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OPTIMIZATION MODELS FOR THE INTEGRATED STEEL PLANT WITHIN THE GAS-MAT RESEARCH PROJECT

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ABSTRACT

This thesis considers optimization issue with respect to technical and operational characteristics of a future steel plant within a potential industrial cluster. It is carried out within a research project called Gas-Mat which is initiated by SINTEF and Norwegian University of Science and Technology (NTNU), and aims to build solid assessment methods for economical and technical feasibility of the potential industrial cluster considered to be established. The purpose of our work is to optimize operations of the future steel plant and based on the models to do further analysis. Following objectives are determined and accomplished in the thesis in order to achieve this purpose. Firstly an extensive literature research is conducted to gain broad knowledge about the required topics. Then the potential industrial cluster is described by mathematical programming model based on an initial programme code supplied by SINTEF. As a next step demand is forecasted by quantitative methods such as moving average and linear regression. Afterwards, in the light of existing theoretical frameworks, an optimization model dealing with deterministic parameters is built for cost minimization and tested for validation. Finally, a stochastic programming model is developed for closer real life representation and to be able to make decisions under uncertainty.

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Milena Vuvunikian and Emrah Arica.

Molde, May 2009

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1 INTRODUCTION

Optimization has broad applications in industry due to the fact that most of the decision-makers have understood that economic profit can be increased easier by reduction of wastes rather than enhancing the revenue in this highly competitive current market conditions. In other words, profitability and efficiency of operations is crucially important to survive in business.

This thesis deals with optimization of operations in a steel plant within an industrial park. The thesis is a part of long-term and very large-scaled research project called Gas-Mat which is initiated by cooperation of SINTEF and NTNU. The Gas-Mat project's main objective is assessment of the potential for the environmentally justifiable utilization and industrial processing of natural gas, together with deposits of ore/minerals in the Barents Region/Northern Region. The specified problem for the thesis is optimizing economic profitability of the future steel plant considered to be established within the potential industrial cluster.

The thesis as a part of the Gas-Mat project shares the same importance with it from many aspects. It has strategic benefits such as creating new industrial opportunities and utilizing the rich resources of Norway. However, it contains many difficulties and challenges. Some of them are: searching and learning about many new concepts including technical information; high uncertainty when measuring and optimizing the efficiency and profitability of a non-existing future plant and its integration in the potential cluster; reliable data unavailability for analysis. Thus, hard work and high creativity will be essential.

The outputs of the thesis will provide SINTEF with better understanding of the steel plant insights and being capable of doing tests and analysis over potential conditions of the plant. Flexibility of analysis during decision-making process will be very beneficial where small improvements might yield large savings.

In our point of view, this thesis is a great opportunity to apply our theoretical knowledge that we have gained during the Masters Degree in Logistics. Contributing to such a major real-life project will be a high motivation reason for us to be hard working and productive to solve our problem. Meanwhile, the thesis will provide us with learning about all aspects of the steel industry and production as well as project management of a large-scaled project.

There are several goals that we expect initially for this research. First one is to develop a deterministic optimization model that minimizes the total costs for the operations in the integrated steel plant and enables us to do further analysis. Second goal is to implement forecasting methods and estimate the uncertain future demand. The last goal is to build a stochastic programming model that maximizes the total profit from the integrated steel plant by taking uncertainties into account. We believe that, by stochastic programming model, this unknown situation will be represented better.

In the following Chapter we will give general information about SINTEF. Chapter 3 will describe the Gas-Mat project in details. In Chapter 4 we will explain the research plan and our role in the Gas-Mat project. Chapters 5 and 6 are devoted to literature review and theory review. In Chapter 7 we will explain a mathematical programming model for whole industrial cluster. Chapter 8 focuses on steel and production process and gives broad knowledge about them. Forecasting for future steel demand is placed in Chapter 9. In Chapters 10 and 11, we will explain the developed mathematical model for integrated steel plant and will demonstrate test results and analysis. In Chapter 12, we will explain the developed stochastic optimization model for the future steel plant. Finally we will conclude our thesis in Chapter 13.

2 SINTEF RESEARCH CENTER

Our Master Thesis was initiated by SINTEF Research and Development Company which is one of the hosts of Gas-Mat project with NTNU. We will introduce the company profile and give the reader an overview of the organizational structure. Following information in this chapter has been taken from SINTEF webpage and contact persons.

2.1 General Information

SINTEF is the largest non-commercial research company in Scandinavia. It was established in 1950 and employs roughly 2145 employees. The main head office of SINTEF is located in Trondheim. In addition, SINTEF has offices in Ålesund, Bergen, Stavanger and Oslo. The company is represented in USA (Houston, Texas), the Former Yugoslav Republic of Macedonia (Skopje), Brazil (Rio De Janeiro) and Denmark (Hirtshals). SINTEF has partnerships with NTNU and Oslo University. NTNU and SINTEF cooperate closely on staff, technologies, laboratories and research. The objective with this collaboration is to obtain best students and researches and extend SINTEF's research areas.

SINTEF carry out a multidisciplinary research in the following areas: natural and social science, medicine and technology. Furthermore, developed solutions and innovations are adopted in Norwegian industry and society. It is supported by Norwegian Government and all income from the research is invested in new equipment, development of new technologies and future research. We want to emphasize the fact that SINTEF has focus on developing energy-friendly and efficient technologies which result in reduction of energy consumption in Norway.

The company is divided into several research divisions as seen in the organization chart below.

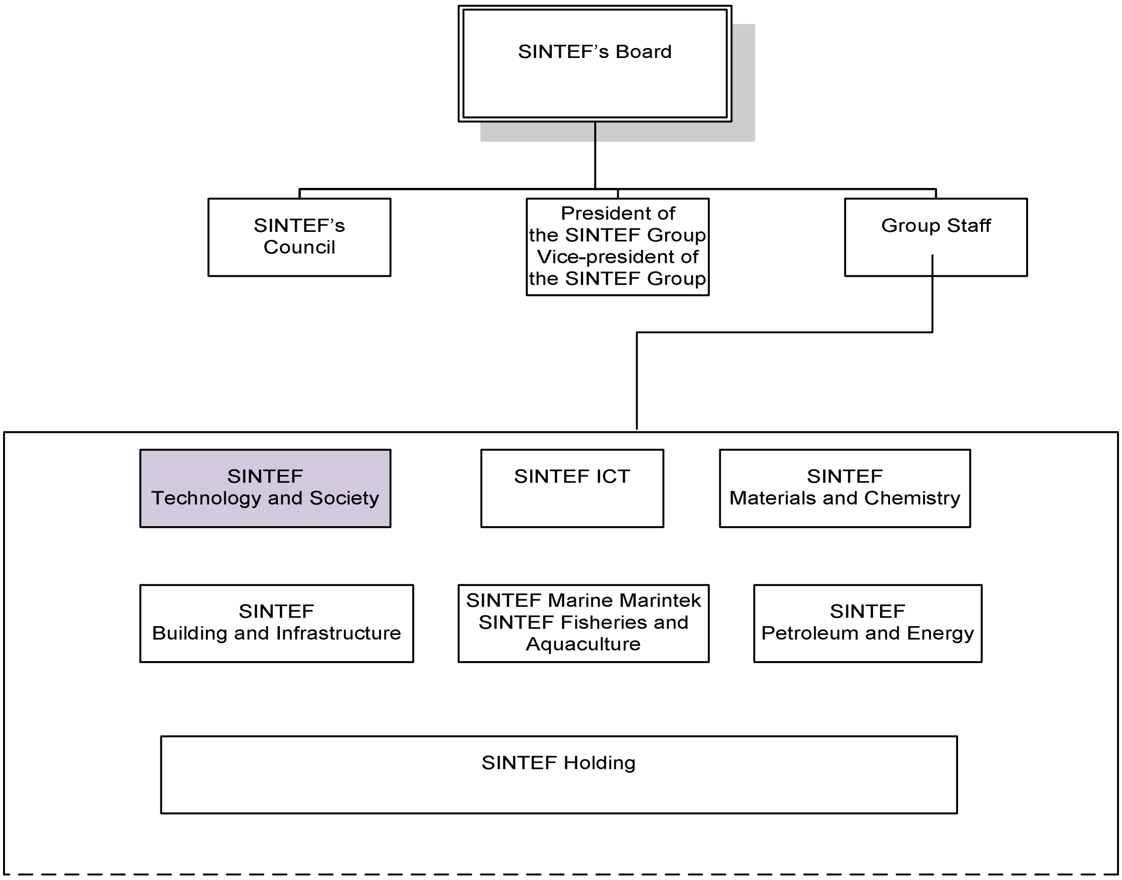


Figure 2-1 Organizational chart

Regarding the master thesis, we are involved in SINTEF Technology and Society Division. Therefore we would like to highlight and introduce it.

2.2 SINTEF Technology and Society Research Unit

SINTEF Technology and Society research division consists of nine departments:

1. **Applied economics and Operations Research**
2. Global Health and Welfare
3. Health Services Research
4. Industrial Management
5. Innovation and industrial development
6. Medical technology
7. Preventive Health Care
8. Transport Research

It employs around 320 people with different educational backgrounds who work together in teams depending on type of projects. The unit is responsible for developing solutions and implementing analysis in the following business areas: Logistics; Productivity and innovation ability; Change processes; Knowledge management; Manufacturing; Working environment; Safety and environmental management; Economic decision models; Transport.

We have worked in closed cooperation with the department of Applied Economics and Operational Research. The department has focus on development of better decision making both in commercial business and public administration. It comprises understanding the actors' behavior, use theory and methods to model and optimize complex relations based on business economics and social economics in combination with operations research.

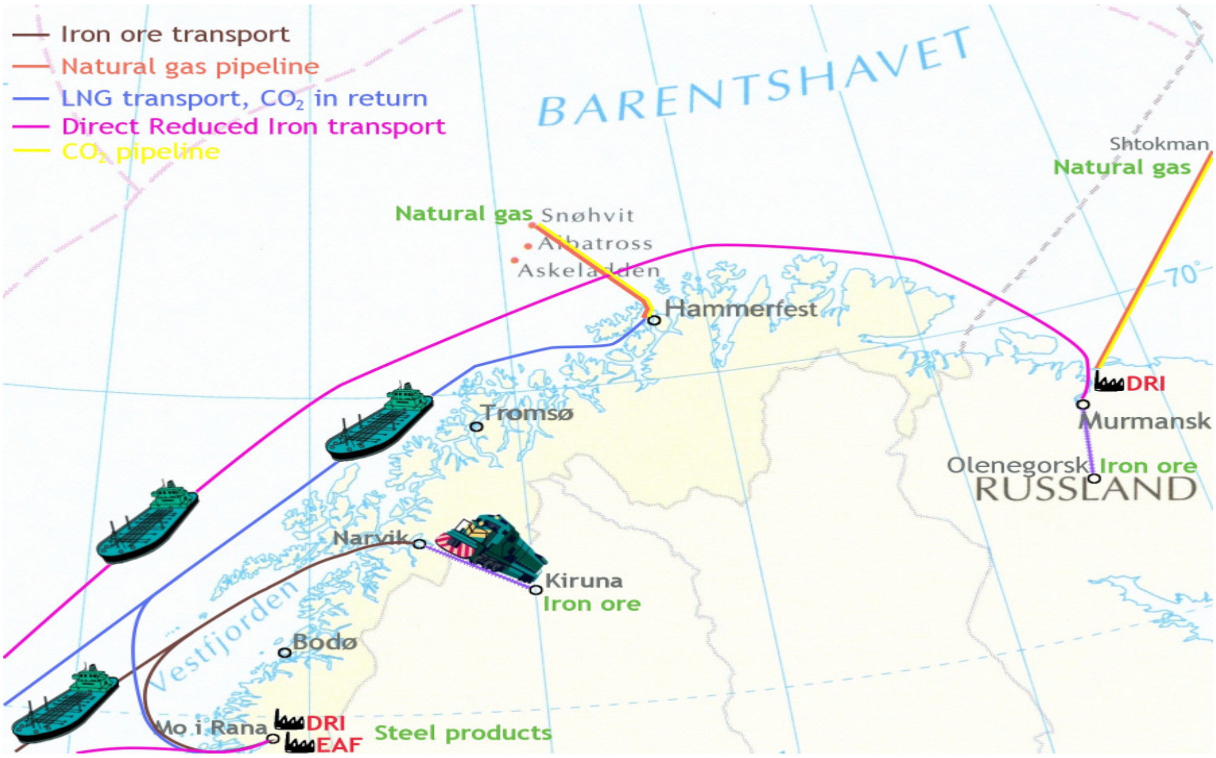
The department's main research fields are within operations research, business administration and economics. The overall focus is to contribute to better decision making for private companies and public authorities. Within operations research and business administration, researchers are engaged in developing models to support strategic and operational decisions. The objective is typically to maximize profit or minimize costs, or to compose portfolio of products and investments opportunities in a world of uncertainty. The projects often deal with value chains comprising input factor selection, processing, logistics/transportation and market modeling. Interaction between technology, management, and economics are essential and the approach to the problems is accordingly use of both technical and economic competence.

Within economics the department's main research activities are industrial development, cost-benefit analysis, regional/spill-over analysis and management within companies and value-chains. We focus on value and job creation, innovation, external effects and other impacts on society from different activities. Helping companies and public authorities to find optimal tools to reduce negative side-effects from economic activities is one of the objectives. The department does contract research for the oil- and energy sector, marine sector, manufacturing, service industries, public services, and for the transport and communication sector.

3 THE GAS TO MATERIALS (GAS-MAT) PROJECT

We have performed our research by working within the corresponding component of the Gas-Mat project being carried out by SINTEF. We have been provided with the comprehensive description of the project by SINTEF as well as initial Xpress code for the industrial cluster. The code is available to see in Appendix A. Gas-Mat is a project in cooperation of SINTEF, NTNU and the companies StatoilHydro ASA, Celsa Armeringsstål AS, Sydvaranger Gruve AS and LKAB. It is funded by the Norwegian Research Council and the involved companies.

The project's main objective is to assess the potential for the environmentally justifiable utilization and industrial processing of natural gas, together with deposits of ore/minerals in the Barents Region/Northern Region. It is considered that this can be realized through the establishment of gas based industrial clusters producing materials where all Carbon dioxide (   ) is captured and deposited in oil/gas reservoirs with zero emissions to the environment. The associated establishment of business and commerce, and with that the establishment of thriving societies in the Northern Regions is one of the most important social effects of the establishment of such industrial clusters.



Map 3-1 Potential place for the industrial cluster (SINTEF, 2009)

By industrial park in this research, concentration of different companies on the same location with shared infrastructure and interrelated value chain is implied. The proposed cluster will be an extension to an existing gas value chain. Therefore price for gas will be connected to the operation in the rest of value chain. The industrial cluster may contain following plants: Separator plant, Air Separation Unit (ASU) plant, Partial Oxidation (POX) plant, Methanol plant, Direct Reduced Iron (DRI) plant, Steel plant, Gas Power plant and Carbon Black plant. Graphical view of all plants in the cluster is demonstrated in Appendix B. In the beginning it most likely seems that DRI, Steel, Gas Power and Carbon Black plant will definitely be established. Decisions regarding establishments for the other plants will be given after comprehensive economic analysis. The following figure demonstrates the potential industrial cluster.

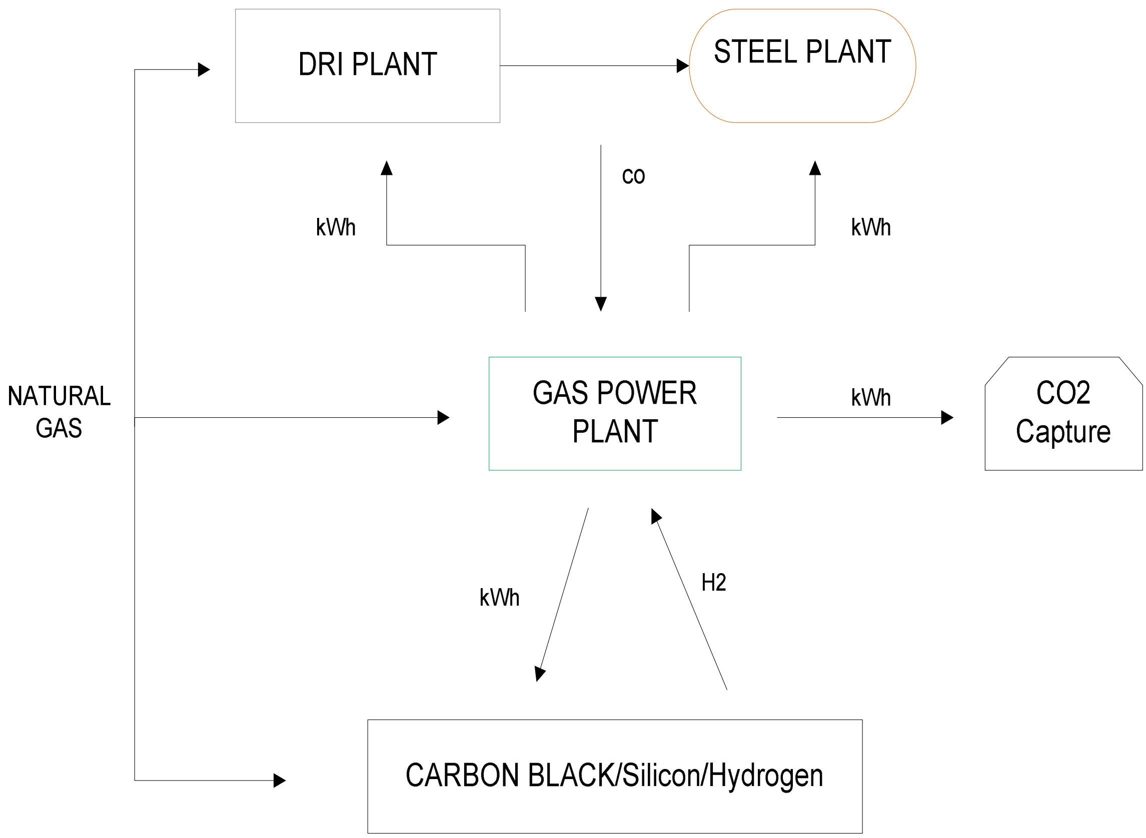


Figure 3-1 Example of a cluster of plants

The project has been divided into 4 sub-projects: technical feasibility; environmental accounts; corporate-economics model/analysis; socio-economic model/analyses.

3.1 Technical Feasibility (Sub-project 1)

Technical Feasibility will focus on which technologies would be relevant to use for the individual process steps. First step in this work is to assess which variables need to be specified for the various types of equipment, and how to compare them. This is also linked to how one chooses to handle the environmental aspect in this context.

3.2 Environmental Accounting (Sub-project 2)

Ideally, it is wished to calculate and compare the total environmental load for the various scenarios, preferably in such a way that this analysis shows which steps in the process chain are the weakest when it comes to the environmental impact, and thus be able to divide the total environmental impact among the products produced.

3.3 Business Analysis (Sub-project 3)

For the project to be commercially sustainable the added value in the project needs to be positive, both viewed as a whole and for each individual actor. In addition to a positive added value for the actors, the project needs to appear favourable in comparison to alternative utilizations of the input factor. One example is the alternative value for gas that can be transported to markets in Europe. The added value chain needs to be constructed in such a way that it appears attractive and profitable to all of the involved parties.

Through mathematical modellin both production processes and profit for each individual plant and for the plants combined can be analyzed. It gives insight in integration gains economically, in terms of process, logistically and environmentally. This may contribute to cover strong and weak aspects of individual plants and combinations of plants. For the project to appear attractive, the value chain needs to appear robust, both technically and financially. Due to high costs in new infrastructures, it is natural that localization considers the existing infrastructure or the planned investments in infrastructure.

3.4 Economic Analysis (Sub-project 4)

In an economic model, the following factors are need to be discussed:

Localization: Assessment of existing local infrastructure, both for company establishment, and for humane living conditions.

Work force: Industrial growth in an area with the need for jobs and pertaining increase in wealth versus established areas with access to a qualified work force.

Product demand: Logistics and possible local product-demand for products produced locally in the region, such as steel pipes for the distribution of oil and gas, something that will affect costs and risks linked to transportation.

Use of Surplus Energy: Integrated industrial plants/facilities will be able to be net producers of energy and not large consumers of energy. There should therefore be room for an analysis of surrounding activities and society's ability to conserve produced energy/power.

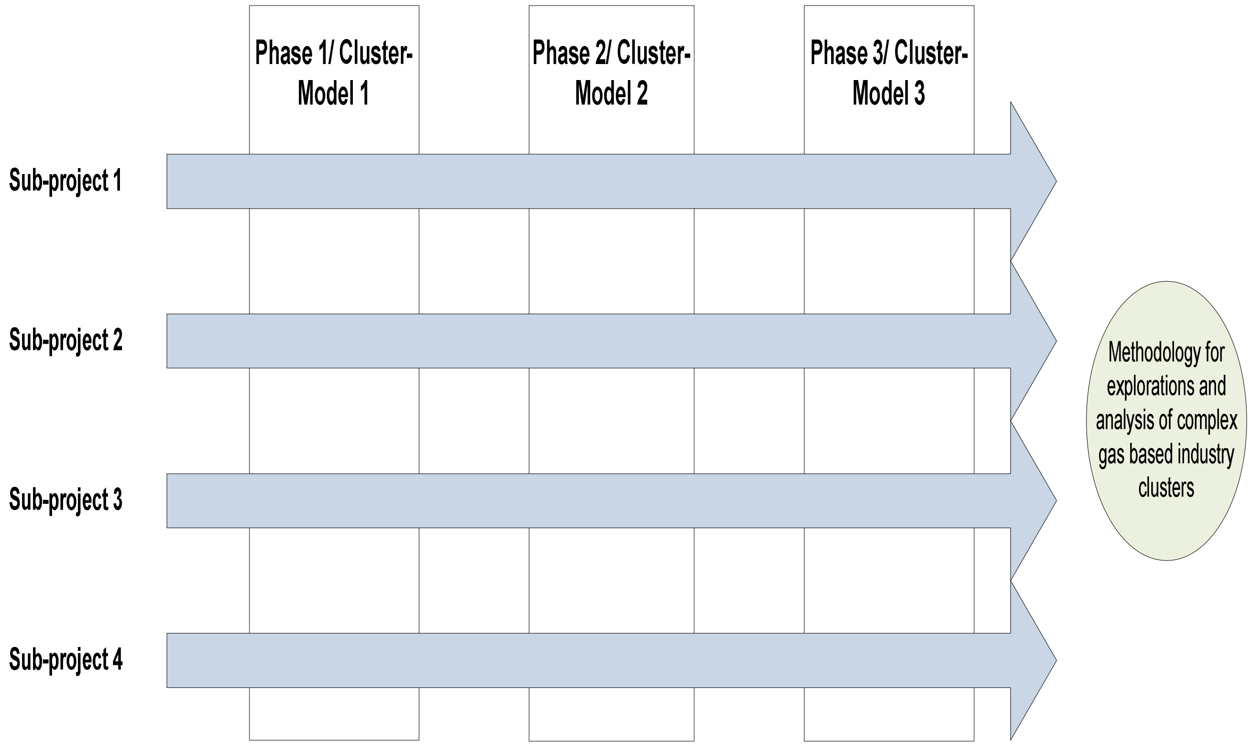


Figure 3-2 Gas-Mat project structure

3.5 Results and Benefits

The Gas-Mat project will define various industrial cluster models and the opportunities for synergies present in the concept of an industrial cluster. This means that it is expected to have established a basis and suitable methods for subsequent and more detailed studies linked to the development of actual industrial clusters.

The project's most important contribution will be to make probable that such industrial concepts take care of environmentally sound, business and economical considerations in the best way possible. A new method will be developed in order to be able to model such effects of coexistence in various industrial clusters using an efficient and accurate approach. The establishment of these carbon-neutral industrial clusters is expected to receive major focus globally in the future. The methods developed in the project will therefore possibly receive considerable international attention.

Moreover the project opens new industrial possibilities in Norway and the Northern Region/Barents Region. Also, it opens the possibility of strong industrial growth based on hydrocarbons as an energy source in these regions. Thus the project may have large environmental effects internationally as well. For the participating institutions, the project will provide increased industrial insight, and it will build important knowledge linked to a nationally and internationally important topic.

Finally, the project is planning an annual project conference in Norway focusing on gas-based industrial cluster concepts. It will result in publications at approximately 5 national/international conferences annually, and also publish approximately 10 scientific publications in international journals. It expects significant interest from national and regional authorities. Furthermore it might initiate several master and phd thesises from different universities.

4 RESEARCH PLAN

4.1 Research Problem Definition

As stated before, we have been incorporated in the Gas-Mat Project to perform our master thesis and to contribute to this large-scaled research project. Our contribution will be to the sub-project 3 called “Corporate-economics model and analysis”. We have intensified our research on the integrated steel plant as suggested by the SINTEF research team. The expectation of the sub-project research team from us is to develop a comprehensive model for optimization in an integrated steel plant. The model will be the extended form of the initial basic code and comply with it, as well as can be integrated further into the model for the whole industrial cluster. The model should allow them to do further economic analysis on the potential plant as it was stated in Section 3.3 in the description of sub-project 3. Furthermore it is crucial that uncertainty has to be taken into consideration when building the model for flexibility. Thus, it seems that a stochastic programming model has to be built.

