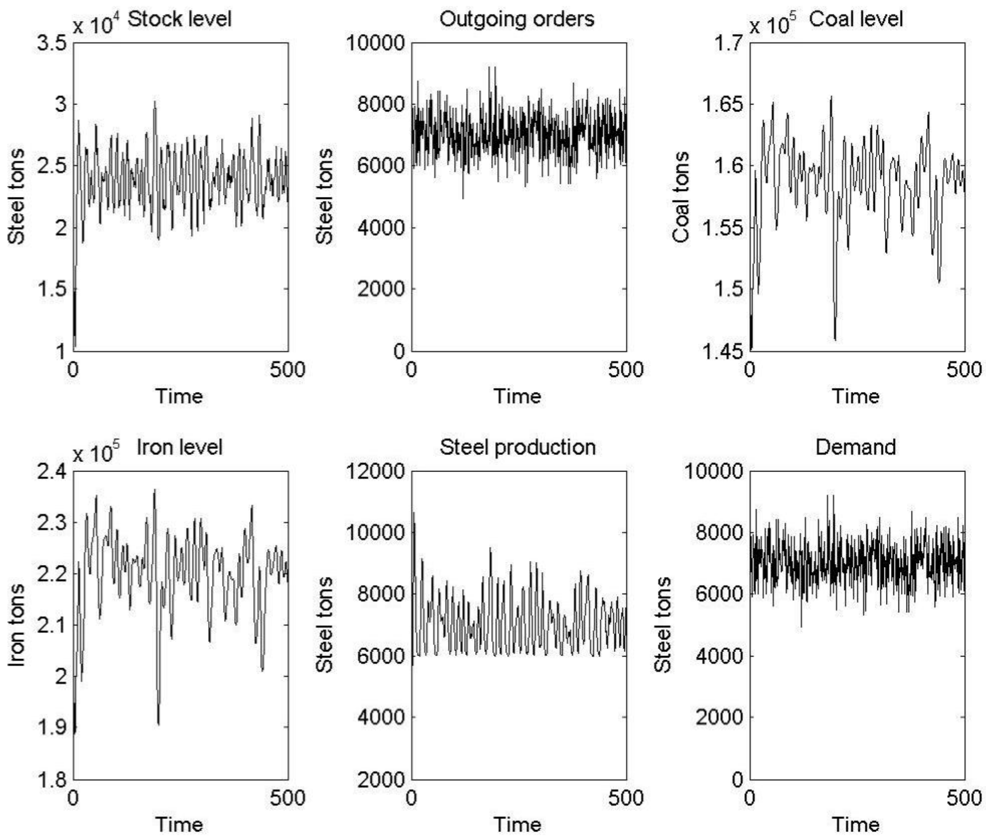

Figure 20. The steel factory in scenario 4

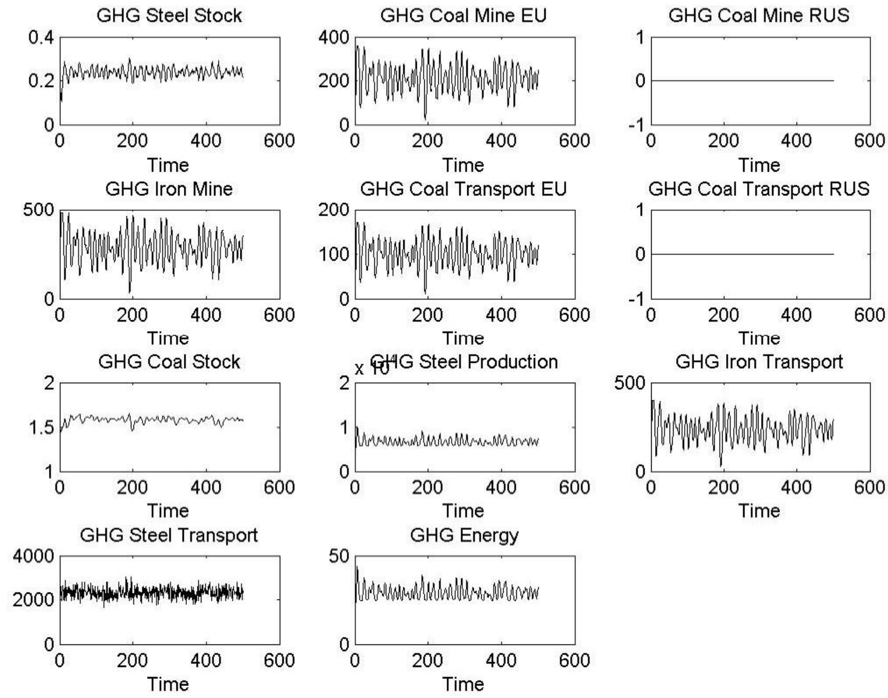

Figure 21. GHG emissions by source in scenario 4 (CO2 tons).