In order to deal with this difficult problem within such large research project we have to first of all understand the work done in the project so far, than conduct literature research related to our topic, see the shortcomings of the code for the plant, produce ideas and develop a valuable optimization model. To build a sufficient and robust model which will provide us with realistic testing and analyzing of potential conditions of future steel plant, we have to search and collect detailed information about steel production and construct a model covering potential characteristics of the facility.

4.2 Research Objectives

The objectives of our master thesis are:

- Comprehensive literature research in order to gain sufficient knowledge about the potential cluster plants, particularly on steel and steel production. This also will help us while building mathematical models
- Mathematical formulation based on the initial cluster code to understand and analyze the operations and characteristics of the plants and the whole cluster.
- Development of a comprehensive deterministic model for optimization of operations in the integrated steel plant, and program the model in the available software as an optimization tool to be used for future analysis.

- Testing the created optimization tool with relevant data in order to see the models efficiency and robustness. Based on testing results to do further analysis and suggestions.
- Implementation of reliable forecasting methods for the future demand.
- Generating a scenario tree to represent randomness and building a stochastic programming model for handling the uncertainty. Programming the model in the available software as a stochastic optimization tool to be used for further analysis.
- Testing the stochastic optimization tool with relevant data and doing further analysis.

4.3 Research Methodology

In this research we will use quantitative methods of operations management field. It is predetermined by the nature of the current project and the objectives of our master thesis. Reiner (2005) divides quantitative model-driven research methodology into two groups: Empirical (descriptive or normative) and Axiomatic (descriptive or normative).

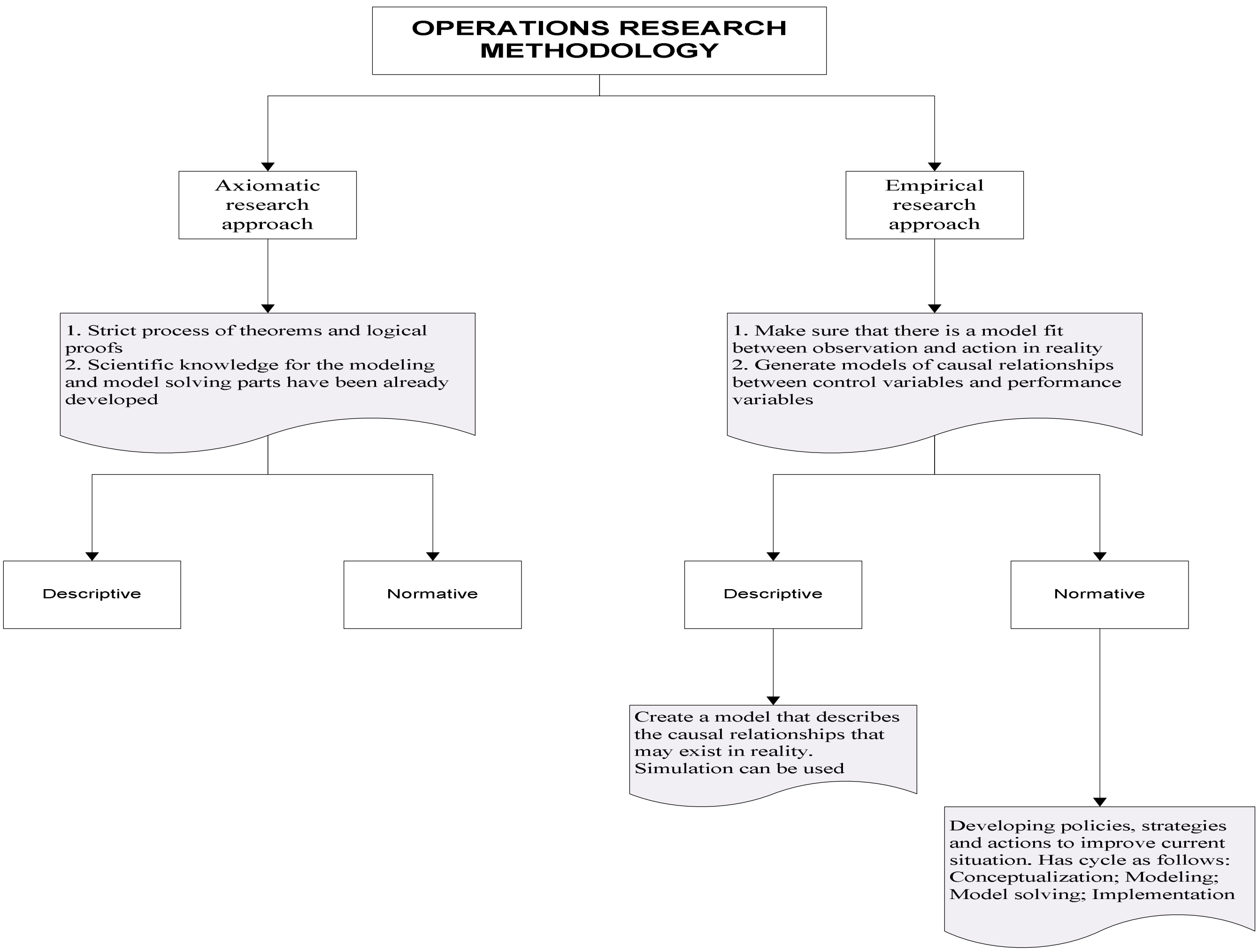


Figure 4-1 Quantitative method driven research

In the thesis, we will use both normative and descriptive empirical research while doing forecasting of demand based on historical data. On the other hand we will have analytical approach while building optimization models for the integrated cluster and analyzing them. The structure of data will not have any influence while building the models and analyzing them. Implementation of the models will be done in AMPL (a mathematical programming language) and CPLEX 9.0.0 solver will be used.

4.4 Research Stages

In this section we would like to illustrate our research stages in order to provide the reader with more clear view. We have divided our work into following stages: The first stage is the conversion of the industrial cluster code into mathematical modeling form (comprehensive understanding of the cluster and each individual plant); Next stage is detailed research on steel production (collecting information about steel industry, steel types as well as production process); Then forecasting methods will be applied to estimate the demand; Afterwards we will concentrate on the integrated steel plant within the cluster and develop an optimization model for it; Finally we will create a stochastic programming model for the integrated steel plant in order to make optimal decisions under uncertainty. In each stage we will conduct literature and theory researches simultaneously. The figure below demonstrates the algorithm that we plan to follow during our research.

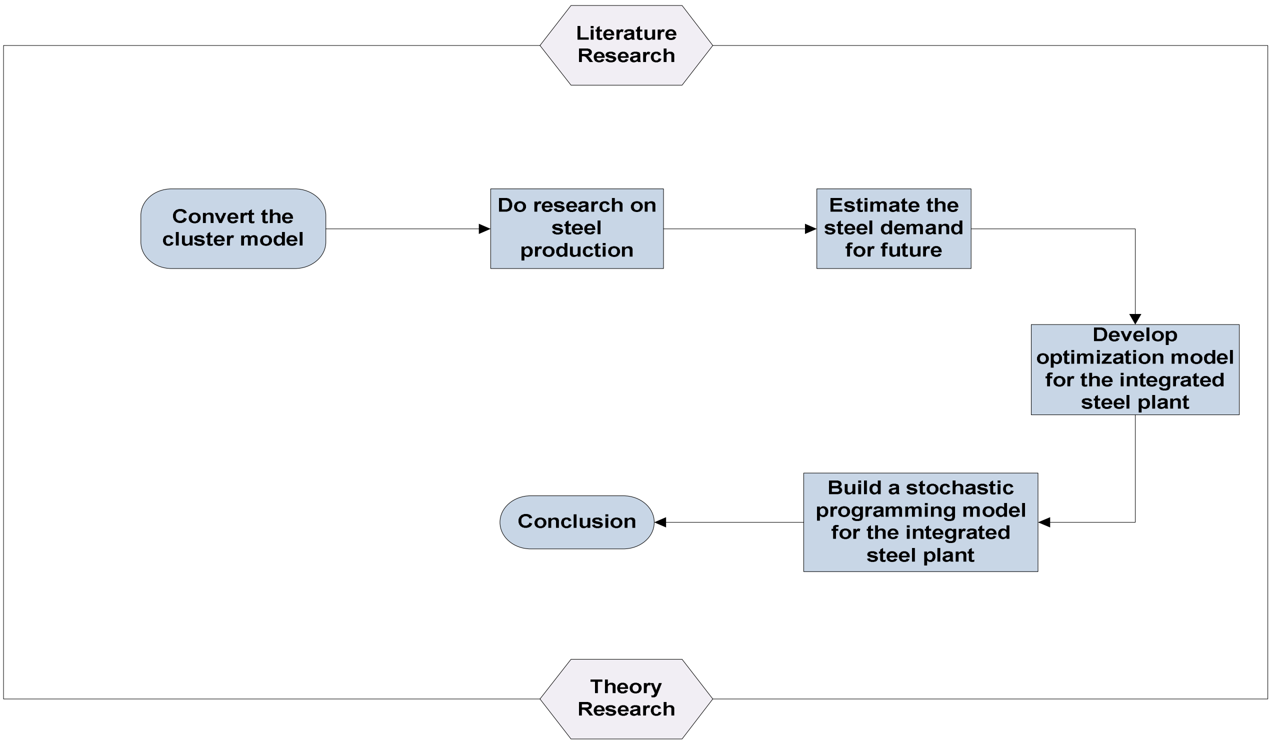


Figure 4-2 Research algorithm

4.5 Data Collection

As mentioned before, validity of data is not important in our master thesis, we need the data to test and analyze our models. Besides, it is not possible to construct completely correct data set regarding potential characteristics of a future plant. However, in order to do more realistic testing, we will set the data approximate to reality. The process of our data collection started right from the first meeting with the representatives from NTNU and SINTEF, when they described the topic, the probable nature of content and probable source of information. We had phone meetings with the research team regularly once in two weeks and discussed the thesis progress as well as data collection. We have gathered most relevant data about our thesis from the sources such as scientific articles, journals, textbooks and internet.

5 LITERATURE REVIEW

We have decided to separate literature review into two sub-chapters. The first sub-chapter reviews the literature which gives an understanding over each unit of an industrial cluster. The reason is that the provided code for the industrial cluster includes plants such as Separator, ASU, POX, Methanol, and Carbon Black and we should gain information about them in order to convert the code properly and understand the operations precisely. The conducted research aims to give background about production processes of these cluster's units. There is a wide range of relevant literature for an industrial cluster but we considered to limit the extent of the literature research and concentrated mainly on major objective of our master thesis due to the limit of available time.

The second section reviews the literature dedicated to the steel industry and steel production that comprises production processes, mathematical modeling in steel production and stochastic programming. It was crucial to conduct a comprehensive literature research for steel industry since first of all, steel branch is quite new field for us, secondly in order to capture objective of our master thesis precisely we need to understand the steel industry, to investigate what have been already done in this field, what analytical approaches were implemented.

5.1 Literature Review Related to Industrial Cluster

In Smith and Klosek (2001), a review of air separation technologies and their integration with energy conversion processes is presented. The paper gives an overview of technologies dedicated to separation of the industrial gases from air and expresses the economic difficulties as well as limits that can occur during the process. It describes a brief review of energy conversion processes for industrial gas plants and gives a comparison of process alternatives. The article is quite technical and requires a broad knowledge of chemical processes. However, it was useful to learn about the ASU plant and technologies of separating the oxygen from the air. In addition, it embellishes an overall understanding of the processes for the whole cluster.

In Westgaard, Faria et al. (2008), price dynamics of natural gas components and their relation with price for natural gas based on implementation of stochastic programming is analyzed. The authors state the fact that the natural gas is mostly used for heating while the gas components are used as input for production, for instance steel production and petroleum production. The gas components prices have their own dynamics since the end-user for them might be different from the consumer of natural gas. The core objective of the article is dedicated to evaluate alternative stochastic processes for the price evolution of these gas prices. In the article, a time series approach is applied with unobservable components. The paper is completed by analyzing the results.

Homayonifar and Saboohi et al. (2004) discusses methane decomposition as an alternative system for iron reduction processes. The hydrogen production technologies based on thermal decomposition technique are presented. Furthermore, thermal decomposition of natural gas without catalyst is discussed in the article. Examples of production methods include the technology so-called Steam Methane Reforming (SMR), electrolysis and thermal decomposition of methane (TDM). A brief review of the MIDREX Syngas System is presented as background information. The paper was beneficial with giving information about the POX plant.

Lange and Tijm (1996) address the approach of converting methane to liquid hydrocarbon fuels and under which conditions it would be profitable in comparison with oil refineries. In the article, estimation of capital cost and energy losses for fuel manufacturing plants and methane conversion processes are explained. Economic evaluation studies conclude that methane conversion process shows a higher capital cost and a lower feedstock cost than oil refineries. A few conceptual methane-to-methanol routes are described and discussed.

Padro and Putsche (1999) give an overview of the economics of hydrogen production, storage and transportation, and end-use technologies. Steam methane reforming (SMR), coal gasification, non-catalytic partial oxidation, biomass gasification, pyrolysis, electrolysis and concentrated solar energy technologies are the discussed approaches in the article. For our master thesis, it was useful to learn about hydrogen production by using steam methane reforming.

Gradassi and Green (1995) explain conversion processes of natural gas to gasoline, distillate and methanol. The paper describes gas conversion technologies and compare with conventional methanol synthesis. The other objective of the article is to analyze the profitability of each process in terms of capital investment, cost margin and payout time. Economic evaluation studies conclude that the described natural gas conversion processes are highly capital intensive. The authors suggested that conversion of natural gas should focus on reducing capital cost as well as improving engineering processes.

Production of methanol is a subject of a high profitable risk mainly due to fluctuations of the methanol prices. Siegfried (1999) discusses the strategy of minimizing the production cost of methanol. Basic Methanol production schemes are presented as background information in the article. The paper was useful to understand the Methanol plant.

5.2 Literature Review Related to Steel Plant

The review summarizes the relevant studies, cases, publications and analysis that have been carried out in the steel industry. The second stage of our literature research is to gain knowledge about the steel industry, production process and products as well as optimization based research done.

Fenton (2005) describes the steel industry as well as steel production processes comprehensively in his article. In addition, environmental issues related to steel production is discussed. This article was very beneficial for us to learn about steel and its production process closely. We have used the knowledge that we gained from the article in the thesis.

Kolstad (2005) is a master thesis analyzes global consequences of two types of restructuring (Basic Oxygen Furnace and Electric Arc Furnace) in steel production. Brief overview of steel production technologies, the steel market in China and its global role as well as environmental challenges are the treated issues in the thesis.

The basics of ferrous metallurgy, standards for steel materials, classification of steel materials, iron and carbon steels, alloy steels, stainless steels and heat treatment of steel are presented as a collection of articles in Key to Metals Comprehensive Steel Database. In general, it includes more than 200 articles. Having analyzed these articles, we gained knowledge about steel processes and types of steel. It provided us with solid background and was very helpful in our thesis as well.

Sustainability report (2008) and Steel Statistical Yearbook (2007) give an overview of the world steel industry in environmental, social and economic areas.

Raab and Mannheim (2008) discuss the position and development of the global steel industry in terms of production, consumption and trade. Czech steel industry is represented and analyzed.

Dutta (2000) presents the real case situation in Indian Steel plant and how the author, who was involved in the project related to the steel plant, handled the problems of theoretical research and operational work. By other words, people who did the theoretical research were far away from understanding the practical issues at the plant. The author underlined that operational research group must be oriented towards solving problems rather than buildings models. The article gives overview of the approach to the practical problem. Nevertheless, as we mentioned above, the article has descriptive nature.

We have also gained elaborated knowledge through internet resources about steel. After learning about steel, our research efforts were intensified in optimization in steel production. A number of researches were done related to modeling and optimization in the steel industry.

The proceedings of the conference on "Optimization of steel product yield" (1967) include series of papers on the optimization yield. "Optimization of yield" implies selling to the customer as finished product the maximum percentage of the liquid steel made or, conversely, minimizing the percentage of iron units it is necessary to return to the steelmaking process for re-melting. The papers deal with several topics such as the effect of input shape and pit practice on product yield; effect of various hot tops and ingot shapes on yield and heterogeneity; optimization of yield in wide strip rolling; optimization of yield in heavy and medium section rolling; and some more papers based on quality control. However, the articles include too much technical details and they were not beneficial for us more than getting familiar with the processes.

The proceedings of the conference on mathematical process models in iron-steelmaking (1973) consist of 5 chapters: Iron-making; Electric Steel-making; Oxygen Steelmaking; Teeming and Solidification; Heating furnaces; Hot and cold-rolling. In each chapter, technical articles are placed. Our interest was on Electric Steel-making Chapter and we got some knowledge with Electric Arc Furnace based production. However, this proceeding also includes too technical descriptions for us.

Fabian (1958) represents a mathematical model of the stages of iron and steel production to determine the rate of inputs with minimum costs. Various materials and production processes can be used in integrated steel plants. Iron may include different ores and steel can be produced with different proportion of steel scrap and iron. The various stages of the production are interrelated through input-output relationships. The amount and type of material used in each stage may affect other stage inputs and outputs in the production process. The paper explains clearly how to find the optimal solution among options faced in each stage of the production with respect to interrelation between stages. Mathematical programming is used effectively to achieve this goal.

Dutta and Fourer (2001) give a broad overview of mathematical programming applications in integrated steel plants. The overview encompasses the following problem classes: national steel planning, product-mix optimization, blending in blast furnaces, coke ovens or steel foundries, scheduling, inventory and distribution, set covering and cutting stock optimization.

Tang, Adulbhan et al. (1981) addresses application of the linear programming model to the aggregated production planning problems in a heavy manufacturing industry. The goal of the model is minimizing the total cost of production within the planning horizon, taking into consideration overtime cost, hiring and firing cost, inventory cost, shortage cost and direct payroll cost. Finally, the results of the model are discussed and implemented to a real case.

Mæstad (2000) shows how the regulations of the environmental issues particularly the emissions of carbon dioxide (CO_2) may affect the structure of the steel industry. Furthermore, how these structural changes may influence the demand for transport services is also investigated. For this purpose, a model, which uses the data such as production data, factor use, factor prices, industry costs, trade costs and CO_2- emissions, is built. Methods used in collecting of the data may be valuable for our thesis. The research was based on the following data resources: 1) CRU (An independent authority) database which contains details about production volumes, capacities, the use of inputs at different stages of production, input prices and costs 2) Steel Statistical Yearbook 1996, International Iron and Steel Institute 3) Global Trade Analysis Project (GTAP) which is a global database containing data on production, consumption, trade, trade policy and factor usage in a number of industry sectors and countries.

Mohanty and Singh (1992) address a production planning problem in an integrated steel plant. A hierarchical system model is built to solve the problem. The model consists of three functions: co-ordination of operations through optimal resource allocation; production planning; scheduling. A goal programming model has been developed in the paper. The goals are: capacity utilization, back order minimization and resource utilization.

Chen and Wang (1997) created a linear programming model for integrated steel production and distribution planning. The case is dedicated to an integrated approach for planning steel production in a major Canadian steel making company. This case was a real practical problem rather than theoretical. The authors built the model which helped to solve the real case problem and gave the optimal solution for the current problem. The model encompasses purchasing the raw materials, capacity of factories, customers demand as well as forecasted demand, production of semi-finished goods as well as finished goods, "outsourcing" of semi-finished goods in some periods. As a result, the authors state that it can be beneficial in the planning large scale steel production by using the integrated planning. The article gives a good starting point for modeling integrated steel plant as well as general understanding of integrated planning approach.

The article called "Melt Control: Charge Optimization via Stochastic Programming" written by Jitka Dupaèová and Pavel Popela (2005) introduces melt control in steel production. Material input represents the significant part of the melt control activities. These materials are composed of certain amount of basic elements. Random losses in the melt must be considered. The goal of the paper is to find amounts of the input materials in the lowest cost so that the output alloy composition is achieved. Having studied this article provided us with beneficial ideas, particularly while modeling the requirement of steel type variety.

Balakrishnan and Geunes (2003) interpret an approach to production planning for steel manufacturing with flexible product specification. A profit maximizing mixed-integer program (MIP) model is developed and tested to justify the flexibility. Real data from a steel manufacturer is used.

Gao and Tang (2003) presents a model for purchasing of bulk raw materials for a large-scale integrated steel plant. The paper explains the purchasing issues and formulates the problem by mathematical programming model by taking most important factors (quality, price and due date) into account. Considered constraints are purchasing budget, production demand, inventory, technology and vendor resource constraints. The article has an economic focus, and the technological aspects are simplified to balancing equations.

Larsson (2004) is a PhD thesis on process integration in the steel industry. The focus on the thesis is energy use and environmental impacts of integrated steel mills. Mathematical programming is used as the process integration method. Energy and material use in coke oven, blast furnace, basic oxygen process and surrounding system is modeled and optimized.

Other difficult problems in steel plants are the scheduling problems. Several methods are continuously applied in the steel industry in order to optimize the scheduling of the plant.

Tang, Liu et al. (2000) and Bellabdaoni and Tenghem (2006) present mathematical models for production scheduling in steelmaking- continuous casting production in their papers. The models are built to determine in what sequence, at what time and on which device molten steel should be arranged at various production stages from steelmaking to continuous casting. Tang, Liu et al. (2000) based Shangai Baoshan Iron and Steel Complex as the study background. Firstly non-linear model was developed and then was converted to a linear model in order to be able to solve it.

Zanoni and Zavanella (2005) built mathematical model for production schedule in the continuous casting process in order to find the optimal production schedule of steel billets. The article represents a real case study. The purpose of the model is to give optimal solution on the sequence of the billet type to be produced and in which period of time horizon. In addition, the model takes into consideration inventory costs since the authors consider the finished product storage as a part of manufacturing cycle. The article gives the overview of continuous casting steel making process. The results obtained show how the inventory holding cost and capacity of warehouse have impact on the production schedule.

Tang, Liu and et al. (2001) introduces and compares the traditional cold charge process with the technologies such as casting-hot charge rolling (CC-HCR), continuous casting – direct hot charge rolling (CC-DCHR) and continuous casting – hot direct rolling (CC-HDR). The paper introduces production management problems in iron and steel production. It reviews the major integrated planning and scheduling systems developed as well as the methods used for integrated planning and scheduling in iron and steel production.

In spite of the fact that the following resources that we have gone through are not directly related to the steel production, they were quite useful in the process of building our deterministic and stochastic programming models.

Pochet and Wolsey (2006) give broad information about modeling and solving production planning problems. It provides a comprehensive modeling and optimization approach for solving production planning and related supply chain planning problems. Solved problems are multi-item, single/multi- machine, single/multi-level, production planning with time varying demands. Mixed Integer Programming (MIP) models and algorithms are used in the book. The book consists of 14 chapters. In the first 5 chapters, Production Planning and MIP are explained comprehensively. Next 3 chapters are devoted to address Basic Polyhedral Combinatorics for Production Planning and MIP. Finally, the last chapters state lot sizing and solving of test problems.

Bradley, Hax et al. (1997) address mathematical programming applications. Especially chapter 5, "Mathematical Programming in Practice" was beneficial for us. It gives broad information about decision making process, framework for a hierarchical integrative approach, formulation and implementation of a model.

We have also performed specific research concerning uncertainty and stochastic programming in order to have the capability of implementing the stochastic programming for our problem. The world's first textbook devoted to stochastic programming has been written by Kall and Wallace in 1994. The book discusses basics of the stochastic programming as well as the ideas why stochastic programming is important. Wallace (2000) discusses the usability of sensitivity analysis to handle uncertainty in problems. Høyland and Wallace (2001) address generation methods of scenario trees for single and multi stage decision problems.

Høyland, Erik et al. (2003) describe an experience of development and implementation of a stochastic model for decision support within an organizational context. The paper is rather qualitatively written. Higle and Wallace (2003) describe a linear programming solution for a simple production planning problem and do sensitivity analysis to capture uncertainty effects. Furthermore they explain modification of the LP model by adding different scenarios for demand uncertainty. Haugen and Wallace (2006) give a simple introduction to stochastic programming and investigate potential hazards of it when random variables reflect market interaction.

To sum up, this extensive literature research provided us with learning many new concepts regarding our master thesis and enlightened us with ideas during the course of our master thesis.

6 THEORY REVİEW

In this chapter we will give an overview of the theories that we used in our master thesis. Furthermore we will state why we implemented them.

6.1 Mathematical Programming

Mathematical programming is a specific problem solving method within operations research. By definition, operations research is the discipline devoted to studying and developing procedures to help in the process of making decisions (Cook and Russell, 1989). Winston (1993) defines the operational research as a scientific approach to decision making .The operation research uses scientific methods to solve different problems and comprises of mathematical modeling, simulation, sensitivity analysis and statistics. There are a wide variety of the real world applications of operations research such as Finance, Marketing, Purchasing, Production Management, Personnel Management, Research and Development. We have implemented mathematical programming method since it is most efficient method for optimization.

Mathematical programming is based on the concept of optimization which is the most possible best way to do something by a decision-maker. The optimization may be maximizing profit, minimizing costs, minimizing distance or maybe maximizing coverage. The goal of optimization is to find optimal solution of the problem while satisfying the constraints. The goal of optimization is to make planning decisions optimizing the economic objectives such as cost minimization or maximization of contribution to profit. In order to deal with the increasing complexity of business, planning systems for coordination and etc., optimization is implemented more and more by planners. The most efficient planning systems, mathematical models, can give superior results and provide the planners with optimizing the utilization of resources and raw materials while satisfying the demand of customers in the most profitable way (Pochet and Wolsey, 2006). There are a lot of articles, scientific papers dedicated to optimization and modeling approach in different industries.

What is implied by optimization in our master thesis is basically that purchasing of the commodities and raw materials, required to produce products meeting customer demand in the most efficient and economical way possible. The planning scope doesn’t cover consideration and integration of distribution decisions.

6.1.1 Linear Programming

Linear Programming (LP) is a part of mathematical programming. It is a widely used tool for solving optimization problems as well as to perform analysis. Researchers have addressed and solved many problems through linear programming. According to Winston (1993), LP is an optimization problem where the objective function is a linear function which we attempt to maximize (or minimize). In addition, the values of the decision variables need to satisfy a set of constraints which are linear. The advantage of LP models compared to non-linear ones is that it is easy to solve them.

For successful formulation of LP model we need to (Cook and Russell, 1989):

1. understand the problem
2. identify the decision variables
3. identify and represent all constraints
4. collect relevant data

LP has been accepted and become popular among students in engineering, business, mathematics study. It is widely used in many educational settings. Reason for this is that high quality software is available to assist researchers conducting LP-based investigations in building models, solving problems, and analyzing output (Higle& Wallace, 2003).

We have also built LP model since there are many commercial software available to test it.

6.1.2 Uncertainty and Stochastic Programming

Wallace (1994) defines that randomness can be replaced with the expression of uncertainty. It can be described as lack of predictability of what will happen. Randomness is divided into two categories: external and internal randomness. External randomness refers to randomness that we cannot control. An example could be the probability of an earthquake within 5 years. Internal randomness refers to ignorance, to our lack of knowledge. An example can be the probability that France had a net export of goods to Germany last year.

Estimation can be done in two ways: distributional and singular. In distributional mode we try to understand a random event by analyzing the cases which are similar and occurred previously, in singular mode we try to understand the event by analyzing it directly.

By definition, stochastic is a problem in which the data and parameters are not known with certainty, but a probability distribution is known (Cook and Russell, 1989). In other words, stochastic programming allows us taking the uncertainty into consideration. Since there are many challenges and unpredictable situations in the industries and managers need to make decisions under uncertainty, stochastic programming models are used in variety of applications. We need to underline the fact that stochastic problems are one of the most complicated optimization problems.

Usually models are firstly built as deterministic models and then turned to stochastic models when the decision-maker realizes the shortcomings of the model when representing the real system. Reconstructing the deterministic model to stochastic model implies redefinition of the objective function as well. (Wallace, 1994)

Scenario trees are often very important in decision analysis and stochastic programming. It consists of nodes and each node in the tree represents state of the world at a particular point in time. Decisions are made at these nodes. The scenario tree branches off for each possible value of a random variable in each period. (Høyland and Wallace, 2001)

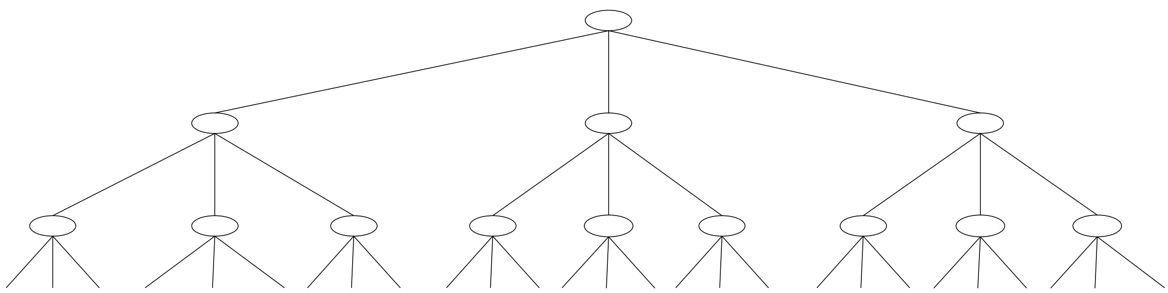


Figure 6-1 A scenario tree

6.2 Sensitivity Analysis

Higle and Wallace (2003) expresses that researchers use sensitivity analysis to explore how changes in the problem data might change the solution to a linear program, for example, how a change in production cost may influence production schedule. Sensitivity Analysis is applied to study the robustness of solutions to LP models. It is performed to investigate how sensitive the solution is to changes in data. A change in the solution shows that a further search is needed. If there is no change, than the proposed solution can be suitable guide for making a decision (Wallace, 1994).

Williams (1999) describes it as follows: "when the optimal solution of a model is obtained there is often interest in investigating the effects of changes in the objective and right-hand side coefficients (and sometimes other coefficients) on this solution. Ranging is the name of a method of finding limits (ranges) within which one of these coefficients can be changed to have a predict effect on the solution."

By using the sensitivity analysis, it is possible to answer the following questions:

1. Whether there are alternative optimal solutions to the problem?
2. How constraints are satisfied in the optimal solution?
3. Explanation of the effect on the optimal objective value of marginal increase or decrease of the right hand side coefficients.
4. What is the effect on the optimal objective value of forcing the variable up above its lower bound or decreasing the lower bound, of forcing the variable down below its upper bound or increasing the upper bound?
5. What is the effect on the optimal objective value of changes of the right hand side coefficients?
6. How do changes of the objective coefficients influence on the optimal solution?
7. Examine the sensitivity of the solution to the accuracy in the right hand side data, in the objective coefficients data.

Cook and Russell (1989) state that sensitivity analysis allows the exploration of changes in output in response to changes in input parameters.

6.3 Difference between Sensitivity Analysis and Stochastic Programming

Sensitivity analysis (SA) investigates the candidate good solutions within sampled deterministic solutions. In fact all the problems implicitly solved by SA are deterministic. It is not suitable for decision making under uncertainty. It measures the stability and robustness of the solution regarding the parameters. In a sense, by sensitivity analysis we simply predict what will happen in the next period and how our model will reflect under uncertainty, when we make a decision now under certain conditions. However this is not a decision making under uncertainty. It is a tool to analyze a deterministic decision problem. Stochastic programming is the suitable tool for decision making under uncertainty. It allows us to consider uncertain parameters that will come out in the future and give decisions in the current time (Wallace, 1994).

Wallace (2000) defines a good example for the use of sensitivity analysis related to uncertainty. Let's assume that we need to give an important decision for next year. All parameters will be known with certainty that time. However, currently the parameters are unknown but even so we need numbers for the next year. If we solve the expected value problem and based on sensitivity analysis find it is very stable, we can be sure that the numbers are good. We should denote that there is no decision here taken in face of uncertainty. It is just simply predicted what will happen next year when we make a decision under uncertainty.

7 OPTIMIZATİON MODEL FOR THE INTEGRATED INDUSTRIAL CLUSTER

SINTEF research team has provided us with a program code written in software called Xpress for the potential cluster. The purpose of this code is to generate economic analysis and assessment of the industrial cluster. The model comprises the description of each process of the cluster as well as the exchanges between the units of the cluster. We want to underline that the code contain many technical and engineering processes. Optimization software called Xpress is a mathematical programming language intended to solve different kinds of optimization problems.

In order to have closer insight of the potential industrial cluster and find our direction in the Gas-Mat project, we have converted the Xpress code into the mathematical modeling form and explained it. The research team has also advised us this to do as starting point. Because after developing a comprehensive mathematical model and analyzing the steel plant, the model should be integrated to cluster model as analysis should be done over the whole integrated cluster as well as each individual plant. However integration and development of whole cluster model requires more work to do since the models for other plants should be modified with respect to their technical and operational properties and in accordance with the developed steel plant model.

In following sections, the mathematical form of the model for the whole integrated cluster along with the detailed description of objective function, constraints related to each plant in the cluster and the description of all plants are placed. In addition, we made the graphical overview for the whole cluster and commodities transfers between plants, resources that enter the plants and finally output of each plant. This will give a better understanding of the input and output flows. First of all we would like to give basic knowledge about industrial cluster concept.

7.1 Industrial Cluster

As we mentioned above, a provided model is intended to generate economic analysis and assessment of an industrial cluster. As described previously in Chapter 3, industrial cluster or industrial park is a common location of interconnected commercial enterprises sharing infrastructure and services of the area as well as producing service to each other. The economic benefits associated with establishment industrial cluster are:

1. Economies of scales
2. Economies of scope
3. Saving of transportation cost
4. Saving of storage cost
5. Exchange of low value byproducts between the units of cluster

The industrial cluster has competitive advantage in terms of economies of scale and scope. In addition, the transportation and storage costs can be shared within cluster. The exchanges between the units of the cluster as well as shared investments in infrastructure for electricity and water lead to cost reduction in the cluster. At this point, the benefits of establishing of industrial cluster are obvious. From another side, the risk associated with the cluster can be as following.

1. Dependency on other companies
2. The risk of losing investments in shared infrastructure
3. The technological uncertainties of the interaction of different production facilities

7.2 Mathematical Model

The objective of the model is to maximize the total profit of whole industrial cluster. Furthermore, it supports to perform further economic analysis. We should emphasize that the model below was only in Xpress code. Our first task was to convert the model into mathematical form, have better understanding of it and especially focusing on the integrated steel plant to see the shortcomings. In the beginning we will describe notations for used sets, common parameters and variables for the cluster. Then we will introduce the common objective function followed by the constraints grouped according to each plant.

Sets

P : set of all plants in the cluster including the market.

C : set of all commodities exchanged in the cluster

C(i) : subset of commodities which determine the operations in the plant i, $i \in P$

T : set of all time periods

Cluster parameters

$(pp)_{ct}$: unit purchasing price for the commodity c in the period t, $c \in C, t \in T$

$(sp)_{ct}$: unit sale price for the commodity c in the period t, $c \in C, t \in T$

$(cm)_i$: maximum capacity of the plant i, $i \in P$

$(cn)_i$: minimum capacity of the plant i, $i \in P$

$(ic)_i$: per unit investment cost in the plant i, $i \in P$

$(if)_i$: fixed investment cost in the plant i, $i \in P$

$(pm)_i$: minimum production in the plant i, $i \in P$

$(ci)_i$: commodities which determine the investment in the plant i, $i \in P$

$(oc)_i$: per unit operation cost in the plant i, $i \in P$

$(ofc)_i$: fixed operation cost in the plant i, $i \in P$

M : very big number (100000000)

$(link)_{ijc}$: transfer link of the commodity c between the plant i and j if exists,

$i \in P, j \in P, c \in C$

$(icl)_{ijc}$: investment cost of the link between plant i and j to transfer the commodity c

$i \in P, j \in P, c \in C$

Cluster variables:

L_i : installed capacity in the plant i, $i \in P$

X_{ijct} : flow of the commodity c from plant i to j in the period t, $i \in P, j \in P, c \in C, t \in T$

Y_i : binary variable to indicate whether the plant will be installed or not, $i \in P$

Z_{ijc} : binary variable to indicate the investment in infrastructure will be done or not to transfer the commodity c between plant i and j, $i \in P, j \in P, c \in C$

7.2.1 Objective function

The objective is maximizing the profit of the whole cluster with respect to all operations and investments in all plants. In other words, plants are interconnected and there is only one unified objective for all plants in the cluster.

Objective function = Revenue from output – cost of input – investment cost- operation cost

$$\text{Maximize} \quad \sum_{c\in C}\sum_{t\in T}\sum_{i\in P}(sp)_{ct}X_{i,'Market'c,t} - \sum_{c\in C}\sum_{t\in T}\sum_{i\in P}(pp)_{ct}X_{'Market',i,c,t}$$

$$- \Big(\sum_{i\in P}(if)_i Y_i + \sum_{i\in P}(ic)_i L_i + \sum_{i\in P}\sum_{j\in P}\sum_{c\in C}(icl)_{ijc}Z_{ijc}\Big)$$

$$- \Big(\sum_{i\in P}\sum_{t\in T}(Y_i + (ofc)_i) + \sum_{i\in P}\sum_{j\in P}\sum_{t\in T}\sum_{c\in C(c=(co)_i)}(oc)_i(X_{ijct} + X_{jict})\Big)$$

7.2.2 General Constraints

$L_i \leq (cm)_i$	$i \in P$	(1)
$L_i \geq (cn)_i$	$i \in P$	(2)
$L_i \leq MY_i$	$i \in P$	(3)
$X_{ijct} \leq MZ_{ijc}$	$i \in P, j \in P, c \in C, t \in T$	(4)

Constraint (1) denotes that capacity of each plant is set to be less then maximum capacity determined for each plant.

Constraint (2) denotes that capacity of each plant is set to be more then minimum capacity determined for each plant.

Constraint (3) denotes that if plant i will not be established than there won't be any capacity assigned for this plant.

Constraint (4) denotes that if the link between the plant i and j to transfer the commodity c will not be established then there won't be flow of the commodity c between these plants.

7.2.3 Separator Plant and Its Constraints

The natural gas flows from the production installation to the Separator plant. The function of the Separator plant is to reduce pressure of the natural gas and then to separate it into various components such as dry gas methane (CH_4) and wet gas (ethane, propane, butane and naphta). Westgaard and Faria et al., (2008) describes the process as following: "the natural gas called rich gas is heated at the bottom of a tall column and the lightest components evaporate and collect at the top of the tower while the residue is sent to another column and reheated. This process continues until all the gas has been split into separate products".

The natural gas is divided into two groups as dry gas and wet gas depending on its contents. Dry gas consists of mostly pure CH_4 when liquid hydrocarbons are removed. In contrary, the natural gas is considered as wet gas when hydrocarbons are present. According to Westgaard and Faria et al. (2008), Liquid Petroleum Gas (LPG) which is called wet gas consist of propane and butane that have been converted to a liquid phase through a pressure of roughly 78 bar or through some cooling. In Norway, LPG consists of 95% of propane and 5% butane since the temperature properties of such gas suit the Norwegian climate.

Current capacity of the Norwegian pipeline system is approximately 100 bcm and Norwegian gas mainly exported to Europe. The good example is Kårsto plant in Norway which is the third biggest LPG producer in the world. Its main task is to receive and process gas. As we already mentioned, most of the dry gas is piped to the Europe market. By establishing industrial cluster, it would be economic to use dry gas in steel production based on the national acceptable prices. Furthermore, the integrated cluster will be the extension to an existing gas value chain. The dry gas is input for POX plant and Carbon Black Plant. The figure below shows the graphical illustration of input and outputs for the Separator plant which is a unit of the steel integrated cluster.

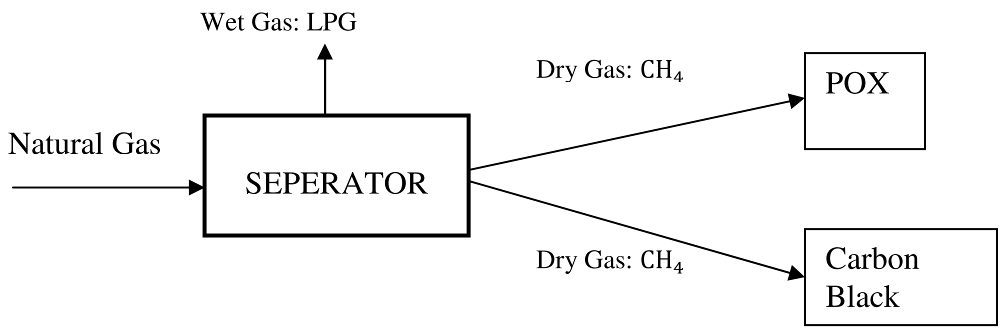


Figure 7-1 Input and output flow of Separator

<u>Separator plant parameters</u>

(wg) : fraction of wet gas used in the separator plant.

<u>Variables:</u>

$(gs)_t$: amount of natural gas that enters the separator in period t, $t \in T$

$(ch)_t$: amount dry gas that comes out of the separator in period t, $t \in T$

$(lpg)_t$: amount of wet gas that comes out of the separator in period t, $t \in T$

<u>Constraints</u>

Input balance:

$$\sum_{i \in P} X_{(i,'Seperator','NaturalGas',t)} = (gs)_t \qquad \forall t \in T \qquad (5)$$

Mass balance:

$$(lpg)_t = (wg)(gs)_t \qquad \forall t \in T \qquad (6)$$
$$(ch)_t = (1 - wg)(gs)_t \qquad \forall t \in T \qquad (7)$$

Production limits:

$$(gs)_t \le L_{Seperator'} \qquad \forall t \in T \qquad (8)$$
$$(gs)_t \ge (pm)_{'Seperator'} \qquad \forall t \in T \qquad (9)$$

Output balance:

$$(lpg)_t = \sum_{j \in P} X_{('Seperator',j,'LPG',t)} \qquad \forall t \in T \qquad (10)$$
$$(ch)_t = \sum_{j \in P} X_{('Seperator',j,'CH4',t)} \qquad \forall t \in T \qquad (11)$$

Constraint (5) defines the amount of the natural gas flow to the separator plant.

Constraints (6) and (7) represent the balance constraints. Particularly, constraint (6) states that amount of wet gas comes out of the separator is equal to multiplication of the fraction of the incoming wet gas by amount of natural gas that enters the separator. Constraint (7) states that amount of dry gas comes out of the separator is equal to (1- fraction of the incoming wet gas) multiplied by the amount of natural gas that enters the separator.

Constraint (8) represents the capacity constraint: natural gas that enters the separator can't exceed the capacity of the Separator plant. Constraint (9) represents that amount of natural gas that enters the separator should be more then the determined minimum production in the plant.

Constraints (10) and (11) represent output balance. Constraint (10) expresses how much wet gas is distributed from the Separator plant to all plants that need it. Constraint (11) tells how much dry gas is distributed from the Separator plant to all plants that need it.

7.2.4 ASU Plant and Its Constraints

Smith and Klosek (2001) state that there are several integration opportunities to separate industrial gases from air. The process is divided to cryogenic and non-cryogenic industrial gas processes.

In this paper we assume that the separation of oxygen from air in the ASU plant will be based on cryogenic industrial gas processes which are considered to be the most effective technologies for producing large quantities of oxygen, high-purity nitrogen and liquid argon.

The main function of ASU plant involved in the integrated industrial cluster is separation of the oxygen from the air. We need to underline the fact that power is required in order to carry out the processes. It is assumed that 770 kWh power is needed to separate a unit of oxygen. Thus, ASU has a strong link with Gas Fired Plant (GFP) which produces power to the cluster. The link is in both-ways: ASU supplies oxygen to GFP and get power to operate machinery, run welding equipment and supply light. Furthermore, the oxygen from the ASU plant is input for the POX plant.

The figure below shows the graphical illustration of inputs and outputs of the ASU plant which is a part of the integrated cluster.

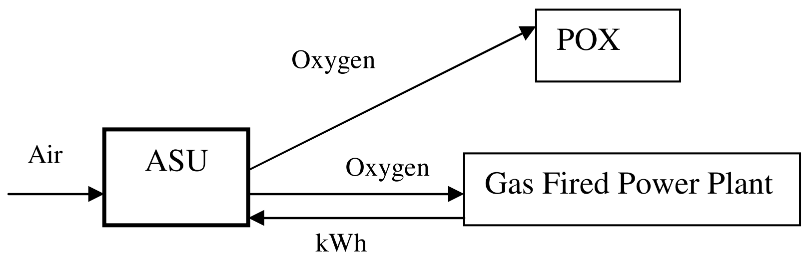


Figure 7-2 Input and output flow of the ASU plant

<u>ASU plant parameters</u>

(ao) : fraction of oxygen gas used in the ASU plant.

Variables:

$(aa)_t$: amount of air that enters the ASU in period t, $t \in T$

$(ox)_t$: amount of oxygen comes out of the ASU in period t, $t \in T$

$(nt)_t$: amount of nitrogen comes out of the ASU in period t, $t \in T$

$(kwh)_t$: total usage of power (kilowatt-hour: kWh) in the ASU in period t, $t \in T$

Constraints

Input balance:

$$(aa)_t = \sum_{i \in P} X_{(i,'ASU','AIR',t)} \qquad \forall t \in T \qquad (12)$$

$$(kwh)_t = \sum_{i \in P} X_{(i,'ASU','Kwh',t)} \qquad \forall t \in T \qquad (13)$$

Mass balance:

$$\frac{1}{32}(ox)_t = \frac{1}{144}(aa)_t \qquad \forall t \in T \qquad (14)$$

$$\frac{1}{112}(nt)_t = \frac{1}{144}(aa)_t \qquad \forall t \in T \qquad (15)$$

$$(ox)_t = \frac{1}{770}(kwh)_t \qquad \forall t \in T \qquad (16)$$

Production limits:

$$(ox)_t \le L_{'ASU'} \qquad \forall t \in T \qquad (17)$$

$$(ox)_t \ge (pm)_{'ASU'} \qquad \forall t \in T \qquad (18)$$

Output balance:

$$(ox)_t = \sum_{j \in P} X_{('ASU',j,'O2',t)} \qquad \forall t \in T \qquad (19)$$

Constraints (12) and (13) represent the input balance constraints. Constraint (12) denotes the amount of air flow to the ASU plant. Constraint (13) denotes the total energy input to the ASU plant.

Constraint (14), (15) and (16) represent the mass balance constraints. Constraint (14) expresses the amount of air used to produce oxygen in the plant. Constraint (15) expresses the amount of air used to produce nitrogen in the plant. Constraint (16) states how much energy we need for separation of oxygen.

Constraint (17) represents the capacity constraint: oxygen produced in the plant can't exceed the capacity of the plant. Constraint (18) represents that produced oxygen in the plant should exceed the determined amount of minimum production.

Constraint (19) expresses the output balance. It tells how much oxygen distributed from the ASU plant to all other plants that need it.

7.2.5 POX Plant and Its Constraints

The Function of the POX plant is to create syntheses gas (syngas) from CH_4. The syngas is used as intermediate in the Methanol plant for methanol production and for reduction of iron ore in DRI plant. We want to underline that syngas is gas mixture of CO and H_2. The steam methane reforming (SMR) approach is widely used in production of H_2. Many experts in steel metallurgy state that SMR is most efficient and least expensive method for hydrogen production. According to Padro and Putsche (1999), almost 48% of the world's hydrogen is produced based on SMR. It should be noted that the price of the natural gas feedstock significantly affects the final price for H_2.

POX is a good alternative for steam reforming where a limited amount of oxygen is allowed to burn with the natural gas feed. This approach is called Auto Thermal Reformer (Homayonifar, Saboohi et al., 2004). The figure below shows the graphical illustration of inputs and outputs for the POX plant.

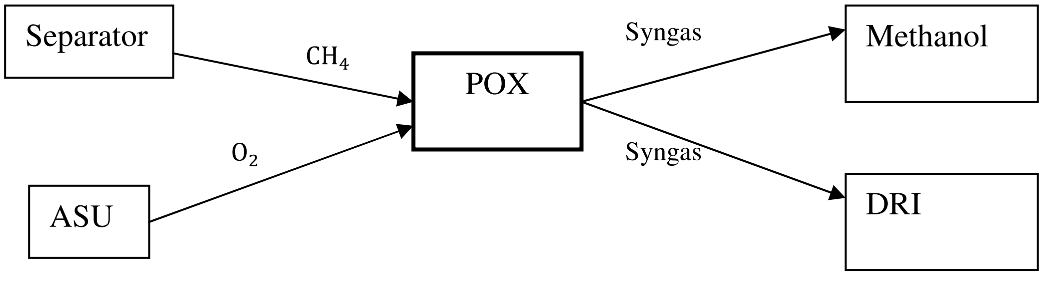


Figure 7-3 Input and output flow of POX plant

POX plant variables:

$(chp)_t$: amount of methane that enters the pox in period t, $t \in T$

$(oxy)_t$: amount of oxygen that enters the pox in period t, $t \in T$

$(hp)_t$: amount of hydrogen produced in the pox in period t, $t \in T$

$(cop)_t$: amount of CO produced in the pox in period t, $t \in T$

$(sy)_t$: amount of syngas produced in the pox in period t, $t \in T$

Constraints

Input balance:

$$(chp)_t = \sum_{i \in P} X_{(i,'POX','CH4',t)} \qquad \forall t \in T \qquad (20)$$

$$(oxy)_t = \sum_{i \in P} X_{(i,'POX','O2',t)} \qquad \forall t \in T \qquad (21)$$

Mass balance:

$$\frac{1}{8}(hp)_t = \frac{1}{32}(chp)_t \qquad \forall t \in T \qquad (22)$$

$$\frac{1}{8}(hp)_t = \frac{1}{32}(oxy)_t \qquad \forall t \in T \qquad (23)$$

$$\frac{1}{56}(cop)_t = \frac{1}{32}(chp)_t \qquad \forall t \in T \qquad (24)$$

$$\frac{1}{56}(cop)_t = \frac{1}{32}(oxy)_t \qquad \forall t \in T \qquad (25)$$

$$(sy)_t = (hp)_t + (cop)_t \qquad \forall t \in T \qquad (26)$$

Production limits:

$$(hp)_t + (cop)_t \le L_{POX'} \qquad \forall t \in T \qquad (27)$$

$$(hp)_t + (cop)_t \ge (pm)_{'POX'} \qquad \forall t \in T \qquad (28)$$

Output balance:

$$(sy)_t = \sum_{j \in P} X_{('POX',j,'Syngas',t)} \qquad \forall t \in T \qquad (29)$$

Constraints (20) and (21) express input balance constraints. Constraint (20) denotes the amount of methane flow to the POX plant. Constraint (21) denotes the amount of oxygen flow to the plant.