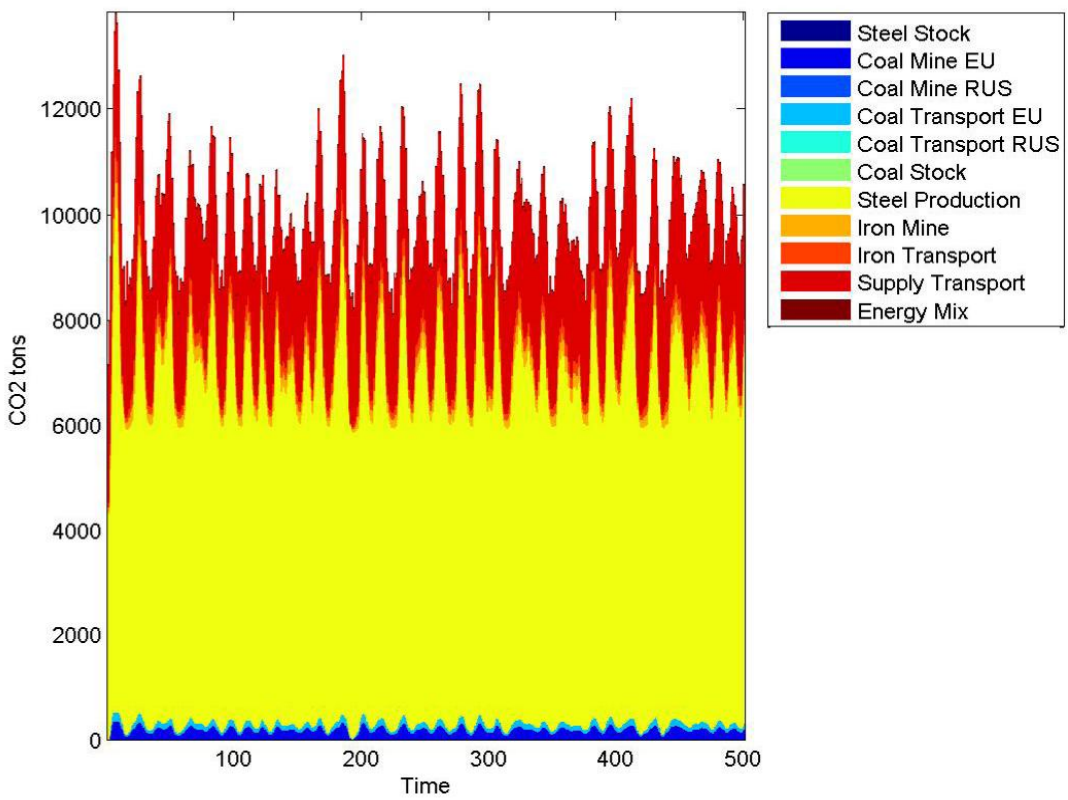

Figure 22. Total GHG emissions in scenario 4

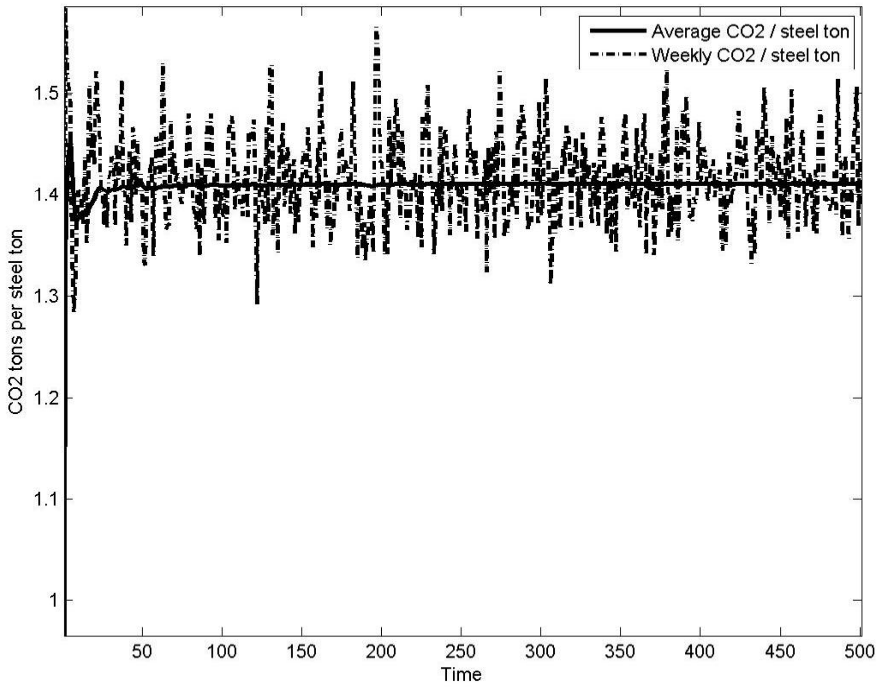

Figure 23. Cumulative GHG emissions per cumulative steel tons in scenario 4

8 Conclusions and possible improvements

The aim of this work was to examine supply chain planning as a means to limit CO2 emissions. Our literature review found that in the last decade, the analysis of greenhouse gas emissions has become an important part of supply chain studies. The field is new and there are several different approaches, such as carbon footprint calculations and life cycle analysis, each with as of yet quite floating definitions. These are however generally not directly linked to traditional supply chain models mainly concerned with inventory planning and service levels of clients.