Constraints (22), (23), (24), (25), (26) represent the mass balance constraints. Constraint (22) expresses how much methane is used for hydrogen production. Likewise, constraint (23) expresses how much oxygen is used to produce hydrogen. Constraints (24) and (25) tell how much methane and oxygen used in order to produce carbon monoxide in the POX. Constraint (26) states that amount of syngas produced in the POX is equal to summation of hydrogen and carbon monoxide produced.

Constraint (27) represents the capacity constraint: amount of produced syngas in the POX can't exceed the capacity of the POX. Constraint (28) represents that amount of produced syngas should be more then minimum production requirement.

Constraint (29) expresses the output balance: the amount of distributed syngas from the POX to all other plants that need it.

7.2.6 Methanol Plant and Its Constraints

Methanol plant produces methanol from syngas which is output of the POX plant. Methanol is commonly used as a raw material for chemical products. It is defined in Annual Information Form (2004) as "a colorless liquid that is typically used as a chemical feedstock in the manufacture of other products". The process of converting syngas to methanol is following: first, syngas coming from POX plant is cooled and compressed. Then, it passes through copper-zinc catalyst. Thus, crude methanol is produced. We want to highlight that crude methanol is not pure methanol but it includes approximately 20% of water. At the last stage the water and impurities are removed in order to get chemical-grade methanol.

Figure below illustrates the process of converting syngas to methanol.

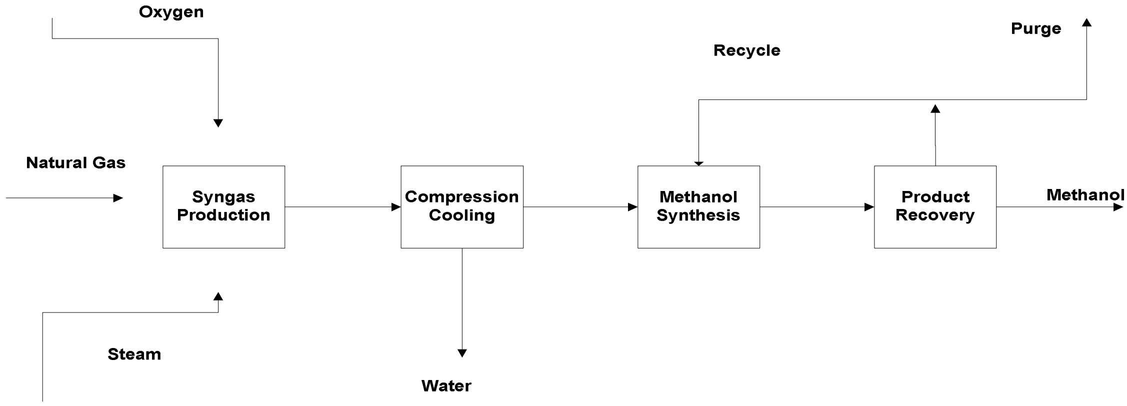


Figure 7-4 Methanol production process (Gradassi and Green, 1995)

The price of methanol strongly depends on the natural gas price and from this point of view, the natural gas prices is critical factor in methanol production. Siegfried (1999), states that the production of methanol is a subject to a high risk in terms of profitability. In many cases it is essential to make analysis whether it is profitable to open a methanol plant in the cluster. This mainly depends on the situation of the market. Figure below represents the flows of the methanol plant.

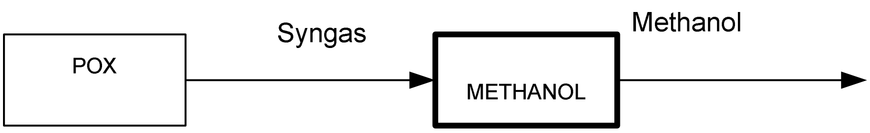


Figure 7-5 Input and output flow of the Methanol plant

In the south of Trondheim in Tjeldbergodden there is an industrial cluster which consists of methanol plant. Air separation plant, bio-protein plant and harbor are linked to the methanol plant. This facility has access to natural gas through the Haltenpipe line (StatoilHydro webpage, 2009)

<u>Methanol Plant variables:</u>

$(cm)_t$: amount of methanol produced in the methanol plant in period t , $t \in T$

$(hm)_t$: amount of hydrogen that enters the methanol plant in period t, $t \in T$

$(com)_t$: amount of CO that enters the plant in period t, $t \in T$

$(sym)_t$: amount of syngas that enters the plant in period t, $t \in T$

Constraints

Input balance:

$$(sym)_t = \sum_{i \in P} X_{(i,'METHANOL','SYNGAS',t)} \qquad \forall t \in T \qquad (30)$$

$$(hm)_t = \frac{1}{8}(sym)_t + \sum_{i \in P} X_{(i,'METHANOL','H2',t)} \qquad \forall t \in T \qquad (31)$$

$$(com)_t = \frac{7}{8}(sym)_t + \sum_{i \in P} X_{(i,'METHANOL','CO',t)} \qquad \forall t \in T \qquad (32)$$

Mass balance:

$$\frac{1}{32}(cm)_t = \frac{1}{4}(hm)_t \qquad \forall t \in T \qquad (33)$$

$$\frac{1}{32}(cm)_t = \frac{1}{28}(com)_t \qquad \forall t \in T \qquad (34)$$

Production limits:

$$(cm)_t \le L_{('METHANOL')} \qquad \forall t \in T \qquad (35)$$

$$(cm)_t \ge (pm)_{('METHANOL')} \qquad \forall t \in T \qquad (36)$$

Output balance:

$$(cm)_t = \sum_{j \in P} X_{('METHANOL',j,'Methanol',t)} \qquad \forall t \in T \qquad (37)$$

Constraints (30), (31), (32) denote the input balance constraints. Constraint (30) denotes the amount of syngas flow to the Methanol plant. Constraint (31) denotes the amount of hydrogen flow to the Methanol plant and the proportion of it in the syngas. Constraint (32) denotes the amount of carbon monoxide flow to the Methanol plant and the proportion if it in the syngas.

Constraints (33), (34) represent the mass balance constraints. Constraint (33) expresses the amount of hydrogen used for methanol production while constraint (34) expresses the amount of carbon monoxide used to produce methanol.

Constraint (35) represents the capacity constraint: produced amount of methanol can't exceed the capacity of the Methanol plant. Constraint (36) represents that produced amount of methanol should be more then the determined amount of minimum production.

Constraint (37) expresses the distributed amount of methanol from the Methanol plant to all other plants that need it.

7.2.7 DRI Plant and Its Constraints

The DRI plant produces direct-reduced iron from iron ore using gas based or coal based process. DRI production process is described very shortly as following: iron oxide is preheated and reduced by reducing gas ($H_2 + CO$) in the shaft. The inputs to DRI plant is Syngas from POX plant, hydrogen from Carbon Black and electricity from Gas fired power plant. The output is direct reduced iron, heat and gases. Some of the output gases are recycled again to produce reducing gas.

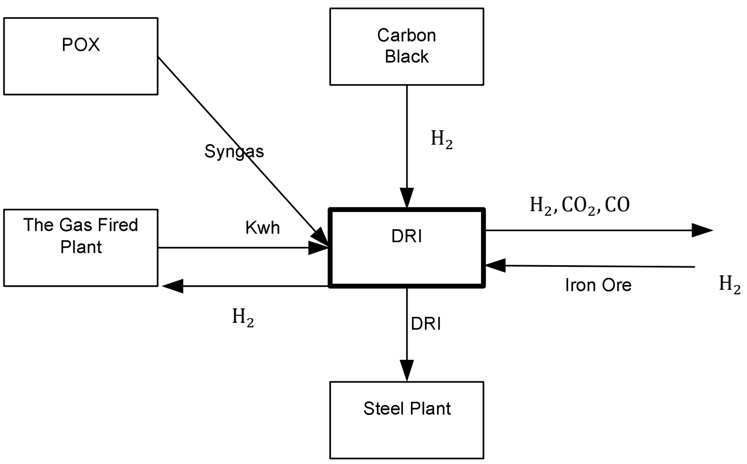


Figure 7-6 Input and output flow of the DRI plant

<u>DRI plant parameters</u>

h : hydrogen (H_2) percentage used in the Direct Reduced Iron (DRI) production.

(*cmo*) : percentage of carbon-monoxide (CO) used in the DRI production.

Variables:

$(fhd)_t$: amount of DRI produced in the plant by using H_2 in period t, $t \in T$

$(fcod)_t$: amount of DRI produced in the plant by using CO in period t, $t \in T$

$(ore)_t$: amount of ore input to the DRI plant in period t, $t \in T$

$(oreh)_t$: amount of iron ore that enters the plant used by H_2 in period t, $t \in T$

$(orec)_t$: amount of iron ore that enters the plant used by CO in period t, $t \in T$

$(hdri)_t$: amount of H_2 that enters the plant in period t, $t \in T$

$(codri)_t$: amount of CO that enters the plant in period t, $t \in T$

$(syndri)_t$: amount of syngas that enters the plant in period t, $t \in T$

$(htodri)_t$: amount of water (H_2O) produced in the DRI in period t, $t \in T$

$(\cot dri)_t$: amount of carbon-dioxide (CO_2) produced in the DRI in period t, $t \in T$

$(kwhdri)_t$: total usage of kWh in the DRI plant in period t, $t \in T$

Constraints

Input balance:

$$(ore)_t = \sum_{i \in P} X_{(i,'DRI','IronOre',t)} \qquad \forall t \in T \qquad (38)$$

$$(ore)_t = (oreh)_t + (orec)_t \qquad \forall t \in T \qquad (39)$$

$$(syndri)_t = \sum_{i \in P} X_{(i,'DRI','Syngas',t)} \qquad \forall t \in T \qquad (40)$$

$$(hdri)_t = \frac{1}{8}(syndri)_t + \sum_{i \in P} X_{(i,'DRI','H2',t)} \qquad \forall t \in T \qquad (41)$$

$$(codri)_t = \frac{7}{8}(syndri)_t + \sum_{i \in P} X_{(i,'DRI','CO',t)} \qquad \forall t \in T \qquad (42)$$

$$(kwhdr)_t = \sum_{i \in P} X_{(i,'DRI','kwh',t)} \qquad \forall t \in T \qquad (43)$$

Mass balance:

$$\frac{1}{112}(fhd)_t = \frac{1}{160}(oreh)_t \qquad \forall t \in T \qquad (44)$$

$$\frac{1}{112}(fhd)_t = \frac{1}{6}(hdri)_t h \qquad \forall t \in T \qquad (45)$$

$$\frac{1}{112}(fhd)_t = \frac{1}{54}(htodri)_t \qquad \forall t \in T \qquad (46)$$

$$\frac{1}{112}(fcod)_t = \frac{1}{160}(orec)_t \qquad \forall t \in T \qquad (47)$$

$$\frac{1}{112}(fcod)_t = \frac{1}{84}(codri)_t(cmo) \qquad \forall t \in T \qquad (48)$$

$$\frac{1}{112}(fcod)_t = \frac{1}{132}(\cot dri)_t \qquad \forall t \in T \qquad (49)$$

$$(fhd)_t + (fcod)_t = \frac{1}{195}(kwhdri)_t \qquad \forall t \in T \qquad (50)$$

Production limits:

$$(fhd)_t + (fcod)_t \leq L_{DRI'} \qquad \forall t \in T \qquad (51)$$

$$(fhd)_t + (fcod)_t \geq (pm)_{'DRI'} \qquad \forall t \in T \qquad (52)$$

Output balance:

$$(fhd)_t + (fcod)_t = \sum_{j \in P} X_{('DRI',j,'DRI',t)} \qquad \forall t \in T \qquad (53)$$

$$(1-h)(hdri)_t = \sum_{j \in P} X_{('DRI',j,'H2',t)} \qquad \forall t \in T \qquad (54)$$

$$(1-cmo)(codri)_t = \sum_{j \in P} X_{('DRI',j,'CO',t)} \qquad \forall t \in T \qquad (55)$$

$$(\cot dri)_t = \sum_{j \in P} X_{('DRI',j,'CO2',t)} \qquad \forall t \in T \qquad (56)$$

Constraints from (38) to (43) represent the input balance constraints. Constraint (38) expresses the amount of iron ore input to the DRI plant. Constraint (39) expresses the balance between the total amount of iron ore input and total iron ore usage in various types of production. Constraint (40) expresses the amount of syngas flow to the DRI plant. Constraint (41) denotes the amount of hydrogen flow to the DRI plant and its proportion in syngas which enters in the plant. Constraint (42) denotes the amount of carbon monoxide flow to the DRI plant and its proportion in snygas which enters the plant. Constraint (43) is the amount of energy sent to the DRI plant.

Constraints from (44) to (50) represent the mass balance constraints. Constraint (44) states the amount of iron ore used to produce iron while hydrogen is used as reducing gas. Constraint (45) states the amount of hydrogen used to produce iron while hydrogen is used as reducing gas. Constraint (46) states the amount of water produced in iron production while hydrogen is used as reducing gas. Constraint (47) states the amount of iron ore used to produce iron while carbon monoxide is used as reducing gas. Constraint (48) states the amount of carbon monoxide used to produce iron while carbon monoxide is used as reducing gas. Constraint (49) states the amount of carbon dioxide produced in iron production while carbon monoxide is used as reducing gas. Constraint (50) states the amount of energy input for total iron production.

Constraint (51) represents the capacity constraint: total production of iron can't exceed the capacity of the DRI plant. Constraint (52) represents that the amount of iron production should be at least as much as the determined minimum production.

Constraints from (53) to (56) are the output balance constraints. Constraint (53) denotes the total amount of DRI distributed from the DRI plant to all other plants that need it. Constraint (54) and (55) denote the amount of unutilized carbon monoxide and hydrogen that is distributed to the other plants that need it. Constraint (56) denotes the amount of carbon dioxide distributed from DRI plant to the other plants that need it.

7.2.8 Steel Plant and Its Constraints

Since the steel plant is our major goal to analyze the initial model, develop a mathematical programming model and do analysis in order to extend the current model, we will give broad information about steel and its production process in the following chapter where we will start to intensify our research particularly on steel production. For the present time, it is important for us to understand the initial code for the steel plant, observe the handled properties of a steel plant and try to see the shortcomings. Hence, we will have the opportunity to develop a comprehensive mathematical model for it.

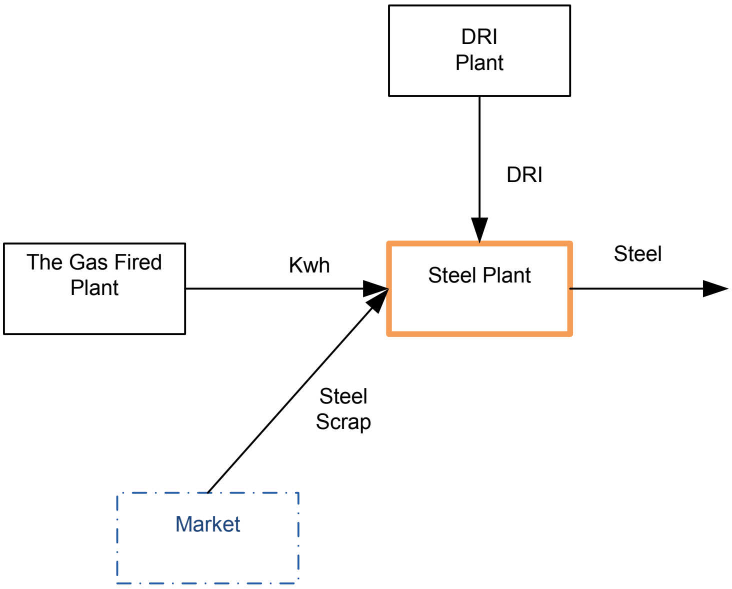


Figure 7-7 Input and output flow of the steel plant

Steel plant parameters

(dri) : proportion of DRI used in the steel production

variables:

$(ps)_t$: amount of steel produced in the plant in period t, $t \in T$

$(dris)_t$: amount of DRI used in the steel production in period t, $t \in T$

$(scs)_t$: amount of steel scrap used in the steel production in period t, $t \in T$

$(kwhs)_t$: total kWh used in the steel production in period t, $t \in T$

constraints

Input balance:

$$(kwhs)_t = \sum_{i \in P} X_{(i,'STEEL,'KWH',t)} \qquad \forall t \in T \qquad (57)$$

$$(scs)_t = \sum_{i \in P} X_{(i,'STEEL,'SteelScrap',t)} \qquad \forall t \in T \qquad (58)$$

$$(dris)_t = \sum_{i \in P} X_{(i,'STEEL,'DRI',t)} \qquad \forall t \in T \qquad (59)$$

Mass balance:

$$(ps)_t = \frac{1}{400}(kwhs)_t \qquad \forall t \in T \qquad (60)$$

$$(ps)_t = (dris)_t + (scs)_t \qquad \forall t \in T \qquad (61)$$

Production limits:

$$(ps)_t \leq L_{'STEEL'} \qquad \forall t \in T \qquad (62)$$

$$(ps)_t \geq (pm)_{'STEEL'} \qquad \forall t \in T \qquad (63)$$

Output balance:

$$(dris)_t = (dri)((dris)_t + (scs)_t) \qquad \forall t \in T \qquad (64)$$

$$(ps)_t = \sum_{j \in P} X_{('STEEL', j, 'Steel', t)} \qquad \forall t \in T \qquad (65)$$

Constraints (57), (58) and (59) are the input balance constraints. Constraint (57) denotes the amount of energy input to the steel plant. Constraint (58) denotes the amount of the steel scrap flow to the steel plant. Constraint (59) denotes the amount of the DRI flow to the steel plant.

Constraints (60) and (61) represent the balance constraints. Constraint (60) states how much energy is required for per unit steel production. Constraint (61) states the equality between the amount of produced steel, and used DRI and steel scrap.

Constraints (62) expresses that the total amount of the produced steel can't exceed the capacity of the steel plant. Constraint (63) expresses that the amount of the produced steel should exceed the determined minimum production for steel.

Constraint (64) states the proportion of DRI used in steel production.

Constraint (65) states the amount of steel distributed from the steel plant to the other plants that need it.

7.2.9 Gas Power Plant and Its Constraints

Gas power plant produces electricity power from natural gas. It has important links with other plants in the cluster since it supplies electricity to all other plants. In addition, the electricity can be sold to the market. Firstly electricity is generated in a gas turbine by burning natural gas. During the process a huge amount of heat is created, which then is used to generate steam which again is used to produce electricity in a steam turbine.

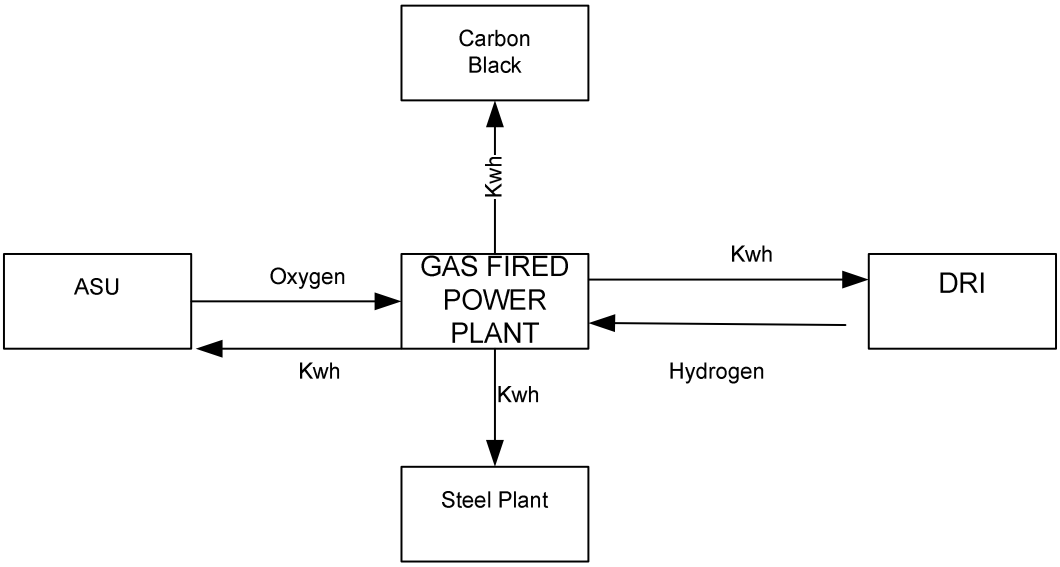


Figure 7-8 Input and output flow of the gas fired power plant

<u>Gas power plant parameters</u>

(ef) : power efficiency in the power plant.

<u>Gas fired plant variables:</u>

$(pkwh)_t$: total production of kWh in the power plant in period t, $t \in T$

$(oxyg)_t$: input amount of oxygen to the power plant in period t, $t \in T$

$(\text{cot})_t$: output amount of CO_2 from the power plant in period t, $t \in T$

$(okwt)_t$: output amount of the kWh from the power plant in period t, $t \in T$

$(pcp)_t$: amount of power production by methane (CH_4) in the plant in period t, $t \in T$

$(php)_t$: amount of power production by H_2 in the plant in period t, $t \in T$

$(pcop)_t$: amount of power production by CO in the plant in period t, $t \in T$

$(mp)_t$: amount of CH_4 used in the power production in period t, $t \in T$

$(hp)_t$: amount of H_2 used in the power production in period t, $t \in T$

$(cop)_t$: amount of CO used in the power production in period t, $t \in T$

$(synp)_t$: amount of syngas used in the power production in period t, $t \in T$

$(ocp)_t$: amount of oxygen (O_2) used in the power production where CH_4 used in period t $t \in T$

$(ohp)_t$: amount of O_2 used in the power production where H_2 used in period t, $t \in T$

$(ocop)_t$: amount of O_2 used in the power production where CO used in period t, $t \in T$

$(htcp)_t$: amount of H_2O produced in the power production where CH_4 used in period t, $t \in T$

$(hhp)_t$: amount of H_2O produced in the power production where H_2 used in period t, $t \in T$

$(ccp)_t$: amount of CO_2 produced in the power production where CH_4 used in period t, $t \in T$

$(ccop)_t$: amount of CO_2 produced in the power production where CO used in period t, $t \in T$

<u>Gas power plant constraints</u>

Input balance:

$$(ocp)_t + (ohp)_t + (ocop)_t = \sum_{i \in P} X_{(i,'POWER','O2',t)} \qquad \forall t \in T \qquad (66)$$

$$(mp)_t = \sum_{i \in P} X_{(i,'POWER','CH4',t)} \qquad \forall t \in T \qquad (67)$$

$$(synp)_t = \sum_{i \in P} X_{(i,'POWER','SYNGAS',t)} \qquad \forall t \in T \qquad (68)$$

$$(hp)_t = \frac{1}{8}(synp)_t + \sum_{i \in P} X_{(i,'POWER','H2',t)} \qquad \forall t \in T \qquad (69)$$

$$(cop)_t = \frac{7}{8}(synp)_t + \sum_{i \in P} X_{(i,'POWER','CO',t)} \qquad \forall t \in T \qquad (70)$$

Mass balance:

$$\frac{1}{0.24448}(pcp)_t = \frac{1}{16}(mp)_t 1000000 \qquad \forall t \in T \qquad (71)$$

$$\frac{1}{0.24448}(pcp)_t = \frac{1}{64}(ocp)_t 1000000 \qquad \forall t \in T \qquad (72)$$

$$\frac{1}{44}(ccp)_t = \frac{1}{16}(mp)_t \qquad \forall t \in T \qquad (73)$$

$$\frac{1}{36}(htcp)_t = \frac{1}{16}(mp)_t \qquad \forall t \in T \qquad (74)$$

$$\frac{1}{0.158888}(php)_t = \frac{1}{4}(hp)_t 1000000 \qquad \forall t \in T \qquad (75)$$

$$\frac{1}{0.158888}(php)_t = \frac{1}{32}(ohp)_t 1000000 \qquad \forall t \in T \qquad (76)$$

$$\frac{1}{36}(hhp)_t = \frac{1}{4}(hp)_t \qquad \forall t \in T \qquad (77)$$

$$\frac{1}{0.1555688}(pcop)_t = \frac{1}{56}(cop)_t 1000000 \qquad \forall t \in T \qquad (78)$$

$$\frac{1}{0.1555688}(pcop)_t = \frac{1}{32}(ocop)_t 1000000 \qquad \forall t \in T \qquad (79)$$

$$\frac{1}{88}(ccop)_t = \frac{1}{56}(cop)_t \qquad \forall t \in T \qquad (80)$$

Energy efficiency and total production:

$$(pkwh)_t = (ef)((pcp)_t + (php)_t + (pcop)_t) \qquad \forall t \in T \qquad (81)$$

Production limits:

$$(pkwh)_t \le L_{('POWER')} \qquad \forall t \in T \qquad (82)$$

$$(pkwh)_t \ge (pm)_{('POWER')} \qquad \forall t \in T \qquad (83)$$

Output balance:

$$(pkwh)_t = \sum_{j \in P} X_{('POWER',j,'KWH',t)} \qquad \forall t \in T \qquad (84)$$

$$(ccp)_t + (ccop)_t = \sum_{j \in P} X_{('POWER',j,'CO2',t)} \qquad \forall t \in T \qquad (85)$$

Constraints from (66) to (70) express the input balance constraints. Constraint (66) states the amount of oxygen flow to the gas fired power plant for the power production. Constraint (67) states the amount of methane flow to the gas fired power plant for the methane based power production. Constraint (68) states the amount of syngas flow to the gas fired power plant. Constraint (69) states the amount of hydrogen flow to the gas fired power plant. Constraint (70) states the amount of carbon monoxide flow to the gas fired power plant.