To combine the breakdown of CO2 factors with system dynamics, we build a supply chain model with integrated life cycle analysis aimed at simulating a steel producer's CO2 emissions on a timescale with a scenario approach. The model allows the adjustment of several different parameters such as demand level, client network structure and CO2-intensities of different parts of the chain. Here, we have focused on the impact of demand fluctuation on CO2 emissions and thus the simulated scenarios include different demand structures and, to illustrate the other dimensions of the model, a change in the use of recycled steel as a raw material.

The results indicate that the most important part of a steel producer's CO2 emissions comes from the production, and consequently the largest reductions are likely to be induced by technological development within the mill, such as CO2 capturing systems and energy efficient production. However, for the total CO2 emissions, reductions can be found in the choice of raw materials suppliers and transport methods as well. A successful demand forecast and subsequent production planning also affect the emissions: based on our demand fluctuation scenarios, an unanticipated step in demand can temporarily cause the CO2 volume to rise.

The supply chain model with integrated life cycle analysis is a novel approach to the problem, and not without its flaws. To limit the scope of the work, we had to make several important simplifications to the supply chain model. The structure of the supply chain was simplified by reducing the number of clients and suppliers and the client structure was further boiled down by not considering service levels of individual clients. These are minor changes however regarding the total CO2 emissions as they mainly affect the transport related emissions.

More importantly, emissions-wise, we have simplified the process of steel production. The actual process includes several energy-intensive stages with different parameters that could be changed to reduce emissions. Here we have, for simplicity, taken the process as one-stage, applying a single energy and raw materials bill to the whole factory. We have also simplified the impact of using recycled scrap metal as an alternative to other raw materials. For a proper treatment of a steel producer's CO2 emission reducing capacity, these factors would have to be thoroughly studied, since the production process is the main cause of emissions. Breaking down the process would thus help identify new scenarios to run the model with and specific ways to reduce CO2 emissions.

Yet another simplification in the model concerns the production planning. The inclusion of several delays in the production and deliveries complicates finding the optimal control of production levels, so instead we have opted for quite simple heuristics both in production and raw material orders. This leads to some rather unrealistic behaviour of the system with certain starting parameters. Thus, finding a more sensible heuristic would help both produce more realistic results and better interpret the results produced.

Our model is based on the cradle-to-gate approach, which means that the environmental impacts of clients using and possibly recycling the steel are not considered. In some respect, our approach neglects the "true" impact of steel production. Also, as the future environmental impact of a product can be a valuable marketing asset, companies are becoming more and more interested in the whole supply chain. A thorough cradle-to-grave analysis could be interesting in the future.

Finally, as the results show that the reductions that can be achieved in the production process outweigh those created through changes in the supply chain, the model might be more appealing to a less energy-intensive industry. As the proportion of CO_2 emissions not caused by production indicated by the life cycle analysis grows larger, introducing a supply chain simulation model becomes more attractive. Therefore, for establishments whose main source of emissions is for example transport, including life cycle analysis in supply chain modelling could help reduce the CO_2 volume. With proper implementation, such CO_2 emissions models could become valuable as a part of regular supply chain planning.