Constraints from (71) to (80) are the mass balance constraints. Constraint (71) states the amount of methane used for methane based power production. Constraint (72) states the amount of oxygen used for methane based power production. Constraint (73) states the amount of carbon dioxide comes out during methane based power production. Constraint (74) states the amount of water comes out during methane based power production. Constraint (75) states the amount of hydrogen used for hydrogen based power production. Constraint (76) states the amount of oxygen used for hydrogen based power production. Constraint (77) states the amount of water comes out during hydrogen based power production. Constraint (78) states the amount of carbon monoxide used for carbon monoxide based power production. Constraint (79) states the amount of oxygen used for carbon monoxide based power production. Constraint (80) states the amount of carbon dioxide comes out during carbon monoxide based power production.

Constraint (81) represents the total produced efficient power. Constraints (82) states that total amount of produced power can't exceed the capacity of the plant. Constraint (83) states the determined minimum power production in the plant.

Constraint (84) denotes the amount of power distributed from power plant to the other plants that need it. Constraint (85) denotes the amount of carbon dioxide distributed from the power plant to the other plants that need it.

7.2.10 Carbon Black Plant and Its Constraints

Carbon black plant produces carbon and hydrogen from methane which is output of the Separator plant. The production process is briefly as following: Preheated natural gas reacts with a small amount of oxygen. The chemical process then splits dry gas methane as an intermediate product into two outputs carbon and hydrogen.

Carbon is a black, powder or granular substance made by burning hydrocarbons in a limited supply of air (Crump, 2000). It is mainly used as reinforcement in rubber. It also has applications in manufacture of automotive tires, industrial industry (rubber products), painting, paper and plastic (Gaudernack and Lynum, 1998). Hydrogen from Carbon black plant is used in the production of the direct-reduced iron. Gas power plant delivers electricity to the Carbon Black plant. The consumption of carbon black is steadily growing over the past decades. It is clearly indicated that it represent a large interest for Norway to set up the production of carbon black since Norway is the largest producer of natural gas in the world.

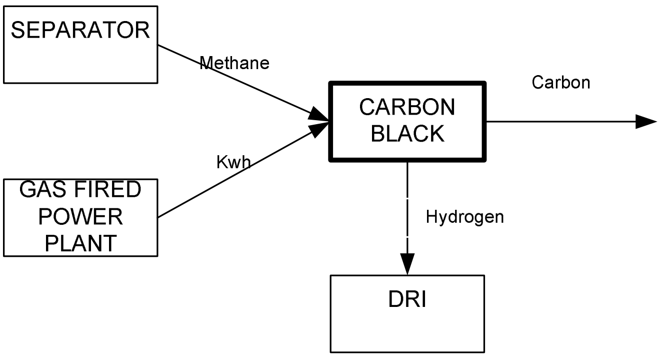


Figure 7-9 Input and output flow of the carbon black plant

Carbon black plant variables:

$(pcb)_t$: total production of the carbon in the carbon plant in period t, $t \in T$

$(kwhc)_t$: total usage of kWh in the carbon black plant in period t, $t \in T$

$(cc)_t$: usage of CH_4 in the carbon black plant in period t, $t \in T$

$(pch)_t$: production of H_2 in the carbon black plant in period t, $t \in T$

Constraints

Input balance:

$$(cc)_t = \sum_{i \in P} X_{(i,'CARBONBLACK','CH4',t)} \qquad \forall t \in T \qquad (86)$$

$$(kwhc)_t = \sum_{i \in P} X_{(i,'CARBONBLACK','KWH',t)} \qquad \forall t \in T \qquad (87)$$

Mass balance:

$$(pcb)_t = \frac{12}{16}(cc)_t \qquad \forall t \in T \qquad (88)$$

$$(pch)_t = \frac{4}{16}(cc)_t \qquad \forall t \in T \qquad (89)$$

$$(pcb)_t = \frac{1}{1700}(kwhc)_t \qquad \forall t \in T \qquad (90)$$

Production limits:

$$(pcb)_t \leq L_{('CARBONBLACK')} \qquad \forall t \in T \qquad (91)$$

$$(pcb)_t \geq (pm)_{('CARBONBLACK')} \qquad \forall t \in T \qquad (92)$$

Output balance:

$$(pcb)_t = \sum_{j \in P} X_{('CARBONBLACK',j,'Carbon',t)} \qquad \forall t \in T \qquad (93)$$

$$(pch)_t = \sum_{j \in P} X_{('CARBONBLACK',j,'H2',t)} \qquad \forall t \in T \qquad (94)$$

Constraints (86) and (87) express input balance constraints. Constraint (86) states the amount of methane flow to the carbon black plant. Constraint (87) states the amount of power flow to the carbon black plant.

Constraints (88), (89), (90) represent the mass balance constraints. Constraint (88) denotes the amount of methane used to produce carbon. Constraint (89) denotes the amount of methane used to produce hydrogen. Constraint (90) denotes the amount of energy used to produce carbon.

Constraint (91) represents that the amount of carbon produced in the plant can't exceed the capacity of the plant. Constraint (92) represents a minimum production constraint for carbon.

Constraint (93) represents the amount of carbon distributed from the plant to the other plants that need it. Constraint (94) represents the amount of hydrogen distributed from the plant to the other plants that need it.

8 STEEL PRODUCTION

In this chapter, firstly an overview of the world steel industry is presented. Afterwards steel, steel classification and production processes are described to provide the reader with background knowledge, without going deeply into technical details.

8.1 Overview of the World Steel Industry

Iron and steel industry is one of the world's most international industries and steel production connects with the world economy as a whole. Steel production plays an important role in the economy of each country and is considered as an indicator of economic progress. Steel has always been a fundamental material for wide variety of applications in many industries. It is the principal material used in the construction of industrial and domestic buildings, motor cars, automotive industry, machinery, merchant ships and the great majority of industry products. According to Sustainability report (2008) "The steel industry's greatest value contribution is providing society with steel products that are indispensable in sustaining and improving our modern world and standard of living."

The biggest advantage of steel is that it is 100% recyclable. In addition to this, it doesn't lose its properties during the recycle process. Recycling the steel results in (Sustainability report, 2008):

1. avoiding CO2 emissions
2. reducing the consumption of raw materials

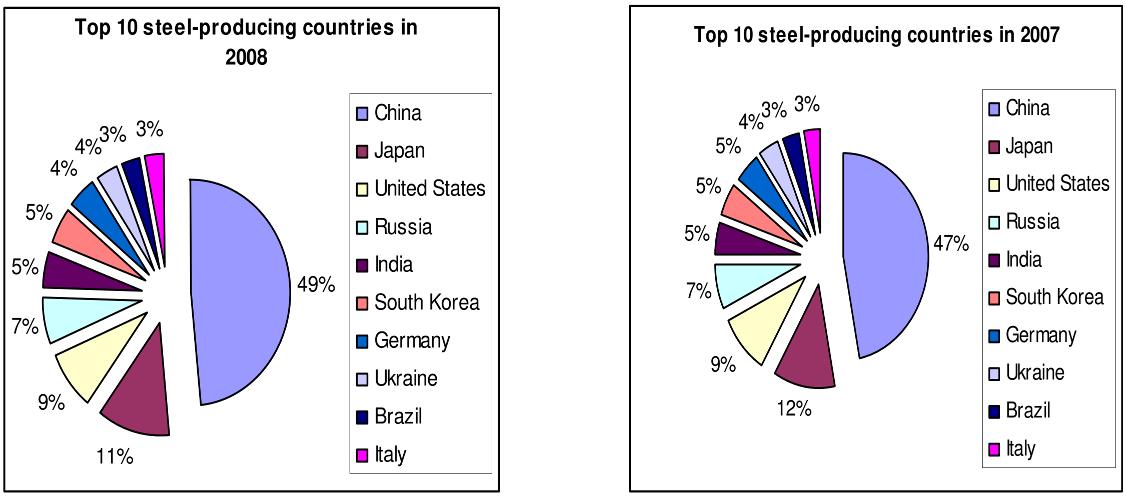
There are few substitutes for steel since the costs of the alternative materials are fairly high. Thus, it is commonly believed that steel is the material of future. Studying of steel trends indicates that steel production has a cyclical demand patterns and variability in earnings. The steel industry is demand driven branch and is influenced by many factors such as economic and political situation, environmental issues and etc. (Cowan, 2009). The globalization of the world economy has forced steel producers to expend global steel production. Thus steel production continues to take steps to strengthen its position in the world.

Crude steel was produced in 79 countries during 2008. China ranks as the first producer in the world. China, Japan, Unites States produced accounted for 69% of world crude steel. Significant growth of the Chinese economy from 2003 till 2007 has considerably affected the competitiveness of steel industry as well as enhanced steel demand (Steel Statistical Yearbook, 2007).

Country	Rank	2008	2007	% 08/07
China	1	502,0	489,2	2,6
Japan	2	118,7	120,2	-1,2
United States	3	91,5	98,2	-6,8
Russia	4	68,5	72,4	-5,4
India	5	55,1	53,1	3,7
South Korea	6	53,5	51,5	3,8
Germany	7	45,8	48,6	-5,6
Ukraine	8	37,1	42,8	-13,4
Brazil	9	33,7	33,8	-0,2
Italy	10	30,5	31,5	-3,4

Table 8-1 Top 10 steel producing countries of crude steel in 2008 and 2007

The graphical demonstration of the table is shown in the graph below:



Graphic 8-1 Top 10 steel producing countries in 2008 and 2007

Average Growth Rates % per annum	
Years	World
1950-70	5,1
1970-75	1,6
1975-80	2,2
1980-85	0,1
1985-90	1,4
1990-95	-0,5
1995-00	2,4
2000-05	6,2
2005-07	8,3

Table 8-2 Average Growth Rate (Steel Statistical Yearbook, 2007)

Growth behavior of the steel market can be described in the following way: the reconstruction work after the Second World War led to increase demand for steel and the average growth rate from 1950 till 1970 was 5.1%. We have to notice that the two deep recessions in steel industry in 1970 and 1990 coincided with recessions in the world economy that leaded to large fluctuations in production and demand. Due to oil crisis in 1970 which reflected in increasing of oil prices, surplus production capacity occurred. All these factors influenced negatively on the economic situation for many steel factories. Fluctuations between supply and demand have reflected in irregular peaks and troughs (Larsson, 2004).

Overall the last couple of years until 2008, global steel production has increased rapidly. The global production reached 1 billion tons of crude steel in 2004. Statistical sources showed the positive growth of steel production until 2008. The annual world's growth rate over the period from 2000 to 2005 was almost 6.2%, which is due to the rapid increase in steel demand in Asia. Consequently steel prices rose significantly in the period from 2000 till 2008. For instance, the price for crude steel in 2007 was 50% higher than in year 2000. This period represented a peak stage for steel industry (Raab and Mannheim, 2008).

Due to the financial crisis in 2008 the steel production of most countries has been declined and showed a negative trend. The World Steel Association states the fact that the crude steel production has been decreased by 1.2% compared to 2007.

The financial crisis strongly related to the global steel industry: steel demand has dramatically decreased; prices for steel have fallen down. Iron and Steel Statistics Bureau (ISSB) expounds that "total crude steel production for the 66 countries was estimated to be 83.8 million tones, a decrease of 22% in February 2008. In the EU crude steel production fell by 41.5% in February 2009 and by 43% to 19.9 million tons in the two month to date compared to the same period last year. Imports of steel outside of EU fell to their lowest level in December 2008 since December 2005. However, Chinese production increased by 4.9% in February and by 2.4% in the two month."

The president of the German Steel Federation at the annual meeting of the German Steel Federation and the Steel Institute VDEh pointed out that despite of downturn in steel industry these days, there is also a positive trend for steel industry in terms of raw materials cost.

Prices for scrap and alloying elements have significantly decreased from their historic all-time high (Garbracht, 2008).

8.2 The Supply and Demand Balance

Undoubtedly, the most important influencing factor on the steel demand is the world economy. Cycles occur in the world economy and as a consequence it has a strong effect on many industries including steel industry. According to Stopford (1997), cycle is "a process by which the market co-ordinates supply with changes in demand by means of the familiar cycle of booms and slumps."

One cycle consists of four stages:

1. Trough
2. Recovery
3. Peak
4. Collapse phase.

The trough phase can be described as surplus in steel capacity which leads to low prices, low volumes and strong competition between steel producers. In the recovery stage supply and demand move towards balance, price for steel is increasing. In the peak demand and supply are in tight balance, prices are fairly high. Finally, in collapse stage supply overtakes demand. Financial losses become huge for companies and price fall significantly.

8.3 Environmental issues

Undoubtedly, the steel industry as any manufacturing industry has impact on the environmental situation. Emissions of carbon dioxide are the consequence of combustion of coal in the blast furnace approach and consumption of large amount energy in Electric Arc Furnace (EAF) process. It leads to increase the concentration of greenhouse gases and climate changes. "The steelmaking and foundry industry is subject to local regulation that deals with water- and air-polluting emissions and solid-waste disposal". (Fenton, 2005)

Hu, Chen et al. (2006) states that the emissions Basic Oxygen Furnace (BOF) approach for producing steel is in 3.5 times higher than EAF approach. Nowadays, the EAF approach is considered as environmental-friendly methods for producing steel which allows reducing significantly CO_2 emissions. Table below illustrates CO_2 emissions of crude steel per ton for two processes routes:

	Common steel	Special steel	Average
BOF	2.127	2.298	2.152
EAF	0.514	0.699	0.563

Table 8-3 CO_2 emissions of crude steel per ton (Hu, 2006)

The steel industry is obliged to take actions in decreasing CO_2 emissions. The following measures have been taken by steel companies in order to reduce emissions and environmental impact (Sustainability report, 2008):

1. investing in clean and advanced technologies
2. to carry out life cycle assessment studies by collecting data on the environmental impact of steel products
3. monitoring and reporting the steel industry emissions
4. close international cooperation on environmental issues

8.4 Iron and Steel Industry in Norway

The metal industry is well developed in Norway. The largest and dominating metal industry is aluminum production represented in Norway by the third largest aluminum supplier in the world, Hydro Aluminum. It makes up the largest part of Norwegian metal industry. Steel and iron production represents only a small part of the metal industry (Ministry of trade and industry webpage, 2009). Therefore, Norway needs to import steel and iron in order to fulfill internal market's demand. According to Statistics Norway (SSB) there are only 16 companies related to iron and steel industry. The largest ones among them are: Celsa Steel Service, Ruukki, Elkem.

Celsa Steel Service is located in Mo i Rana, Bergen, Drammen, Kristiansand, Oslo and Ålesund. The main production facility – a steel mill combined with rolling mill technologies with production capacity for 725,000 mt of liquid steel is situated in Mo i Rana. The major produced products are reinforcement bar and wire rod. The production process is based electric arc furnace (EAF) approach based on the input recycled scrap steel. According to the company's web-site, Celsa Steel Service is considered as Norway's largest recycling company.

Ruukki Norge is a part of Ruukki Metals which has facilities in 26 countries. In Norway Ruukki supplies different types of steel and steel components to the industries such as construction, offshore, shipping. It has many departments in Norway: from Kristiansand in the south till Tromsø in the north. Elkem AS is represented in Norway which is a supplier of special alloys for the foundry industry, carbon, etc.

The rest steel and iron companies in Norway produce mainly steel finished products based on the imported crude steel. The type of steel finished products is usually depended on the requirements of the end consumers.

Norsk Stålforbund is a Norwegian Steel Association responsible for steel branch in Norway. It certifies the steel products according to Scandinavian and European standards.

We want to emphasize that there is a little data available about Norwegian steel industry. As we mentioned above the reason is that iron and steel industry is a really small part of the metal industry in Norway.

8.5 Steel and Types

Steel is an alloy of iron and carbon. It contains mostly iron and up to 2 percent carbon. In practice, it usually contains some additional chemical elements such as phosphorus, silicon and sulfur which may cause impurities. Depending on the steel type, it may contain many different alloying chemical elements.

Crude (raw) steel is the first solid state after melting the raw materials and is suitable for further processing or sale. By finishing processes in rolling mills, raw steel is turned to semi-finished and final products such as ingots and blooms, sheets and strip, rails and accessories, wire and wire rods, bars and tool steels. Steel has more than 3,500 different products that have many different physical and chemical properties. (Fenton, 2005)

According to Key to Metals database, Steels can be classified by a various methods depending on:

- The composition, such as carbon, low-alloy or stainless steel.

- The manufacturing methods, such as open hearth, basic oxygen process, or electric furnace methods.
- The finishing method, such as hot rolling or cold rolling
- The product form, such as bar plate, sheet, strip, tubing or structural shape
- The deoxidation practice, such as killed, semi-killed, capped or rimmed steel
- The microstructure, such as ferritic, pearlitic and martensitic
- The heat treatment, such as annealing, quenching and tempering, and thermomechanical processing
- Quality descriptors, such as forging quality and commercial quality.

We will deal with the first classification method which is composition based and the most common one. Thus we can sort the steel types in 3 main categories: Carbon steel; Low-alloy steel; High-alloy steel. Following information is obtained through research in Key to Metals steel database.

8.5.1 Carbon Steels

The American Iron and Steel Institute (AISI) defines carbon steel as follows: "Steel is considered to be carbon steel when no minimum content is specified or required for chromium, cobalt, columbium, molybdenum, nickel, titanium, tungsten, vanadium or zirconium, or any other element to be added to obtain a desired alloying effect; when the specified minimum for copper does not exceed 0.40 per cent; or when the maximum content specified for any of the following elements does not exceed the percentages noted: manganese 1.65, silicon 0.60, copper 0.60."

Carbon (C) steels are most frequently used steels in the world. There are three sub-categories of carbon steels:

- Low carbon steels contain up to 0.3 % C. The largest category of final products that uses this class of steel is sheet and strip products.

- Medium carbon steels contain C within ranges from 0.30 to 0.60% and the manganese from 0.60 to 1.65%. The uses of medium carbon steels include shafts, axles, gears, crankshafts, couplings, forgings, rails, railway wheels and rail axles.

- Ultrahigh carbon steels contain C from 1.25 to 2.0 %.

8.5.2 Low-alloy Steels

Low-alloy steels constitute alloying elements such as nickel, chromium, and molybdenum that exhibit properties superior to plain carbon steels. Total alloy content can range from 2.07% up to levels just below that of stainless steels, which contain a minimum of 10% Cr. For many low-alloy steels, the primary function of the alloying elements is to increase hardenability in order to optimize mechanical properties and toughness after heat treatment. In some cases, however, alloy additions are used to reduce environmental degradation under certain specified service conditions.

Low-alloy steels can be categorized into 4 major groups: (1) low-carbon quenched and tempered (QT) steels; (2) medium-carbon ultrahigh-strength steels; (3) bearing steels and (4) heat-resistant chromium-molybdenum steels.

8.5.3 High-alloy Steels

These are strong corrosion resistant; heat resisting and wear resistant steels. The group includes Stainless steels which are iron-based alloys containing at least 10.5% Chromium (Cr). Few stainless steels contain more than 30% Cr or less than 50% Iron (Fe). They achieve their stainless characteristics through the formation of an invisible and adherent chromium-rich oxide surface film. There are some other chemical elements also added to improve characteristics including nickel, molybdenum, copper, titanium, aluminum, silicon, niobium, nitrogen, sulfur, and selenium. Carbon is normally present in amounts ranging from less than 0.03% to over 1.0% in certain grades.

Over the years, stainless steels have become widely used for cooking utensils, fasteners, cutlery, flatware, decorative architectural hardware, and equipment for use in chemical plants, dairy and food-processing plants, health and sanitation applications, petroleum and petrochemical plants, textile plants, and the pharmaceutical and transportation industries. Stainless steels are commonly divided into five groups: Martensitic stainless steels; Ferritic stainless steels; Austenitic stainless steels; Duplex stainless steels; and Precipitation-hardening stainless steels.

Following figure demonstrates the steel types and finished steel products.

Figure 8-1 Steel types and final products

8.6 Steel Production Process

According to Sustainability Report, 2008 steel is produced by the following methods:

- Combination of the blast furnace (BF) and basic oxygen furnace (BOF). In this process the raw materials such as iron ore, coal, limestone and recycled scrap steels are used.
- Electric arc furnace (EAF) approach based on the recycled steel scrap and/ or DRI and electricity input.

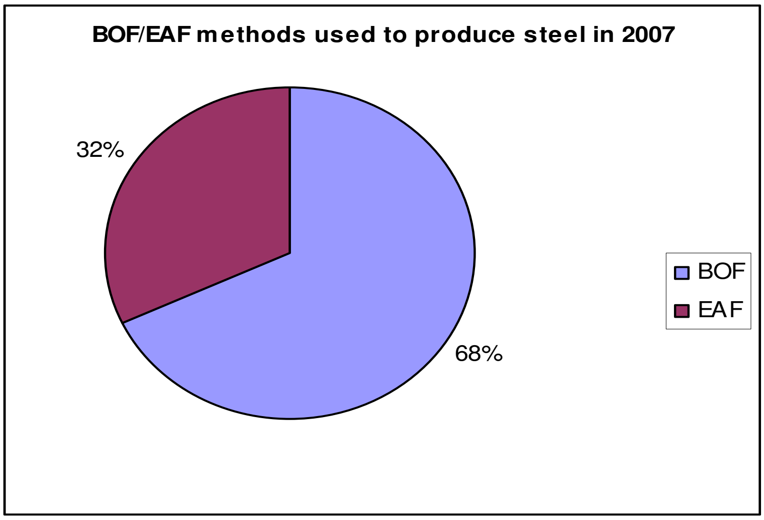


Figure 8-2 BOF/EAF methods used to produce steel in 2007 (Sustainability report, 2008)

In steel production, firstly iron is made and it is charged into EAF or BOF for melting. Scrap is also charged as raw material and melted. After steel has been made in the EAF or BOF, it is transferred to a ladle in which refining operations and the addition of alloying elements are performed. From the ladle, steel is passed to the continuous-caster machine. Here semi-finished products such as slabs are produced. Finally semi-finished steel is processed in rolling mills and turned into finished products (Fenton, 2005). More detailed explanation of the processes will be explained in the following parts.

8.6.1 Iron-making

Iron is produced from iron ore either by blast furnaces or direct reduction. In our case, DRI plant will be located in the cluster and iron production will be done by this method. Therefore we think that it is more appropriate to explain DRI. Iron ore is reduced to solid iron by reducing gases (CO and H_2) when producing DRI. The temperature in the shaft and the composition of the reducing gas influence the reduction speed and rate. The output from the conversion is Fe (in addition to oxidated reducing gases). It can be in the form of lump, briquettes and pellets. In addition, CO_2 and H_2O (as well as CO and H_2) are output from the shaft. Parts of this gas are recycled together with new methane gas to produce more reducing gas.

DRI is efficiently used by continuous charging through the EAF. It is especially valuable to make high-grade steel because the unwanted elements are lower than those scrap normally contains. It is used to control the quality, however, more expensive than scrap.

8.6.2 Steelmaking

In this process, DRI and/ or scrap are converted into steel by a refining process that reduces carbon and silicon content and removes impurities. It has been already determined that EAF will be the structured approach to be used in the steel plant of the cluster. Thus, we will describe EAF process.

EAFs have the most recent technology in steelmaking and have an important advantage of operating with a cold charge in which scrap can be used up to 100 percent. DRI is a substitute for scrap and used to produce high-grade steel. Quality can be controlled by usage of EAF. Another advantage of the EAF process is its relatively low capital cost per ton of steel produced.

In EAF, firstly raw materials are melted and refined in a second vessel. Carbon is removed from molten steel by argon-oxygen-decarburization (AOD) process or reduced into the required low level by oxygen lancing method. Insertion of the ferrous-alloys is done in this process in order to provide the required mechanical properties.

8.6.3 Casting

Steel is poured from ladle into continuous-casting machine where it is cut into billets, blooms or slabs. Continuous-casting machines have the following components; water-cooled copper mold; a cooling chamber; pinch rolls and rollers for supporting the casting. A steel plant contains an EAF and thin-slab caster has a much lower investment cost, and less energy is consumed to reheat the slab.

8.6.4 Rolling and Finishing

From continuous casting machine slabs, billets and blooms are passed through hot and cold rollers in the rolling mill in order to produce finished products.