9 References

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10 Appendix A

Main program

```
%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Helsinki University of Technology (Teknillinen korkeakoulu)
% Mat-2.4177 Seminar on Case Studies in Operations Research
% Spring 2009
%
%
% How to reduce CO2 Emissions Through Better Supply Chain Planning
% Supply Chain Simulation Model
% Main Program
%
%
% Authors:
%
% Niklas Tapola
% Oskari Eskola
% Lari Järvenpää
% Antti Koulumies
% Maija Mattinen
% Heikki Peura
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%% Clearing memory and screen
clear all
close all
clc

%% Model parameters
cap_max=12000;
stock_0=24000;
coal_0=150000;
iron_0=200000;

production_delay=1;
coal_transport_delay=0;
coal_delay_EU=1;
coal_delay_russia=2;
iron_delay=1;

recycling_speed=0;
recycled_step=150;
recycled_percentage=0;
```

```
Coal_per_steel = 0.69-0.63*recycled_percentage;
% change here the desired percentage of recycling!
recycled_percentage_step=0; %percentage of production is with recycled steel
Coal_per_steel_step=0.69-0.63*recycled_percentage_step;
Coal_per_electricity = 0.7;
iron_per_steel = 1.6-1.1*recycled_percentage;
iron_per_steel_step = 1.6-1.1*recycled_percentage_step;

cps0=0.69;
ips0=1.6;
CO2ps0=0.96;
slopetime=26;
d_recycling=recycled_percentage_step-recycled_percentage;
recycling_speed_coal=-d_recycling*cps0*1/slopetime;
recycling_speed_iron=-d_recycling*ips0*1/slopetime;
recycling_speed_CO2s=-d_recycling*CO2ps0*1/slopetime;


% Delivery constants
max_iron_delivery = 30000;
max_coal_deliveryRUS = 12000;
max_coal_deliveryEU = 5000;
demand_initial_value = 4;

% PID controller parameters
P=1/20000;
I=8/1000000;
D=0;

simtime=500;
global SCENARIO

% scenario 0: base scenario, constant deterministic demand
% scenario 1: step demand
% scenario 2: random demand
% scenario 3: ramp demand
SCENARIO=1;


%% Customer list

customers=cell(0);

customers=addCustomer(customers, 'A', 'Dilbeek', 1489, 0, 0, 'truck');
customers=addCustomer(customers, 'B', 'Heilbronn', 1498, 0, 0,'truck');
customers=addCustomer(customers, 'D', 'Shanghai', 21720, 0, 0, 'container');
```

```
customers=addCustomer(customers, 'E', 'Köping', 142, 0, 0, 'railroad');
customers=addCustomer(customers, 'F', 'Beerwalde', 1184, 0, 0, 'truck');
customers=addCustomer(customers, 'G', 'Valparaíso', 15720, 0, 0, 'ship');
customers=addCustomer(customers, 'I', 'Busan', 22140, 0, 0, 'container');
customers=addCustomer(customers, 'K', 'Xingang', 21984, 0, 7000, 'container');
customers=addCustomer(customers, 'L', 'Vantaa', 600, 0, 0, 'truck');
customers=addCustomer(customers, 'M', 'Antwerp', 1448, 0, 0, 'ship');
customers=addCustomer(customers, 'N', 'Skellefteå', 885, 0, 0, 'truck');
customers=addCustomer(customers, 'O', 'Novosibirsk', 4189, 0, 0, 'railroad');


orders=countOrders1(customers);
customers_vector=struct_to_vector(customers);
clear i


%% CO2 related parameters

CO2_per_Steel=0.96;
CO2_per_iron_production=0.025;         % tons/pellet ton
CO2_per_Steelstock=0.00001;
CO2_per_Coalstock =0.00001;
% Sweden
CO2_per_electricity=0.0041;            % tons/steel ton (vattenfall)
% Finland
%CO2_per_electricity=0.185;
CO2_per_coal_production_EU=0.0432;%*CO2_per_electricity;
CO2_per_coal_production_RUS=0.0382;%*CO2_per_electricity;


% Emissions per kilometre cargo ton
train_emissions=0.00002;
ship_emissions =0.000015;
dist1 = 300;              % Kiiruna - Luleå
dist2 = 1000;             % Luleå - Oxelösund


% Transfering iron ore to Oxelösund
% by train 300 km
multip1 = train_emissions * dist1;
% by ship 1000 km
multip2 = ship_emissions * dist2;
CO2_iron_transport_multip = multip1 + multip2;

% Tranfering coal from Poland
% by train Katowice - Gdansk 540 km
```

```
% by ship 650 km
dist1 = 540;                % Katowice - Gdansk
dist2 = 650;                % Gdansk - Oxelösund
multip1 = train_emissions * dist1;
multip2 = ship_emissions * dist2;
CO2_coal_transport_multip_EU = multip1 + multip2;

dist1 = 3000; % Novosibirsk - St. Petersburg
dist2 = 1000; % St. Petersburg - Oxelösund
multip1 = train_emissions * dist1;
multip2 = ship_emissions * dist2;
CO2_coal_transport_multip_RUS = multip1 + multip2;


%% Simulation and plotting of results

sim('modelCO2_release.mdl',simtime);
figure(1)
subplot(2,3,1),
plot(t, stock);title('Stock level');xlabel('Time');
subplot(2,3,2),
plot(t,Outgoing_orders);title('Outgoing orders');xlabel('Time');
subplot(2,3,3),
plot(t,coal_level);title('Coal level');xlabel('Time');
subplot(2,3,4),
plot(t,iron_level);title('Iron level');xlabel('Time');
subplot(2,3,5),
plot(t,steel_production);title('Steel production');xlabel('Time');
subplot(2,3,6),
plot(t,sum_demand);title('Demand');xlabel('Time');
saveas(gcf, 'stock', 'jpg');


figure(2)
subplot(4,3,1),
plot(t,GHG_Steel_Stock);title('GHG Steel Stock');xlabel('Time');
subplot(4,3,2),
plot(t, GHG_Coal_MineEU);title('GHG Coal Mine EU');xlabel('Time');
subplot(4,3,3),
plot(t, GHG_Coal_MineRUS);title('GHG Coal Mine RUS');xlabel('Time');
subplot(4,3,4),
plot(t, GHG_Iron_Mine);title('GHG Iron Mine');xlabel('Time');
subplot(4,3,5),
plot(t, GHG_Coal_transportEU);title('GHG Coal Transport EU');xlabel('Time');
subplot(4,3,6),
plot(t, GHG_Coal_transportRUS);title('GHG Coal Transport RUS');xlabel('Time');
```

```
subplot(4,3,7),
plot(t,GHG_Coal_Stock);title('GHG Coal Stock');xlabel('Time');
subplot(4,3,8),
plot(t,GHG_Steel_Production);title('GHG Steel Production');xlabel('Time');
subplot(4,3,9),
plot(t,GHG_Iron_transport);title('GHG Iron Transport');xlabel('Time');
GHG_supply_transport=0;
for i=1:length(customers)
    GHG_supply_transport=GHG_supply_transport+GHG_shipment(delivery,...
demand_vector, customers, i);
end
subplot(4,3,10),
plot(t,GHG_supply_transport);title('GHG Steel Transport');xlabel('Time');
subplot(4,3,11),
plot(t,GHG_Energy_Mix);title('GHG Energy');xlabel('Time');
saveas(gcf, 'GHG', 'jpg');

GHG_all=[GHG_Steel_Stock GHG_Coal_MineEU GHG_Coal_MineRUS GHG_Coal_transportEU ...
    GHG_Coal_transportRUS GHG_Coal_Stock GHG_Steel_Production GHG_Iron_Mine ...
    GHG_Iron_transport GHG_supply_transport GHG_Energy_Mix];
figure(3)
bar(GHG_all, 'Stack')
% legend('Steel Stock', 'Coal Mine EU','Coal Mine RUS','Coal Transport EU',...
%      'Coal Transport RUS','Coal Stock','Steel Production','Iron Mine',...
%      'Iron Transport','Supply Transport','Energy Mix')
axis tight
saveas(gcf, 'sum_GHG', 'jpg');

figure(4)
GHG_cumsum=cumsum(sum(GHG_all,2));
steel_cumsum=cumsum(steel_production);
ratio=GHG_cumsum./steel_cumsum;
ratiom=mean(ratio);
ratio1=sum(GHG_all,2)./steel_production;
plot(ratio,'LineWidth',2);hold on;% plot(t,ratiom, 'r');
plot(ratio1,'k-.','LineWidth',2);
%title('Cumulative GHG per Cumulative Steel Production');xlabel('Time');
legend('Average CO2 / steel ton', 'Weekly CO2 / steel ton');
axis tight
saveas(gcf, 'ave_GHG', 'jpg');
```