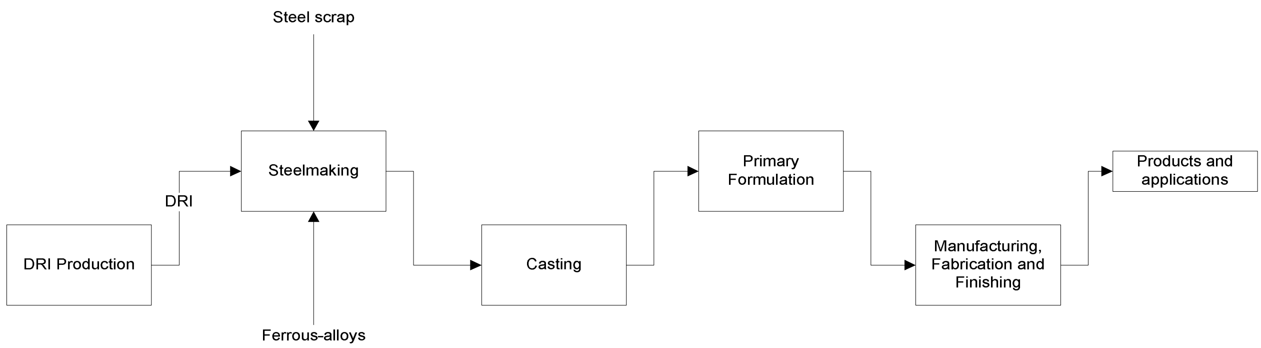


Figure 8-3 Steel production process

9 FORECASTING OF THE DEMAND

This chapter will familiarize the reader with the different forecasting methods used in business. Then, based on the theory we will make the forecasting for demand of crude steel in Norway. Since the potential plant is considered to be ready for production in following years it is essential to implement reliable estimation methods for the demand of crude steel. It is obvious that demand is the driving force of business.

We believe that accurate forecasting of demand may influence on the design of the plant in terms of capacity. In addition, it will reduce the uncertainty in decision making as well as make better estimation for the future. There are many ways to forecast future but we will implement quantitative methods rather than qualitative ones.

By this work, our primary goal is to implement applicable and practical forecasting methods to contribute decision making process for the future plant. Secondly we can use the forecasting results as reliable demand data while testing our mathematical models.

Since the steel demand in Norway is one of the goals to be satisfied by the potential industrial cluster, we have estimated particularly Norway demand. Due to the lack of data, while implementing the methods, we have assumed that the consumption of steel in Norway for the previous years is the historical data for the demand in Norway. Moreover, in this stage the potential steel plant is considered to sell crude steel, therefore the data and forecasting is related to crude steel demand.

9.1 Data for forecasting

According to Steel Statistical Yearbook (2007) apparent consumption of crude steel for Norway is given in the table below:

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Consumption (.000 tons)	1880	1995	1230	1260	1260	1300	1301	1812	1388	1656

Table 9-1 Apparent consumption of crude steel for Norway

We will make forecasting for 2010 by using different methods of forecasting since the plant is considered to be ready for production at the end of 2010. As can be observed on table above, there were no available data we found for years 2007 and 2008.

9.2 Forecasting methods

Accurate forecasting may affect decisions and activities of different sectors such as accounting, finance, production, marketing, human resources. All planning processes require forecasting in order to avoid unexpected expense and cope with uncertainty in the future. Forecasting methods allow us to predict and estimate future based on the past data, experience. Forecasting can be performed for (Cook and Russell, 1989):

1) Long-term decisions: they are used mainly to support strategic decisions such as capacity decision for example.
2) Short-term decisions: they are useful for operational planning in order to meet day-to-day demand.

Forecasting can be carried out monthly, yearly or quarterly. We need to remember those:

1) accuracy of forecasting depends on both time horizon and techniques for performing forecasting
2) the longer the forecast time horizon, the less accurate forecasting will be
3) aggregate forecasting is more accurate

Companies that implement forecasting approach have the following benefits:

1) ready to meet in advance demand occurring
2) the ability to identify the trend of activities
3) planning capacity and production
4) the ability to reduce cost
5) the ability to increase efficiency

As we have already written that forecasting is used to predict what will occur in the future. That's why forecast accuracy is playing a significant role whether the forecasting will be implemented or not. Forecast accuracy is measured by Mean Average Deviation (MAD) or the Mean Squared Error (MSE) or Mean Absolute Percentage Error (MAPE). We will calculate all of them but will give decisions based on MAPE since it doesn't depend on the magnitude of the values of demand. MSE is similar to the variance of a random sample. MAD is often used for measuring the forecast error because it doesn't require squaring. (Nahmias, 1993)

We will benefit from the following formulas:

Mean Absolute Deviation: $$MAD = \frac{1}{n}\sum_{i=1}^{n}|e_i|$$

Mean Squared Error: $$MSE = \frac{1}{n}\sum_{i=1}^{n}e_i^2$$

Mean Absolute Percentage Error: $$MAPE = \left[\frac{1}{n}\sum_{i=1}^{n}\left|\frac{e_i}{D_i}\right|\right]*100$$

Where $e_i = F_i - D_i$ is the forecast error in period i,

D- is the actual value in period i,

F- is the forecasted value in period i.

n- number of time periods

There are many different approaches for conducting a forecast. First of all, forecasting technique is divided into two types: quantitative methods and qualitative methods. Qualitative is based on insights, experiences, opinions and judgments. They do not involve any mathematical computations. The latter approach is used for numerical analyses when sufficient data are available. They rely on the statistical methods. Quantitative methods are divided into two types (Cook and Russell, 1989):

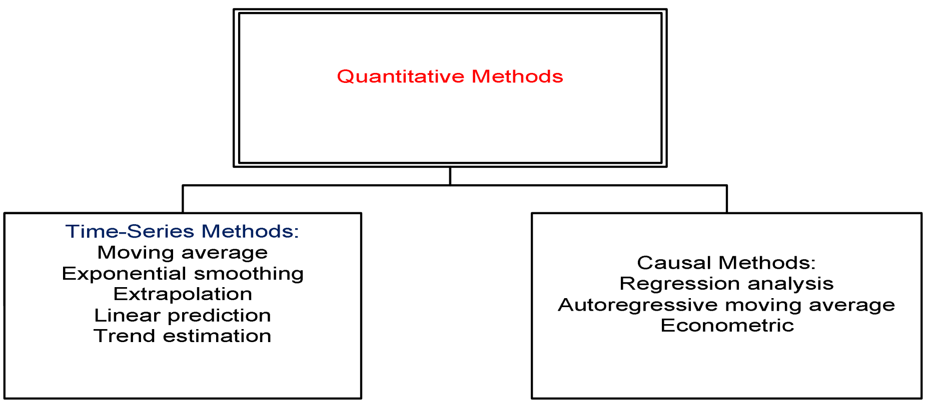


Figure 9-1 Quantitative forecasting methods

The difference between these methods is that time-series methods are based on the historical data to develop a function to forecast demand while in causal methods forecasted variable is dependent on the underlying factor.

In our research paper we will focus on quantitative methods such as moving average and linear regression. In the end of this chapter we will compare forecasting values obtained different methods and suggest the most appropriate method which gives minimum MAPE. Hence, we will obtain the demand of crude steel for 2010.

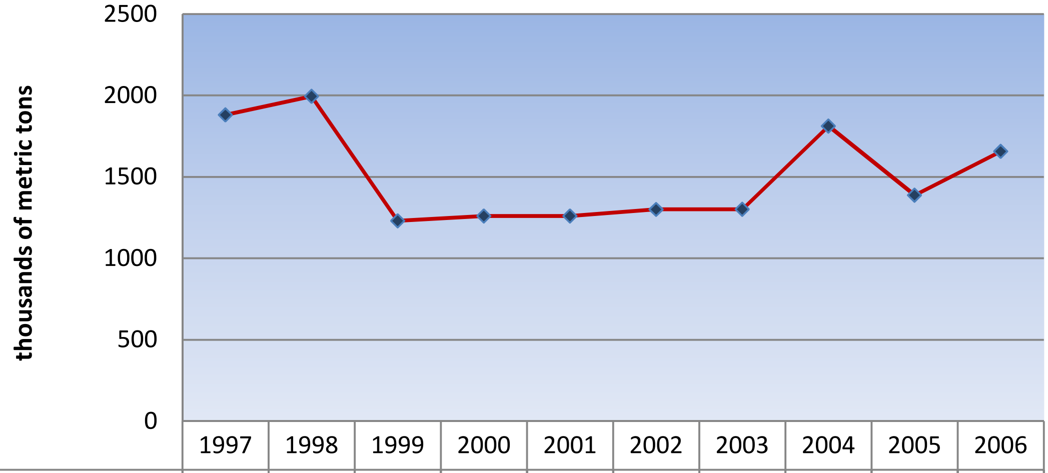
9.3 How to Forecast During the Recession

This section will give an overview how to make forecasting during a recession. In 2007 the news about steel production was very optimistic. The headlines of all articles related to steel industry began with the following words: "World crude steel production jumped to record in 2006, World crude steel production increased by 5.3%". World Steel Association stated that 2008 will be another strong year for the steel industry. However, the financial crisis has occurred in 2009. It has strongly affected the steel industry: steel demand has dramatically decreased and prices for steel have fallen down.

In the current situation steel industry experience that supply overtakes demand. It leads to collapse phase and results in cutting the production of steel and waiting what happened in the future. In this stage to make forecast is a challenge. Nowadays forecasts in big companies are carried out by expensive forecasting software. Shah (2009) expresses that the managers of big companies have a challenge how to make the forecast in these days. The results of forecasting systems gives the forecasting which is away by 40% from the truth. Forecasting software is not able to identify patterns during recession. Of course human beings can identify different patterns and trends in historical data but it is difficult to handle all data gathered in database. He suggests implementing simple algorithms such as weighted moving average, exponential smoothing.

9.4 Analysis of the Historical Data

Analysis of historical data is an essential part of forecasting. Graphic below demonstrates the historical data for consumption (demand) of crude steel in Norway



	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Consumption	1880	1995	1230	1260	1260	1300	1301	1812	1388	1656

Graphic 9-1 Apparent consumption of crude steel for Norway

The current plot encompasses consumption of crude steel in Norway between the periods from 1997 to 2006 year. From the graph we can see that maximum consumption was recorded in 1998. From 1999 to 2003 the behavior of the consumption line is quite stable. Then it reached the peak in 2004. Values increase or decrease over the period from 2004 to 2006.

9.4.1 Moving average

In this section we will implement moving average forecasting method. In this method, the estimations are based on the last n period observations. We can decide ourselves the best appropriate period for moving average: 2-period, 3 period, etc. Moving average forecasting method is quite accurate over short time period. The main advantages of the method are simplicity, cheap to run, gives good accuracy but it doesn't work well when there is a trend or seasonal effect in data. The following formulas are used in this method (Winston, 1993):

$$F_t = \frac{\sum_{i=1}^{N} S_{t-i}}{N} \qquad (1)$$

where F_t = forecast for time period t

S_{t-i} = actual consumption for period t-i

N = number of time periods used in the averaging process

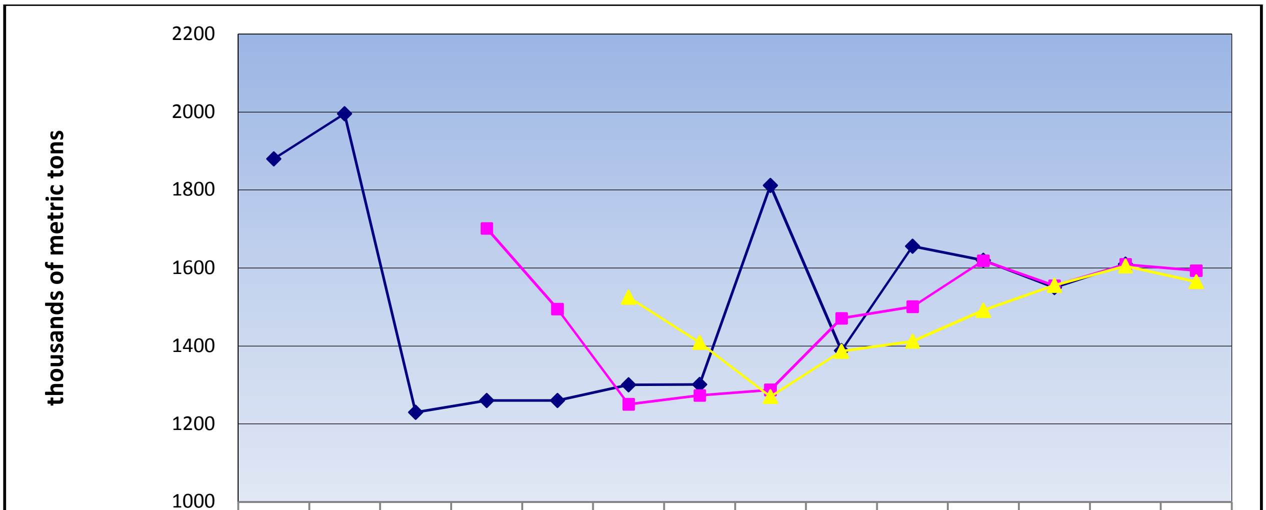
We generated forecast for 2010 based on the historical data and implemented 3-period and 5 – period moving averages. In the tables below you can see the obtained results:

Forecasted demand	Moving average 3- period	Moving average 5- period
2010	1593.33	1564.8

Table 9-2 Forecasting results for 2010 by moving average method (.000 of metric tons)

Type of Error	Moving average 3- period	Moving average 5- period
MAD	152.53	157.35
MSE	56033.13	53983.35
MAPE	10.45%	9.86%

Table 9-3 Errors for 2010 estimations by moving average



	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Consumption	1880	1995	1230	1260	1260	1300	1301	1812	1388	1656	1620	1550	1610	
Forecast_3				1701,6	1495,0	1250,0	1273,3	1287,0	1471,0	1500,3	1618,6	1554,6	1608,6	1593,3
Forecast_5						1525,0	1409,0	1270,2	1386,6	1412,2	1491,4	1555,4	1605,2	1564,8

Graphic 9-2 Interpretation of the results for moving average method

It is clearly indicated that consumption of crude steel will be decreased but not significantly. In our case due to lack of data we assumed that the forecasted values for 2007 and 2008 as the real values in order to generate forecast for 2010. The results are attached as Appendix C.

9.4.2 Linear Regression

In this section brief description of the linear regression method is presented. Based on this method we will estimate the steel demand in Norway for year 2010. We would like to highlight that Linear Trend Equation and Least Square Method are alternative names for this method.

Least Square Method is a powerful technique used to make forecasts when the data represent a linear trend. It determines which line best fits the historical data by minimizing sum of squared deviations around the line.

According to Nahmias (1989), the relationship between x and y is given by equation:

$$\bar{y}(x) = a + bx$$

It allows doing forecasting for any year in the future. Values a and b are determined such that the line best fits the data.

Where a - y-axis intercept

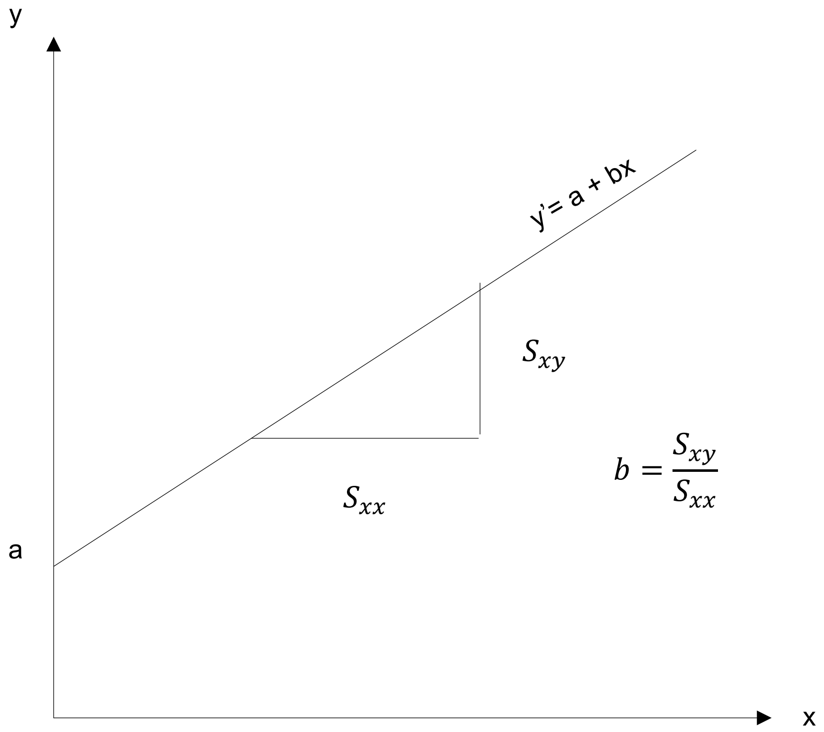
b - slope of the regression line

y - dependent variable

x - independent variable

$\bar{y}$ - predicted value of y

The graphical interpretation of a straight line is shown in the graph below:



Graphic 9-3 Graphical interpretation of the formula

The formulas below used to compute coefficients a and b (Johnson and Bhattacharyya, 2001):

$$b = \frac{S_{xy}}{S_{xx}} = \frac{\sum_{i=1}^{n}(x-\bar{x})(y-\bar{y})}{\sum_{i=1}^{n}(x-\bar{x})^2} = \frac{n\sum_{i=1}^{n}x_i y_i - \sum_{i=1}^{n}x_i \sum_{i=1}^{n}y_i}{n\sum_{i=1}^{n}x_i^2 - (\sum_{i=1}^{n}x_i)^2} \qquad (1)$$

$$a = y - \frac{S_{xy}}{S_{xx}}x = \frac{1}{n}(\sum_{i=1}^{n}y_i - b\sum_{i=1}^{n}x_i) \qquad (2)$$

where : $\bar{x}$ and $\bar{y}$ are the sample means of the x and y values;

S_{xx} and S_{yy} - are the sums of squared deviations from the means

S_{xy} is a sum of the cross products of deviations.

Since $\sum_{i=1}^{n} x_i = \sum_{i=1}^{n} i = \frac{n(n+1)}{2}$ and $\sum_{i=1}^{n} x_i^2 = \sum_{i=1}^{n} i^2 = \frac{n(n+1)(2n+1)}{6}$, we can

Write the formulas (1) and (2) as follows:

$$b = \frac{n\sum_{i=1}^{n} iy_i - \frac{n(n+1)}{2}\sum_{i=1}^{n} y_i}{\frac{n^2(n+1)(2n+1)}{6} - \frac{n^2(n+1)^2}{4}} \quad (3)$$

$$a = \frac{1}{n}\left(\sum_{i=1}^{n} y_i - b\frac{n(n+1)}{2}\right) \quad (4)$$

In our case we have:

x - value of the independent variable (time).

y - predicted value of the dependent variable (steel consumption).

n - number of observation.

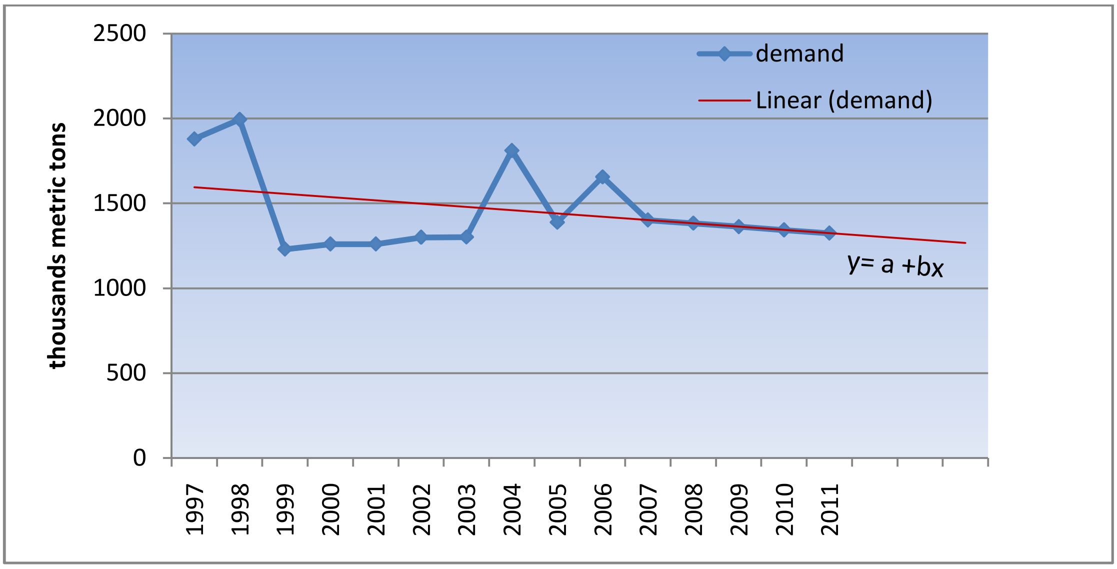
By computing coefficients using formulas (3) and (4) we got a line which best fits to our data: y(x) = 1614.5 – 19.3x. Excel calculations are attached in the Appendix D

Year	Forecasted value
2010	1343.92

Table 9-4 Forecasting result for 2010 by linear regression method (.000 of metric tons)

Type of Error	Least Square Method
MAD	198.66
MSE	58446.35
MAPE	13.20%

Table 9-5 Errors for linear regression method



Graphic 9-4 Graphical interpretation of results

Approximately the same result was obtained by using Excel Statistical Tool Pack. In addition, Excel offers the value R-squared. In our case R^2=0.100597. R-squared indicates how well the data match the resulting line. R-squared value is always in the ranges from 0 to 1. If R^2 is close to 0, it means that forecast is not close to reality. In contrary, if forecast is reliable, R-squared will be close to 1.

In our case due to lack of data for 2007-2008 we made the same assumption as the one we did in moving average: we assumed the forecasted values as real values in order to perform forecast for 2010.

9.4.3 Conclusion and Comparing Results

In this chapter we generated forecast for consumption of steel in Norway in 2010 based on the historical data from 1997 to 2006. We implemented two approaches: moving average and linear regression. A brief review of methods was described. The challenge to make a forecast was the lack of data for years 2007-2008. Therefore, we decided to assume the forecasted values for 2007-2009 as the real data. The results of forecasts are summed up in the table below:

Forecasted Year	**Moving average** 3- period	**Moving average** 5- period	**Linear Regression**
2010	1593.33	1564.8	1343.92

Table 9-6 Forecasting results by moving average and linear regression

Type of Error	Moving average 3- period	Moving average 5- period	Least Square Method
MAD	152.53	157.35	198.66
MSE	56033.13	53983.35	58446.35
MAPE	10.45%	9.86%	13.20%

Table 9-7 Forecast accuracy for 2010

Based on MAPE results we will recommend the moving average 5-period method as the most accurate forecasting technique in this case. Thus, the estimation of steel demand in Norway for 2010 is 1564.8 thousands of metric tons which mean 1,564,800 tons.

10 OPTIMIZATION MODEL FOR THE INTEGRATED STEEL PLANT

After converting the initial code to mathematical model and understanding the operations, parameters, variables, mass balances, inputs and outputs of each plant and observing the shortcomings of the model we have focused on the steel plant for improvement as it is suggested by SINTEF research team as well. Steel plant is interconnected with DRI plant; power plant and market because DRI, power and steel scrap commodities are supplied by these plants respectively. One of the most important objectives of the Gas-Mat project is to turn the rich iron, oil and natural gas resources into value by producing steel and satisfy the demand in Norway. Therefore we believe that our contribution will be indeed valuable for this major research project.

10.1 Motivation

As its core function, our optimization model should be able to provide us with understanding the steel plant, doing economic analysis and optimizing the design and operations. In addition to the supplied code for the steel plant which basically deals with the mass balance, the model should also consider the following issues:

- various types of steel
- element composition of the outputs
- impact of the demand
- scrap and losses that may occur during production
- inventory balance

Since, in this stage, the model will not consider uncertainties and data will be deterministic, it will be a deterministic optimization model.

10.2 Assumptions and Definitions

In our master thesis, we have exemplified 2 main composition based classification of steel: Carbon Steel and Stainless Steel. We can increase the number of the product types, however, our aim is to build the model for multi-products and we can success this as long as there won't be just one product type exemplified. There are many sub-product-groups and different products which are element composition variations of these main categories. However we have selected one representative product from each main type to set the data for element composition bounds. For instance, if we would like to test the model for stainless steel type than we choose any sub-product group of stainless steel such as martensitic stainless steel and adjust the composition of elements, costs and other relevant data according to what is provided by SINTEF and we found about the type. Although, steel scrap may have different types comprised various compositions and qualifications, we have assumed that our two representative steel types are recycled as scrap purchased from the market.

We didn't add 'set-up' feature into the problem and assign a decision variable that demonstrates whether we need to produce the particular steel type or not. In other words, we assumed that there is no set-up cost or time for producing a new product. Variety of products can be supplied by using different amounts and combinations of raw materials which will give desired composition of elements for the particular product. Thus, the problem didn't become unnecessarily more complex and hard to solve since it can be solved by LP model instead of Mixed Integer Programming (MIP) model which contains binary decision variables. Besides, in this phase, it is not crucially important to have ability of such decision.

As stated previously, DRI and steel scrap are required raw materials for the steel production. Moreover in order to obtain different types of steel which may be demanded by the market, Ferro-Alloys should be considered as a raw material as well. These are quite expensive materials to purchase, however, necessary to obtain the elements such as Nickel, Chrome, Molybdenum, Manganese and Magnesium which are required to produce various types of steel. Other used commodities such as electricity, oil and gas weren't handled as raw materials and treated in the model as new index of set since they don't have any influence on the type of the product.

On the other hand, losses may come out during the processes, thus our model concerns the losses as well. Moreover, at the end of the production process, some steel scrap may occur due to fails on product qualification, specification or any other reason. These failed steel products are called home scrap and can be recycled.

The model doesn't consider any capacity constraint for steel plant and for the plants from where raw materials are supplied. Because the plants have not been established and further investment decisions on capacities in the cluster can be adapted in accordance with requirements to satisfy the demand.

The research team from SINTEF wanted us to deal with the steelmaking and refining process in EAF. In other words, while building the model, handled processes will be: charging DRI and steel scrap into EAF (Electric Arc Furnace) as the first one and adding Ferro-alloys with respect to the desired product type as the second one. Therefore we don't take into account rest of the production process in our model.

10.3 Mathematical Model

While building the model, we have been inspired by the research done previously in this area as mentioned in literature review chapter. Furthermore our model contain some of the generalized forms of constraints from the code provided by SINTEF research team since it was required to be compatible with the initially provided model.

Since it is definite that steel plant will be established and it is assumed that it will at least satisfy the demand for Norway, we have changed the model structure a bit. This means that sale of the steel plant is fixed to demand value so that there is no such objective for the plant as increasing the sales. We will absolutely sell as much as the demand. Therefore it was also important to perform reliable forecasted value for demand.

The planning horizon is divided into several periods since there is also a life after our first decision. The number of periods can be changed as per planner's wish our aim is to build multi-period model. Inventory balance is added to the model, because the planning horizon consists of several periods. At the beginning of the planning horizon the inventory is assumed as 0. There has to be a final inventory at the end of the planning horizon because it will be quite unrealistic to assume that the production and sales will stop right after the end of the planning horizon and the plant will not sell anything. We have determined the final inventory level as a fraction of the final demand. Moreover the model considers Carbon and Silicon reduction to the required level as well.

All in all, the model aims to minimize the total cost of required raw materials, commodities, production and inventory holding cost while satisfying the demand. It gives the optimal amount of raw materials and commodities to be purchased as well as the optimal inventory levels at each period. Furthermore, flexible generation of compositions can be performed within the model in order to satisfy the concern of steel type variety.

We will first give the notations of sets, parameters, variables and then will explain the objective function followed by all constraint explanations.

Sets

J: set of raw materials.

F: set of Ferro-alloys.

E: set of chemical elements.

C: set of used commodities.

P: set of products.

Parameters

T : number of the last period in the planning horizon.

c_{jt} : unit cost of the raw material j in the period t. $j \in J, t \in T$

f_{ft} : unit cost of the Ferro-alloy f in the period t. $f \in F, t \in T$

e_{ct} : unit cost of the commodity c in the period t. $c \in C, t \in T$

i : unit inventory holding cost of a product.

a_{je}^{1} : percentage of the element e in the raw material j. $j \in J, e \in E$

a_{fe}^{2} : percentage of the element e in the Ferro-alloy f. $f \in F, e \in E$

a_{ep}^{3} : percentage of the element e in the scrap type p. $p \in P, e \in E$

k_c : coefficient that indicates the balance between the amount of production and the amount of consumed commodity c. $c \in C$

u : unit cost of production.

l_e^1 : remained percentage of element e after losses occurred in the first process. $e \in E$

l_e^2 : remained percentage of element e after losses occurred in the second process. $e \in E$

b_p : lower bound of product amount at the end of the first process. $p \in P$

d_{pt} : demand for the product p in the period t. $p \in P, t \in T$

h_{ep}^1 : lower bound percentage for element e within product p at the end of the first process. $e \in E, p \in P$

g_{ep}^1 : upper bound percentage for element e within product p at the end of the first process. $e \in E, p \in P$

h_{ep}^2 : lower bound percentage for element e within product p at the end of the second process. $e \in E, p \in P$

g_{ep}^2 : upper bound percentage for element e within product p at the end of the second process. $e \in E, p \in P$

m : obliged DRI usage percentage within the total raw material.

s_p : home scrap amount. (In percentage of the product) $p \in P$

Variables

x_{jpt}^1 : amount of the purchased raw material j for the product p in the period t. $j \in J, p \in P, t \in T$

x_{fpt}^2 : amount of the purchased Ferro-alloy f for the product p in the period t. $f \in F, p \in P, t \in T$

y_{ept}^1 : amount of the element e obtained at the end of the first process and adhered to the product p in the period t. $e \in E, p \in P, t \in T$

y_{ept}^2 : amount of the element e obtained at the end of the second process and adhered to the product p in the period t. $e \in E, p \in P, t \in T$

y_{ept}^3 : amount of the reduced element e in production of the product p in the period t. $e \in E, p \in P, t \in T$

w_{pt}^1 : amount of the product p at the end of the first process in the period t. $p \in P, t \in T$

w_{pt}^2 : total amount of the product p in the period t. $p \in P, t \in T$

z_{ct} : total amount of the consumed commodity c in the period t. $c \in C, t \in T$

I_{pt} : inventory level of product p in the period t. $p \in P, t \in T$

Objective function

The objective is the minimization of the total cost.

Total cost = Total raw material cost + Total Ferro-alloy cost + Total used commodity cost + Total production cost + Total inventory holding cost

Minimize

$$\sum_{j \in J} \sum_{p \in P} \sum_{t\ in\ 1..T} c_{jt} x_{jpt}^1 + \sum_{f \in F} \sum_{p \in P} \sum_{t\ in\ 1..T} f_{ft} x_{fpt}^2 + \sum_{c \in C} \sum_{t\ in\ 1..T} e_{ct} z_{ct} +$$

$$\sum_{p \in P} \sum_{t\ in\ 1..T} u\, w_{pt}^2 + \sum_{p \in P} \sum_{t\ in\ 1..T} i\, I_{pt}$$

Constraints

$$\sum_{j\in J} l_e^1\ x_{jpt}^1\ a_{je}^1\ +\ s_p\ w_{pt}^2\ a_{ep}^3 =\ y_{ept}^1 \qquad \forall\ e \in E\ , \forall p \in P, t\ in\ 1..T \qquad (1)$$

Constraint (1) expresses that at the end of the first process, amount of each chemical element, which adhered to the product, is obtained from raw materials with respect to the element percentages and losses. In addition to this, since home scrap is recycled and joins to beginning of the first process, chemical elements are also obtained and adhered to the product in the first process by home scrap recycling.

$$y_{ept}^1\ + \sum_{f\in F} l_e^2\ x_{fpt}^2\ a_{fe}^2 = y_{ept}^2 \qquad \forall\ e \in E\ , \forall p \in P, t\ in\ 1..T \qquad (2)$$

Constraint (2) expresses that the amount of each chemical element, at the end of the second process, is the summation of coming element amount from the first process and gained from Ferro-alloy insertion in the second process.

$$\sum_{e\in E} y_{ept}^1 = w_{pt}^1 \qquad \forall p \in P, t\ in\ 1..T \qquad (3)$$

$$\sum_{e\in E} y_{ept}^2 =\ w_{pt}^2 \qquad \forall p \in P, t\ in\ 1..T \qquad (4)$$

Constraints (3) states that total amount of the product, at the end of the first process, is the summation of all chemical elements obtained in this process.

Constraint (4) states that total amount of the product, at the second process, is the summation of all elements obtained from both processes.

$$w_{pt}^1\ \geq b_p \qquad \forall p \in P, t\ in\ 1..T \qquad (5)$$

Constraint (5) expresses the lower bound for the weight of the product p at the end of the first process. The constraint is set to allow metallurgists in the cases that are required by technological needs to setup the lower bound for product amount in the first process.

$$I_{p,t-1} + (1 - s_p)w_{pt}^2 =\ d_{pt} + I_{pt} \qquad \forall p \in P,\ t\ in\ 1..T \qquad (6)$$

Constraint (6) represents the inventory balance at each period for each product. Inventory coming from the previous period plus produced product at the present period should be equal to demand plus inventory of the present period.

$$I_{p,0} = 0 \qquad \forall p \in P \qquad (7)$$

Constraint (7) denotes that the initial inventory level is 0 for each product.

$$I_{p,T} = 0.2 * d_{p,T} \qquad \forall p \in P \qquad (8)$$

Constraint (8) denotes that there is an obliged amount of inventory for the last period for each product.

$$k_c \sum_{p \in P} w_{pt}^2 = z_{ct} \qquad t\ in\ 1..T\ , \forall c \in C \qquad (9)$$

Constraint (9) calculates the required amount of commodity c for total production of steel.

$$h_{ep}^1 w_{pt}^1 \leq y_{ept}^1 \leq g_{ep}^1\ w_{pt}^1 \qquad \forall\ p \in P, t\ in\ 1..T\ , \forall e \in E \qquad (10)$$
$$h_{ep}^2 w_{pt}^2 \leq y_{ept}^2 \leq g_{ep}^2\ w_{pt}^2 + y_{ept}^3 \qquad \forall\ p \in P, t\ in\ 1..T\ , \forall e \in E \qquad (11)$$

Constraints (10) states the obliged upper and lower bound percentages for each element obtained at the end of the first process. Similarly, Constraints (11) states the obliged upper and lower bound percentages for each element obtained at the end of the second process. The help variable y_{ept}^3 is used to indicate the reduced amount of Carbon and Silicon. Because the Carbon and Silicon amounts within the raw material input should be more than that within the output. Furthermore this variable makes the model feasible.

$$x_{'DRI',p,t}^1 \geq m \sum_{j \in J} x_{jpt}^1 \qquad \forall\ p \in P, \qquad t\ in\ 1..T \qquad (12)$$

Constraint (11) expresses the obligation of DRI usage in order to be able to control the quality.

The whole model is demonstrated in Appendix E.

All in all we should emphasize that we have improved the basic code significantly. By additional constraints regarding technical and operational characteristics of the future plant, the model considers multi-products and their compositions, home scrap recycling, losses that may occur during processes, Carbon and Silicon reduction (this feature can also represent cleaning impurities when needed), inventories in periods, first and last period inventories and a metallurgical requirement and Ferro-alloy insertion.

11 VALIDATION OF THE OPTIMIZATION MODEL

Prior to the stochastic programming implementation, we have tested the deterministic model with data supplied by SINTEF and that we have found through a search in the internet. Although data is associated with the reality and collected from reliable sources which represent other similar cases, it still implies much artificiality. As a research project to measure the economic feasibility of an imaginary future facility, assumptions were compulsory to be done in order to be able to test the model.

We would like to emphasize again that accuracy of the data is not critically important in our master thesis. Because, as expressed before, our ultimate aim is to build a relevant model which can provide us with doing analysis over possible conditions of the plant. Furthermore there was no possibility to obtain real and certain data.

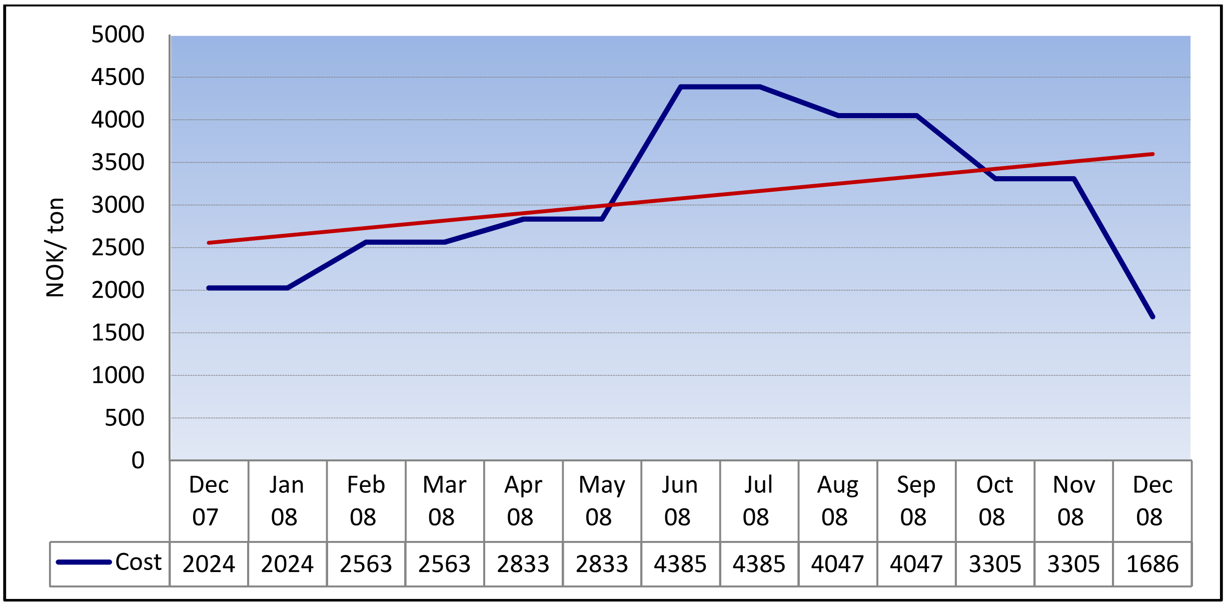
For instance the compositions of raw materials and Ferro-alloys as well as bounds for elements within products are obtained by a simple search in internet and we can’t assure that the data is totally reliable. Nevertheless, planner can install more accurate data by going through discussions with chemistry specialists or anyone else who will be in possession of chemical and metallurgical knowledge in the facility. Thus, we don’t consider it as an obstacle when testing our model and analyzing the results.

11.1 Data

We have implemented the model for two time periods since it is enough to test the model. Number of periods can be increased arbitrary. As stated before, carbon steel and stainless steel are the types that we have structured our data for. DRI and steel scrap are the raw materials handled while testing. Used Ferro-alloys are Ferro-Chromium, Ferro-Manganese, Ferro-Nickel and Ferro-Molybdenum. While testing the model we have also assumed that commodity set consists of only electricity. Natural gas can be added as per planner’s wish.

11.1.1 Costs

Historical data for DRI cost were provided by SINTEF. Chart and table below demonstrates the costs for DRI:



Graphic 11-1 Cost of DRI

Since the plant is estimated to be ready for production in 2010, it will be more realistic to estimate cost parameters for future. In order to generate numbers for the following years, we have performed a simple method based on differentiation between the values. We didn't see it appropriate to calculate the expected value of costs and use it as parameter. Because, as can be observed in Graphic 11-1 there is a trend with rising manner which is demonstrated by red line, nevertheless the cost decreased drastically between November and December 2008 due to extraordinary circumstance of economic recession. Thus, when applying the method, we neglected the last value.

The method is used to deal with the trend. Firstly we have found differentiation ratio between values by the following formula:

$$\Delta c_n = \frac{c_n - c_p}{c_n}$$

Where; c_n: cost at the present period

c_p : cost at the previous period

For example if we would like to find Δc of the third value, February 2008, than the formula is:

$$\Delta c_3 = \frac{c_3 - c_2}{c_3} \quad , \quad \Delta c_3 = \frac{2563 - 2024}{2563} = 0.211$$

Cost differentiation values are shown in the table below:

Date	Dec 07	Jan 08	Feb 08	Mar 08	Apr 08	May 08	Jun 08	Jul 08	Aug 08	Sep 08	Oct 08	Nov 08
Differentiation		0	0,211	0	0,095	0	0,354	0	-0,083	0	-0,224	0

Table 11-1 DRI cost differentiation between years

Afterwards we have calculated the expected value which is also the average value since all probabilities are assumed to be equal to each other.

Expected cost differentiation value (Δc_μ) = 0.032

Than we could generate the future costs by following formula:

$$c_f = c_n \left(1 + \Delta c_\mu\right)$$

Where; c_f: cost for the future period

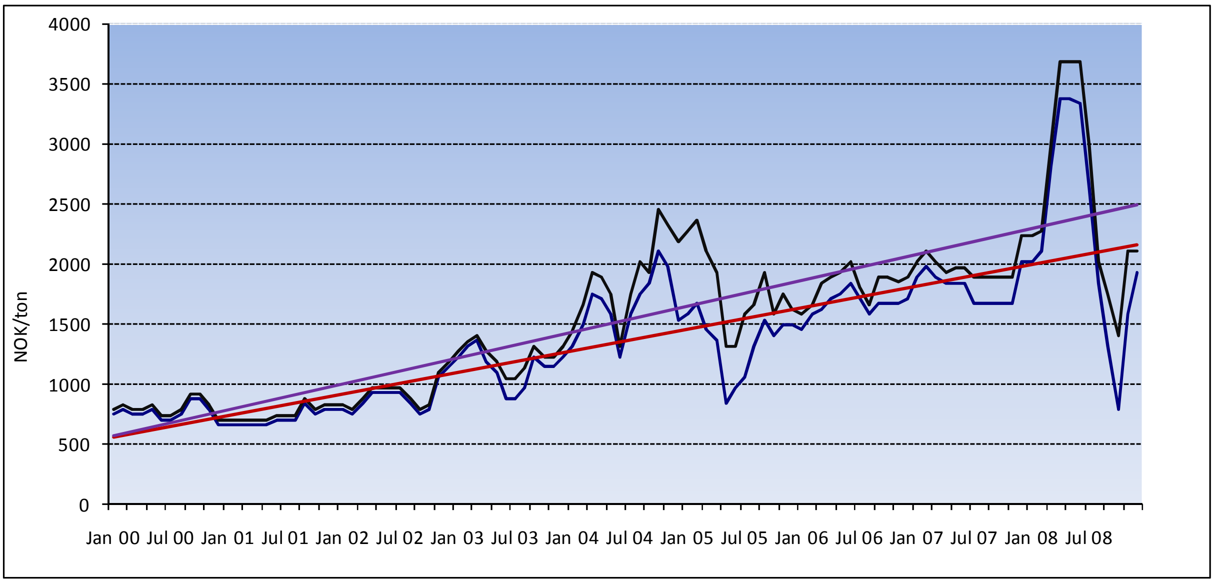
c_n: cost at the present period

Calculated cost for 2009: $\mathrm{c}_{2009} = 3305(1 + 0.032) = 3411$ NOK / ton

Calculated cost for 2010 period-1: $\mathrm{c}_{2010} = 3411(1 + 0.032) =$ **3520 NOK / ton**

Calculated cost for 2010 period-2: 3520 (1+0.032) = **3632 NOK / ton**

Historical data for steel scrap cost were provided by SINTEF as well. Graphic and table below shows the costs in the past for steel scrap:



Graphic 11-2 Scrap cost

The graphic includes maximum and minimum price for steel scrap as well as trend lines. It is obvious that there is also rising trend in steel scrap cost therefore we have applied the same method as in the previous section to generate parameters for steel scrap. Furthermore we assumed that both of the scrap types have the same cost.

When we calculate the expected value of the cost differentiations:

$\Delta c_{\mu} = 0.00059$

As a result we have found the following values for 2010:

Period	Cost (NOK/ton)
1	2018
2	2019

Table 11-2 Generated scrap costs

We have adjusted the cost parameters of Ferro-alloys by finding some relevant data through a search in the internet and generating close and realistic numbers. However, there is still some artificiality in data.

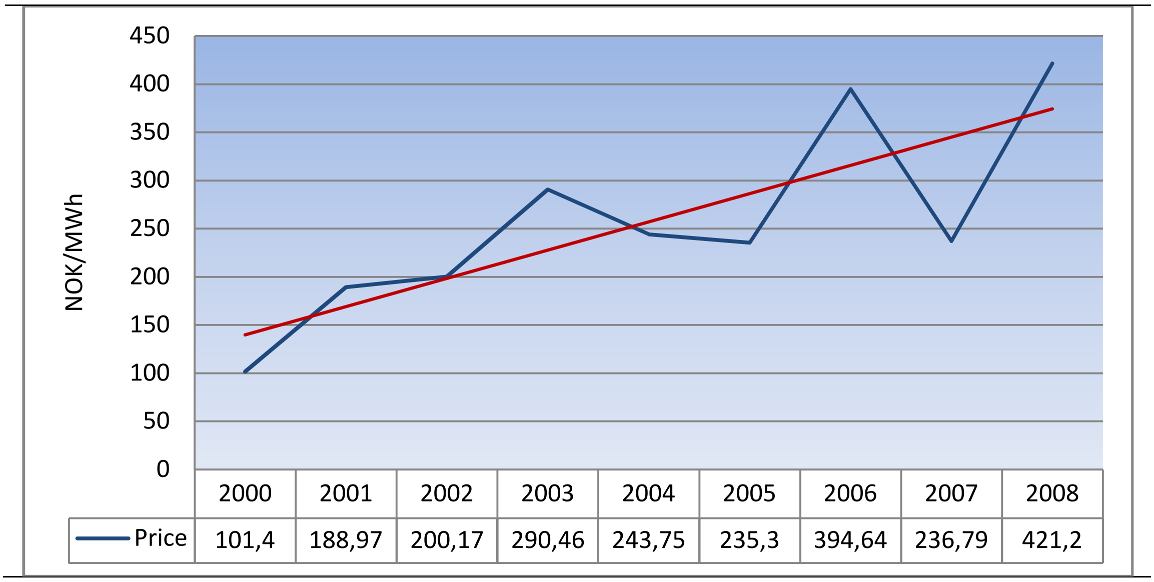
In spite of the fact that there are many Ferro-alloys are used in steel production we have just picked four types which take part in production of our representative steel types. As stated before, number and types of Ferro-alloys as well as produced steel types can be increased as per planner’s wish.

Following table shows the costs for used Ferro-alloys:

Ferro-Alloy	Price (NOK/ton) Period 1	Period 2
Ferro-Chromium	6120	6150
Ferro-Manganese	9200	9250
Ferro-Nickel	12200	12300
Ferro-Molybdenum	104745	104800

Table 11-3 Ferro-alloys costs

Electricity is the only commodity tested in the model. The historical cost data for it were provided by SINTEF. Graphic for the historical cost data is shown below:



Graphic 11-3 Historical cost data for electricity

Electricity prices also have a rising trend. Thus, we have applied same method to generate the parameters.

When we calculate the mean value for the price differentiations:

$\Delta c_{\mu} = 0.097203$

Then we can generate the future values as following:

$c_{2009} = 421.2(1 + 0.097203) = 462.1$

$\mathrm{c}_{2010-1} = 462.1(1 + 0.097203) = \mathbf{507\ NOK/mWh = 0.5\ NOK/kWh}$

$\mathrm{c}_{2010-2} = 507(1 + 0.097203) = \mathbf{556.3\ NOK/mWh = 0.5563\ NOK/kWh}$

We have set numbers for production and inventory holding cost of per ton steel artificially.

11.1.2 Demand

Demand data is taken from forecasting results which are obtained and explained in the Chapter 9. The estimated demand for 2010 is 1564.8 thousands of metric tons. We have divided this demand into two types of steel according to the general market information that more than 85% of the steel consumed in the market is Carbon Steel. Therefore we assumed that demands for Carbon Steel and Stainless Steel are 1330.08 and 234.72 thousands of metric tons respectively. Demand for the next period is adjusted totally artificial.

11.1.3 Composition

We have set the data for element percentages within raw materials according to information we have found through research in internet. We had to do some assumptions here as well. Created parameters for compositions are shown in the tables below.

		RAW MATERIALS		
		DRI	Scrap_1	Scrap_2
ELEMENTS	Iron	0.94	0.80	0.983
	Carbon	0.04	0.01	0.003
	Chromium	-	0.16	-
	Nickel	-	0.02	-
	Molybdenum	-	0.01	-
	Manganese	-	-	0.004
	Silicon	0.02	-	-

Table 11-4 Raw material composition

		FERROALLOYS			
		Ferro-Chromium	Ferro-Nickel	Ferro-Manganese	Ferro-Molybdenum
ELEMENTS	Iron	0.4	0.62	0.3	0.35
	Carbon	-	-	-	-
	Chromium	0.6	-	-	-
	Nickel	-	0.38	-	-
	Molybdenum	-	-	-	0.65
	Manganese	-	-	0.7	-
	Silicon	-	-	-	-

Table 11-5 Ferro-alloy composition

11.1.4 Bounds

Lower and upper bounds of element containment at the end of the processes were adjusted in compatible with the compositions of the representative products: martensitic stainless steel and low carbon steel. Bounds for the elements within the products were created by the following method. Firstly we have divided the elements into 2 groups as "iron" and "the other elements". According to the element containment ranges of the representative products, we have assigned the highest percentages for "the other elements" that product may contain. Hence, we have determined the upper bounds of "the other elements" for the second stage. Since the total amount of the element percentages has to be 100% we have subtracted the total percentage amount of "the other elements" from 100 and found the lowest percentage of Iron, namely lower bound of Iron. We have applied the same idea while determining the lower bounds of "the other elements" and the highest percentage of Iron.