addCustomer.m

```
function customers=addCustomer(customers, name, town, distance, max_delay, order_size, means)
```

```
id=length(customers)+1;
client=struct('id',id,'name',name,'town',town,'distance',distance,'max_delay',max_delay,
'order_size',order_size,...
    'means', means);
customers{id}=client;

end
```

countOrders.m

```
function orders=countOrders(t,customers,SCENARIO)

if customers(1)==0

    orders=zeros(1,12);

else
    if (isvector(customers))
        customers=vector_to_struct(customers);
    end
    demands=getDemands(customers);

    for i=1:length(customers)

        switch(SCENARIO)

            case 0
                orders(i)=max(0,demands(i));

            case 1 % step demand
                if t<200
                    orders(i)=max(0,demands(i)+0.1*randn*demands(i));
                else
                    orders(i)=max(0,demands(i)*1.4+0.1*randn*demands(i));
                end
            case 2 % random demand
                orders(i)=max(0,(demands(i)+0.1*randn*demands(i)));
            case 3 % ramp demand
                orders(i)=max(0,(t/100*(demands(i)+10*randn/t*demands(i))));
        end
    end
end
```

deliveries.m:

```
function f=deliveries(a,b,c,d,e)

customers=a;orders=b;time=c;Outgoing_orders=d;orderList=e;

if customers(1)==0
    customers=cell(0);
    for i=1:10
        customers=addCustomer(customers,     'name',     'town',     100000*rand,     10*rand,
floor(10*rand));
    end

    f=[0 0 0 0 0 0 0 0 0 0 0];

else
    if (isvector(customers))
        customers=vector_to_struct(customers);
    end

    for i=1:length(customers),
        orderList(i)=orderList(i)+orders(i);

    end

    maxcap=Outgoing_orders;
    for i=1:length(customers)
        %if there's something to be delivered
        if (orderList(i) > 0)
            maxcap1=maxcap;
            maxcap=max(0,maxcap-orderList(i));
            % ...we try to fill as much as possible
            orderList(i)=max(0,orderList(i)-maxcap1);
        end
    end

    f=orderList;
end
```

getDemands.m

```
function demands=getDemands(customers)

for i=1:length(customers)
    demands(i)=customers{i}.order_size;
```

```
end
```

GHG_shipment.m

```
function retval=GHG_shipment(backlog, demand, customers, id)

% backlog ^= delivery

means=customers{id}.means;

switch means
    % from literature
    case 'truck'
        coeff=120;
    case 'railroad'
        coeff=20;
    case 'container'
        coeff=15;
    case 'ship'
        coeff=15;
end

shipment=(cumsum(demand)-backlog); %cumulative shipments
temp=shipment(:,id)*customers{id}.distance*coeff;

%weekly emissions in tons
retval=10^-6*[temp(1);diff(temp)];
```

deliveryDecisionFunction.m

```
function retval = deliveryDecisionFunction(demand,stock,production)

if stock>0
    available=stock+production;
    toDeliver= demand;
else
    available=production;
    toDeliver=-stock+demand;
end

retval=min(available,toDeliver);
```

muxTest.m

```
function f=muxTest(a,b,c,d,e)

customers=a;orders=b;time=c;Outgoing_orders=d;orderList=e;

time;

if customers(1)==0
    customers=cell(0);
    for i=1:10
    customers=addCustomer(customers, 'name', 'town', 100*rand, 10*rand, floor(10*rand));
    end

    f=cell(0);


else
    if (isvector(customers))
        customers=vector_to_struct(customers);
    end


    if (isvector(orderList))
        if orderList(1)==0
            orderList=cell(0);
        else
            orderList=vector_to_struct(orderList);
        end
    end

    for i=1:length(customers),
        id=length(orderList)+1;
        orderTemp=struct('id',customers{i}.id,'time',time, 'size',orders(i),...
        'notDelivered',orders(i), 'priority',(customers{i}.max_delay)+time);
        orderList{id}=orderTemp;
    end

% sorting by priority?
%

    maxcap=Outgoing_orders;
    for i=1:length(orderList),
        %if there's something to be delivered
        if (orderList{i}.notDelivered > 0)
            % ...we try to fill as much as possible
            orderList{i}.notDelivered=max(0,orderList{i}.notDelivered-maxcap);
```

```
            maxcap=max(0,maxcap-orderList{i}.notDelivered);
        end
    end

% CO2 counting by customer profile
%

f=struct_to_vector(orderList);
%f=orderList;

end
```

Submodels of the system

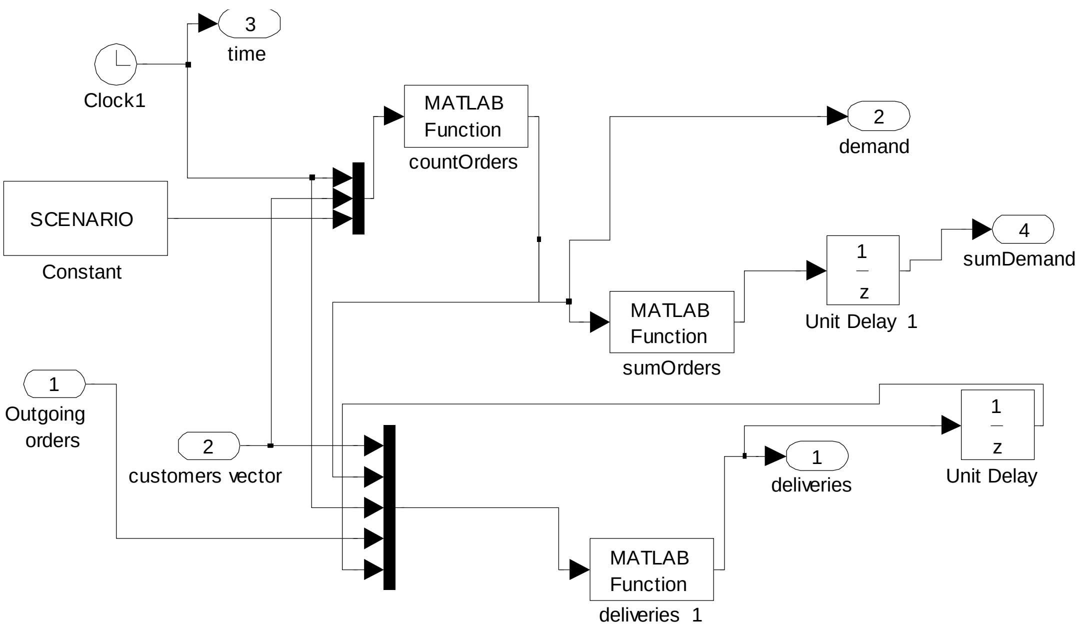

Figure 24. Customer Relations.mdl

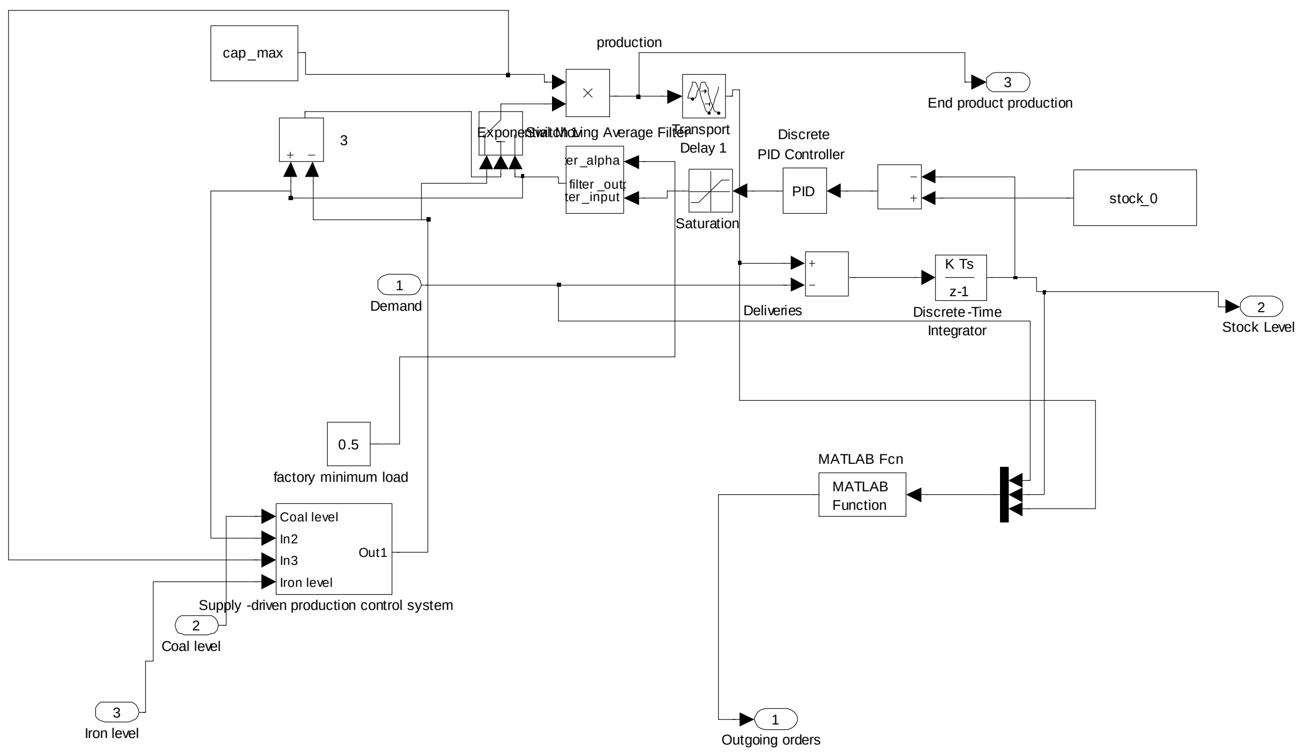

Figure 25. Factory.mdl

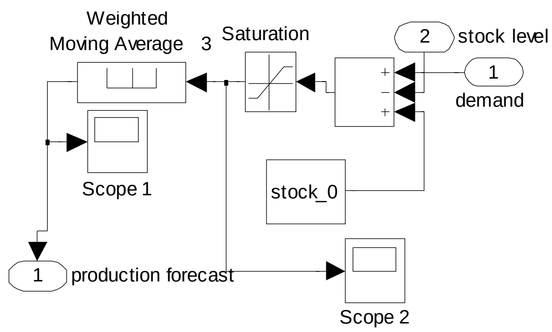

Figure 26. Moving Average.mdl

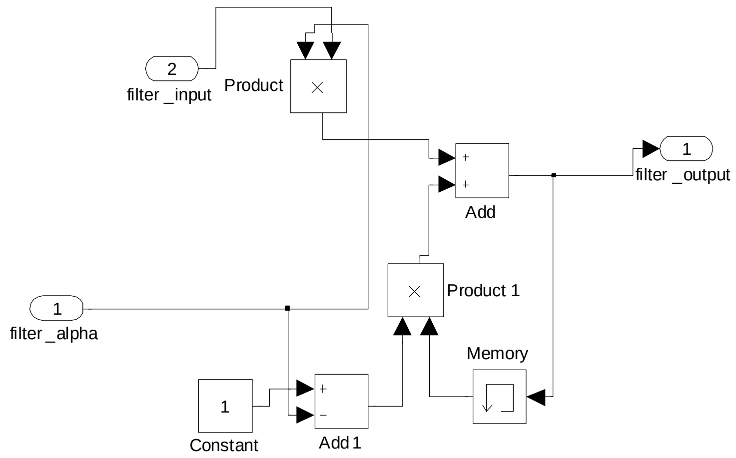

Figure 27. Exponential Filter.mdl

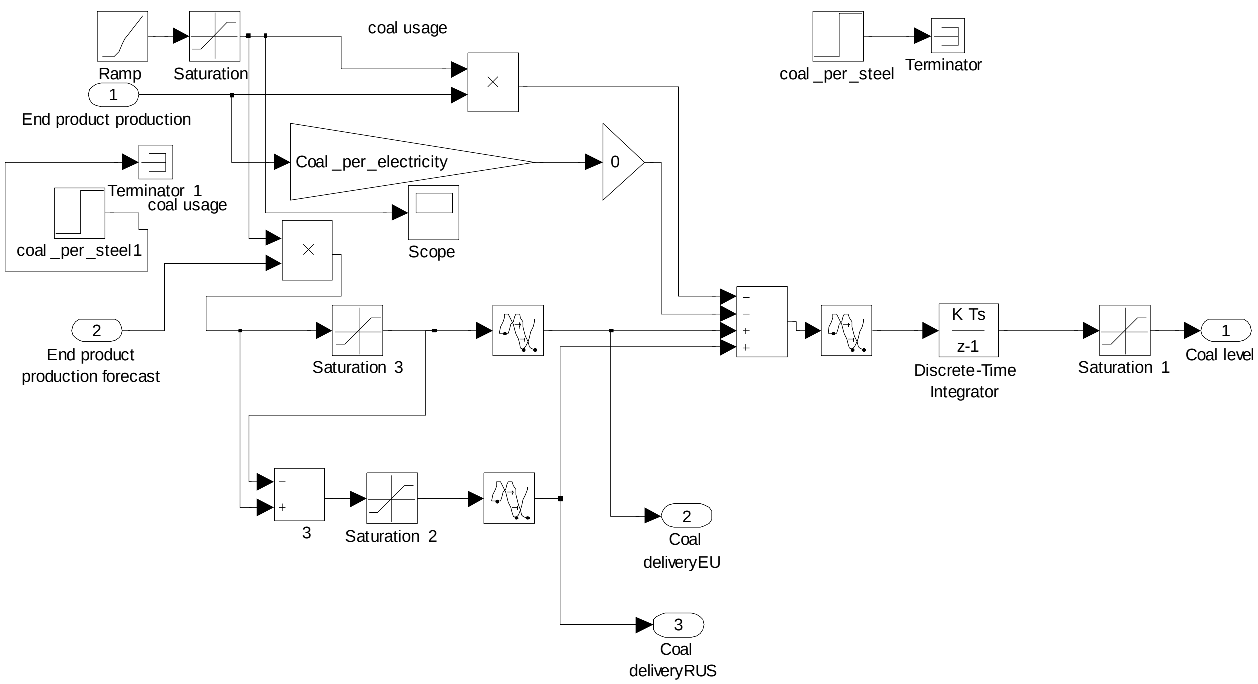

Figure 28. Coal.mdl

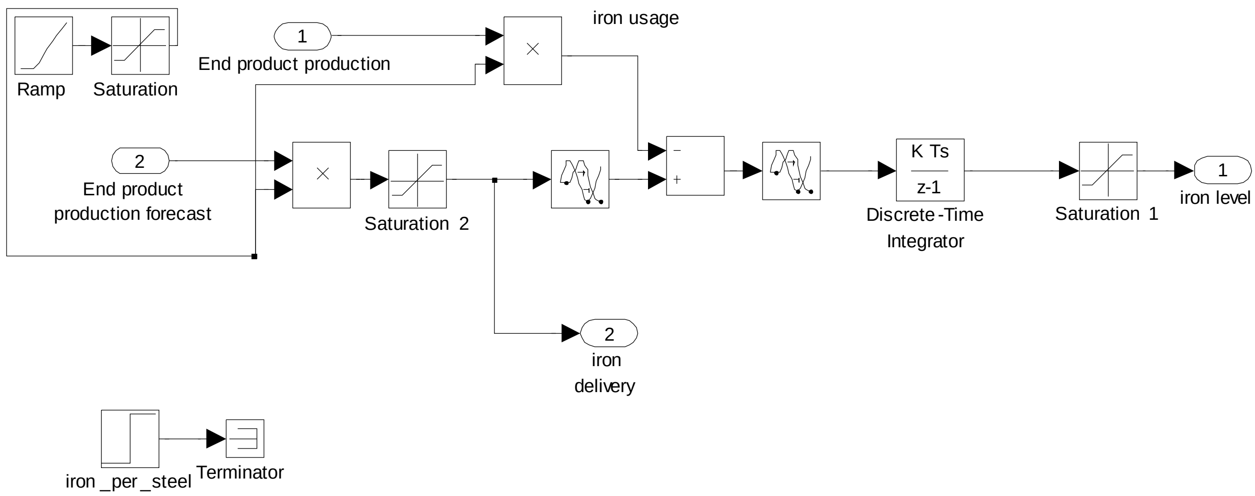

Figure 29. Iron.mdl

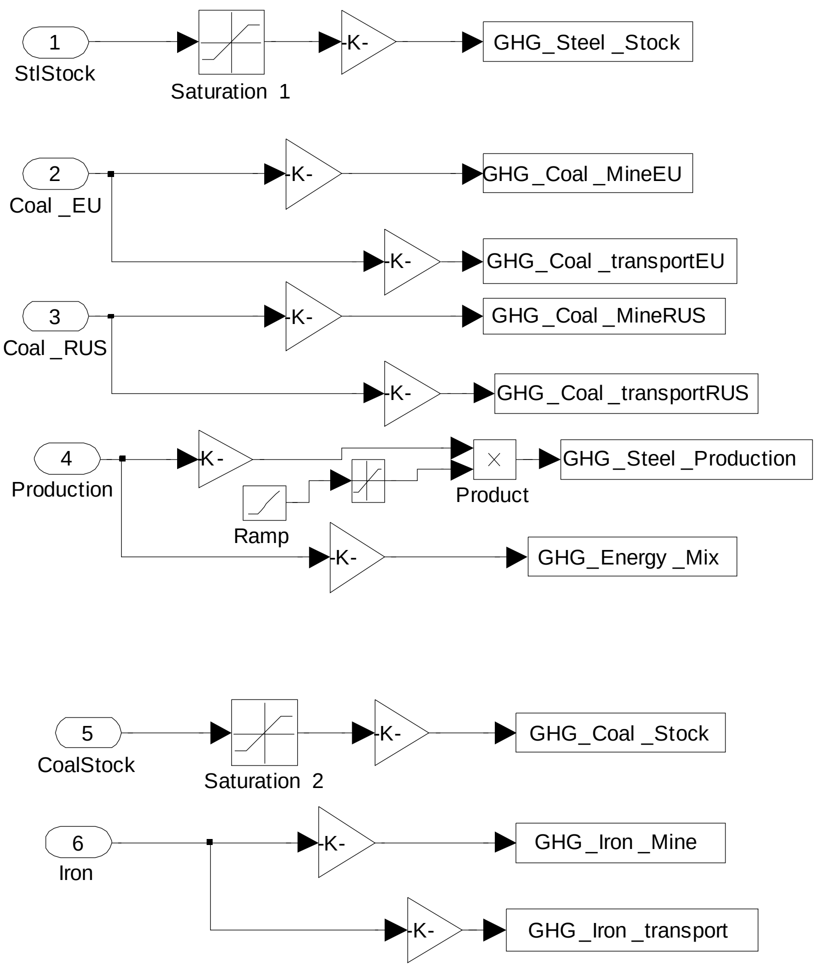

Figure 30. CO2 Counter.mdl