For example; martensitic stainless steel contains chromium (10.5-18%), molybdenum (0.2-1%), nickel (0-2%), and carbon (about 0.1-1%). We have determined the upper bounds of the second stage by assigning the maximum percentages for "the other elements": Cr-18%, Ni-2%, Mo-1% and C-1% in case all these elements will have highest amounts. Then we have summarized these numbers and subtracted the total from 100%. Hence we have found the lower percentage of Iron which is 78%. Afterwards we have determined the lower bounds of "the other elements" by assigning the minimum percentages and calculated upper bound of the Iron by subtracting the total of the minimum percentages from 100%. We have applied this method for both representative products.

Determination of the first stage bounds can be explained by the following example. Martensitic stainless steel contains Carbon (C) element. Thus we have checked the C amount within each raw material. DRI contains 4% of C while Scrap_C and Scrap_S do 1% and 3% respectively. We have assigned 4% as upper bound of C at the first stage in case of that DRI might be the only raw material to be used at the first stage in the optimal solution. Thus, as DRI contains 4% of C and if we would assign a lower number then this number, our model would become infeasible in this situation. Lower bound of the element can be assigned as 0.

We have applied this method for each element except Iron and determined the upper bounds of "the other elements". Lower bound of Iron has been found by subtracting the total maximum percentages of "the other elements" from 100%.

Obliged DRI usage within used raw materials, loss percentages and scrap composition data are totally artificial.

11.2 Test and Analysis

We have implemented the model in AMPL mathematical programming language in order to test it. The program code is in Appendix F.

When we test the model with the parameters given above we have found the following results. Table below displays the optimal amount of raw materials to be purchased for each product in order to satisfy the demand at each period.

Period 1					Period 2				
Carbon Steel		Stainless Steel			Carbon Steel		Stainless Steel		
DRI	Scrap_CS	DRI	Scrap_SS	Fe-Cr	DRI	Scrap_CS	DRI	Scrap_SS	Fe-Cr
593793	890689	98686.8	148030	1764.49	803581	1205370	126133	189200	2255.22

Table 11-6 Optimal raw material and Ferro-alloy amounts to purchase

It can be analyzed from the table that we don't need to use any Ferro-alloy while producing the Carbon steel in this artificial case. The reason can be that home scrap contains enough amounts of elements such as Molybdenum and Chromium to satisfy the required amounts within the Carbon steel product. On the other hand, although Ferro-Chromium is expensive to purchase we have to buy the amount shown on table above in order to satisfy the required Chromium within the Stainless steel product.

Table below displays the optimal production amount of each product at each period.

Periods	Carbon Steel (ton)	Stainless Steel (ton)
1	1400080	260800
2	1894740	333333

Table 11-7 Optimal production amount for each product type

Production amounts exceed the demands for the products. There can be two reasons for this issue. Firstly production should be more then the demand due to the potential losses may occur during production process and secondly we have made it compulsory to have inventory for the last period since business has to continue even after our planning horizon. We can see the inventory levels at each period in the following table.

Period	Carbon Steel Inventory (ton)	Stainless Steel Inventory (ton)
0	0	0
1	0	0
2	300000	50000

Table 11-8 Inventory levels

Table below displays the required amount of electricity power to be able to produce the amounts demonstrated above.

Period	Power (kWh)
1	664354000
2	891228000

Table 11-9 Optimal amount of commodities to purchase

As explained before, we have assumed that 400 kWh electricity power is consumed to produce per ton of any product.

When we have such case with the stated parameters above and all the optimal results have taken into consideration, the minimum total cost for the planning horizon will be 13,175,200,000 NOK.

All in all we would like to emphasize again that the accuracy of the parameters and found results are not primarily important. Our main goal was to build a comprehensive model for the steel plant and to see if it works properly as it is supposed to.

11.3 Sensitivity Analysis

As stated before, this case involves much uncertainty. Thus, we think that it will be honest to do further analysis on our optimization model and test results with respect to the uncertainty. We have performed sensitivity analysis to see the effect of marginal increase or decrease in cost parameters, as it was also asked by SINTEF research team. Implementation of sensitivity analysis was again done in AMPL and CPLEX solver.

As an example, we would like to investigate and demonstrate the effect of an objective coefficient, raw materials cost, on purchasing decision. By this investigation, we will be able to understand between what cost ranges it is worthy to buy the particular raw material.

In order to do this we have added a code line into .run file which can be seen in Appendix F in the run file.

As a result of the implementation, the table below has been obtained.

		Carbon Steel (NOK/ton)			Stainless Steel (NOK/ton)		
		Lower	Actual Cost	Upper	Lower	Actual Cost	Upper
Period 1							
	DRI	3468.92	3520	10807.2	3462.79	3520	11682.2
	Scrap_CS	1983.95	2018	3200.57	-	2018	-
	Scrap_SS	-	2018	-	1979.86	2018	4268.15
Period 2							
	DRI	2220.5	3632	3683.08	301.914	3632	3689.21
	Scrap_CS	0	2019	2053.05	-	2019	-
	Scrap_SS	-	2019	-	3754.68	2019	2057.14

Table 11-10 Results of sensitivity analysis for raw material costs

The table displays the marginal cost ranges of raw materials purchased to produce each representative type at each period. The values under "lower" column indicate each raw material's lowest cost until that the purchasing decision doesn't change, namely below that cost it changes anymore. Likewise, the values under "upper" column show each raw material's highest cost until that the purchasing decision doesn't change, namely above that cost it changes. In other words, within these ranges the solution is optimal.

There is no correlation between decisions done for product types. If the cost is out of the ranges shown on the table for carbon steel production but within the ranges determined for stainless steel production, then purchasing decision changes just for the carbon steel type. However, if the cost is within ranges at one period but not at the other one, then purchasing decision changes for both periods since they are correlated.

To clarify our explanation we can give the following example. If DRI cost appears to be 3468.93 NOK/ton instead of the actual cost parameter which is 3520 NOK/ton, there won't be any change in purchased amount of DRI when producing carbon steel and stainless steel. Because, for both product, this cost value is over the lowest cost values of DRI at each period. However, let's assume that the DRI cost appeared to be 3463 NOK/ton. This value is lower than the lowest cost value found for DRI at first period in production of carbon steel but not in production of stainless steel. Therefore purchasing decision of raw materials will change for carbon steel but not stainless steel.

Amount of purchased raw materials with the actual cost parameter was demonstrated on table 11.6. We would also like to display the results when the cost will be 3463 NOK/ton in order to give the reader better understanding of our example.

Period 1					Period 2				
Carbon Steel		Stainless Steel			Carbon Steel		Stainless Steel		
DRI	Scrap_CS	DRI	Scrap_SS	Fe-Cr	DRI	Scrap_CS	DRI	Scrap_SS	Fe-Cr
1185320	1777980	98686.8	148030	1764.49	212056	318084	126133	189200	2255.22

Table 11-11 Optimal amount of raw materials to purchase with the new parameter

As seen on table above, the purchased amounts of raw materials have been changed in production of carbon steel but remained the same in production of stainless steel. Moreover the correlation of periods and raw material types can be observed. Sensitivity analysis can be applied by the same method to other cost parameters as well.

12 STOCHASTIC PROGRAMMING MODEL

Uncertainty is commonly faced in real life problems and most of the decisions are given under it. Our case contains uncertainty as well and effect of randomness has to be captured. In Section 11.3 we have performed sensitivity analysis by investigating effect of marginal increase or decrease in the raw materials cost. However, as explained in Section 6.3, sensitivity analysis can't be counted on as handling uncertainty since all decisions are still given under deterministic conditions. It is just about analyzing the effects of parametric changes.

We have developed an optimization model which deals with certain deterministic parameters, however, aspects such as price, losses and scrap can't be viewed as deterministic entities. Our optimization model has to carry out measurement and solution capability to the selling price, losses and scrap uncertainties. Thus, it is clear that stochastic programming should be implemented. Since the steel plant is in the establishment phase as whole cluster and this is a research project, neglecting the stochastic programming would be quite unrealistic. In addition, by stochastic programming, optimization model will approximate more to real life. Scenario tree generation method is applied to represent the randomness.

12.1 The Scenario Tree

Theoretical description of a scenario tree was explained in Section 6.1.2. Since the planning horizon divided into 2 periods to build a multi-period model; we had to generate a multi-period scenario tree which is more complicated because it implies that inter-temporal dependencies need to be considered. In other words, the decision for the next period is effected by the first period outcomes. The starting node is called root where the first decision is done and last nodes are called leaves where random variables for the second period are represented. Since there is no certain data exists that we should concern and adjust our model in accordance with its properties, in this stage, we didn't apply any scenario generation method and have assumed that each node branches off 4 child nodes symmetrically, for simplicity. This implies that there are four possible random numbers of each uncertain parameter. Moreover another assumption is that every node in the same stage has the same occurrence probability. Number of random variables can be increased; however, this assumption was done for simplicity reason because the size of the tree increases exponentially by the number of branches. In addition, while there is no binding data exists, it is not necessary to increase the size. We have named each node by a number in increasing order from the root. The created tree is below.

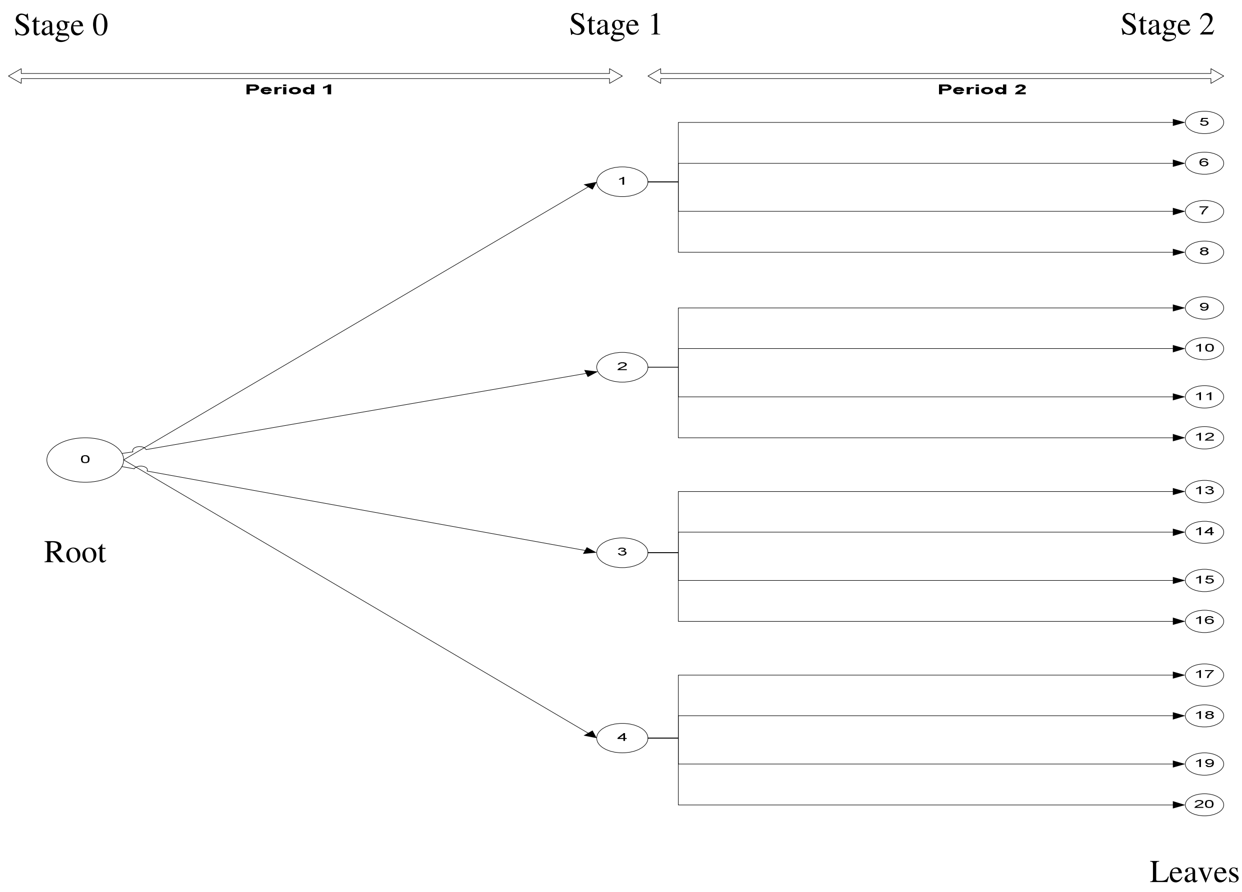


Figure 12-1 Generated scenario tree

As a first step we have determined the random variables. We had to decide what kind of constant and uncertain information we have at the time when giving the decision. Hence, we could determine which decision variables belong to which node with respect to dependency on stochastic parameters. For instance, will we know the price for the present period or it is not predictable and will become known clearly after the decisions are made? Is it possible to face with raw material cost changes after giving decision at the present time? Can we control the losses during the production? Likewise can we exactly determine if the home scrap will occur at the end of the production processes and the percentage of it?

Uncertain parameters that have to be handled are price, losses and home scrap as stated before. Therefore they will be placed in the tree beginning from the future nodes in order to represent their randomness. We have captured the uncertainty of demand by forecasting methods. Thus, demand will be considered as fixed parameter. Although there is unpredictability and randomness on some parameters in continuous time, we have to give decisions in discrete point of time. For example in our problem, we will have losses during the production period and the information will arrive us later, we have to take it into consideration when we make decision at the current time.

Amount of raw materials and Ferro-alloys to be purchased are the decisions that we have to give in the time being. Obtained amount of each element and produced amount of each product are dependent on loss parameter as well as home scrap parameter. Consequently we have placed these variables in the future nodes of each period namely where randomness were represented. We would like to clarify the “future nodes for a period” term as well. For example future nodes for period-1 are nodes 1, 2, 3 and 4. Future nodes for period-2 are nodes 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19 and 20.

We have assumed the stochastic property of parameters as discrete random variables by generating random values within intervals. Moreover there is no correlation between parameters. It could be between demand and price. However, our demand data represents Norway while price data is set globally. Therefore they are not correlated. Data generation will be clarified in the testing part.

All in all we have obtained the capability of giving decisions at the beginning of each period by taking into consideration the random variables that will occur during the period. Constant and stochastic variables as well as probability of each scenario have been illustrated on the tree below. Furthermore, what decisions have to be given at each event node is also demonstrated. The figure below will provide better understanding of what is explained above.

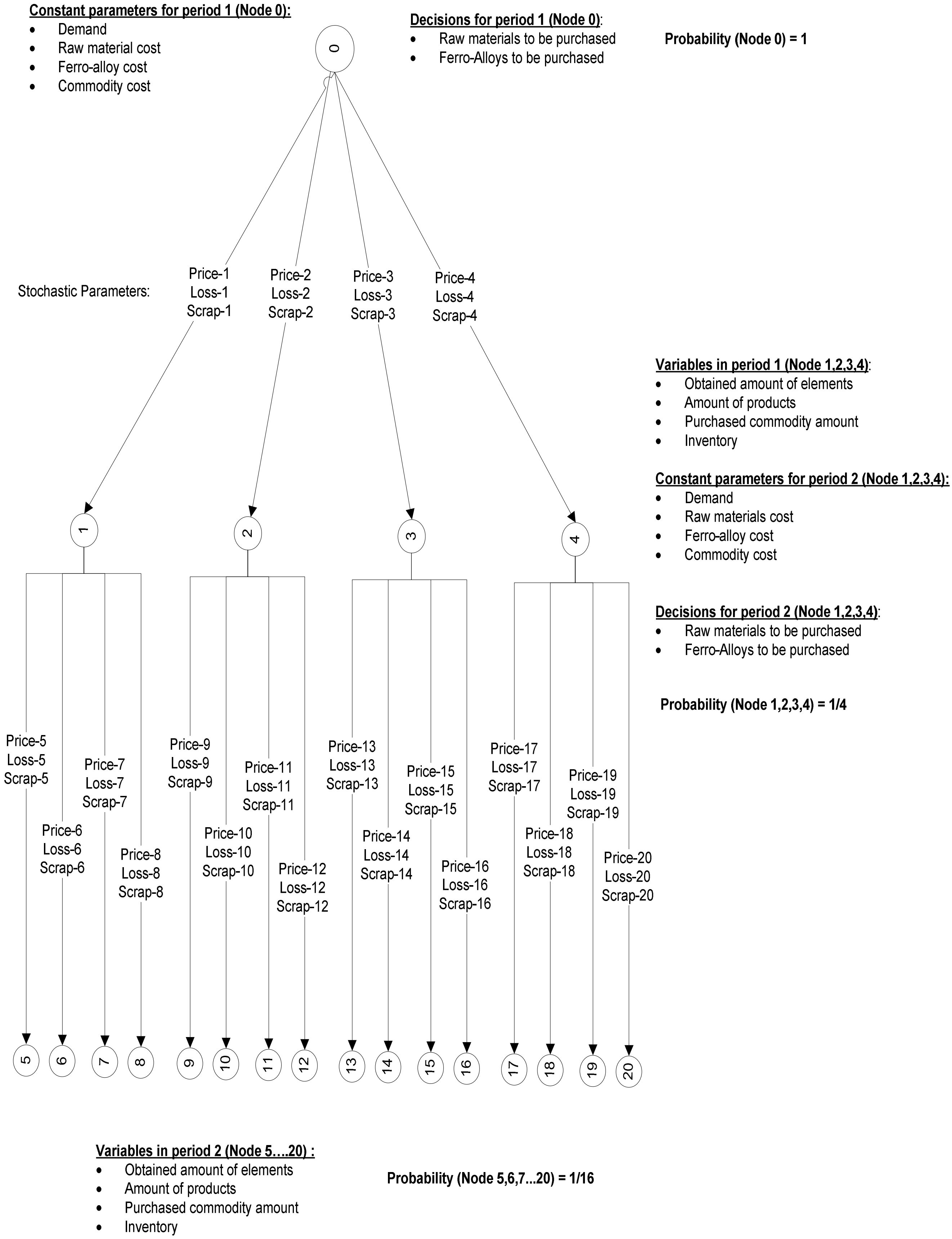


Figure 12-2 Demonstration of variables and parameters on the scenario tree

12.2 The Model

We have built a stochastic programming model based on the optimization model that is developed before. To do this, we have programmed the scenario tree and based our deterministic model on it. In other words we have programmed the model based on event nodes. However since price has uncertain random values, our objective has changed. Our new goal is the maximization of the total profit.

We will firstly express the notations used while generating the scenario tree. Then notations for sets, parameters and variables will be given. Finally we will describe the objective function along with all constraints.

<u>Scenario Tree</u>

(ln) : last node number

N : set of all nodes ($N = 0\ldots(ln)$)

r : root node number = 0

B : set of future nodes ($B = N / r$)

c : number of child nodes of per node.

q_b : predecessor node of the future node b.

v : first leaf node number.

L : set of leave nodes = ($v\ldots(ln)$)

t_n : probability of node n

<u>Sets</u>

J: set of raw materials.

F: set of Ferro-alloys.

E: set of chemical elements.

C: set of used commodities.

P: set of products.

<u>Parameters</u>

$c_{j,n}$: unit cost of the raw material j at each node except leaves. $j \in J, n \in N/L$

$f_{f,n}$: unit cost of the Ferro-alloy f at each node except leaves. $f \in F, n \in N/L$

$e_{c,n}$: unit cost of the commodity c at each node except leaves. $c \in C, n \in N/L$

i : unit inventory holding cost.

a_{je}^1 : percentage of the element e in the raw material j. $j \in J, e \in E$

a_{fe}^2 : percentage of the element e in the Ferro-alloy j. $f \in F, e \in E$

a_{pe}^3 : percentage of the element e in the scrap type p. $p \in P, e \in E$

p_{pb} : unit selling price of the product p at the future node b. $p \in P, b \in B$

k_c : coefficient that indicates the balance between production and used commodity c amount.

u : unit cost of production.

l_{eb}^1 : remained percentage of element e after random loss occurred in the first process at the future node b. $e \in E, b \in B$

l_{eb}^2 : remained percentage of element e after random loss occurred in the second process at The future node b. $e \in E, b \in B$

o_p : lower bound for product amount at the end of the first process. $p \in P$

d_{pn} : demand for the product p at each node except leaves. $p \in P, n \in N/L$

h_{ep}^1 : lower bound percentage for element e within product p at the end of the first process. $e \in E, p \in P$

g_{ep}^1 : upper bound percentage for element e within product p at the end of the first process. $e \in E, p \in P$

h_{ep}^2 : lower bound percentage for element e within product p at the end of the second process. $e \in E, p \in P$

g_{ep}^2 : upper bound in percentage for element e within product p at the end of the second process. $e \in E, p \in P$

m : obliged DRI usage percentage within total raw material usage.

s_{pb} : home scrap of product p at each the future node b. (In percentage of the product) $p \in P, b \in B$

Variables

x_{jpn}^1 : amount of the purchased raw material j for product p at each node except leaves ($j \in J, p \in P, n \in N/L$)

x_{fpn}^2 : amount of the purchased Ferro-alloy f for product p at each node except leaves ($f \in F, p \in P, n \in N/L$)

y_{epb}^1 : amount of the element e obtained at the end of first process at the future node b.

$e \in E, p \in P, b \in B$

y^2_{epb} : amount of the element e obtained at the end of second process at the future node b.

$e \in E, p \in P, b \in B$

y^3_{epb} : amount of the reduced element e within product p in the future node b.

$e \in E, p \in P, b \in B$

w^1_{pb} : amount of the product p at the end of the first process at the future node b.

$p \in P, b \in B$

w^2_{pb} : total amount of the product p at the end of the second process at the future node b.

$p \in P, b \in B$

z_{cb} : total amount of consumed commodity c at the future node b. $c \in C, b \in B$

I_{pn} : inventory level of product p at the node n. $p \in P, n \in N$

<u>Objective function</u>

The objective is to maximize the total profit.

Total profit = Total revenue – Total raw material cost – Total Ferro-alloy cost – Total used commodity cost – Total production cost – Total inventory holding cost

Maximize

$$\sum_{p \in P}\sum_{b \in B} t_b\, p_{pb}\, d_{p,(q_b)} - \sum_{j \in J}\sum_{p \in P}\sum_{b \in B} t_b\, c_{j,(q_b)}\, x^1_{j,p,(q_b)}$$
$$-\sum_{f \in F}\sum_{p \in P}\sum_{b \in B} t_b\, f_{f,(q_b)}\, x^2_{f,p,(q_b)} - \sum_{c \in C}\sum_{b \in B} t_b\, e_{c,(q_b)} z_{cb}$$
$$-\sum_{p \in P}\sum_{b \in B} t_b\, u\, w^2_{pb} - \sum_{p \in P}\sum_{n \in N} i\, I_{pn}$$

<u>Constraints</u>

$$\sum_{j \in J} l^1_{eb}\; x^1_{j,p,(q_b)}\, a^1_{je} + s_{pb}\, w^2_{pb}\, a^3_{pe} = y^1_{epb} \quad \forall\, e \in E, \forall p \in P, \forall b \in B \qquad (1)$$

Constraint (1) expresses that in the future node b, amount of each chemical element gained at the end of the first process, is obtained from raw materials with respect to the element percentage compositions and random loss. In addition to this, since home scrap is recycled and joins to the process in the beginning of the first process, chemical elements are also obtained and adhered to the product in the first process by home scrap recycling. Furthermore we should point out that the decision variable $x^1_{j,p,(q_b)}$(purchased amount of raw materials) is assigned to predecessor node of node b. This means that this decision will be given for the predecessor node of the future node b.

$$y^1_{epb} + \sum_{f\in F} l^2_{eb}\, x^2_{f,p,(q_b)}\, a^2_{fe} = y^2_{epb} \qquad \forall\, e \in E\,, \forall p \in P, \forall b\ \in B \qquad (2)$$

Constraint (2) expresses that in the future node b, the amount of each chemical element gained at the end of the second process, is the summation of coming element amount from the first process and gained from Ferro-alloy insertion in the second process. Here the decision variable $x^2_{f,p,(q_b)}$ (purchased amount of Ferro-alloys) is assigned to predecessor node of the future node b as well.

$$\sum_{e\in E} y^1_{epb} = w^1_{pb} \qquad \forall p \in P, \forall b \in B \qquad (3)$$

$$\sum_{e\in E} y^2_{epb} = w^2_{pb} \qquad \forall p \in P, \forall b \in B \qquad (4)$$

Constraints (3) states that in the future node b, the total amount of the product gained at the end of the first process, is the summation of all chemical elements obtained in this process. Constraint (4) states that in the future node b, total amount of the product gained at the last process, is the summation of all elements obtained from both processes.

$$w^1_{pb} \geq o_p \qquad \forall p \in P, \forall b \in B \qquad (5)$$

Constraint (5) expresses the lower bound for the weight of the product p at the end of the first process in the future node b.

$$I_{p,(q_b)} + (1 - s_{pb})w^2_{pb} = d_{p,q_b} + I_{pb} \qquad \forall p \in P,\ \forall b \in B \qquad (6)$$

Constraint (6) represents the inventory balance in the node b for each product. Inventory coming from the predecessor node plus produced amount of product at the present node b should be equal to demand of the predecessor node plus inventory of the present node b. Demand is assigned to predecessor node because it is a fixed parameter.

$$I_{p,0} = 0 \qquad \forall p \in P \qquad (7)$$

Constraint (7) denotes that the initial inventory level is 0 for each product.

$$I_{pl} = 0.2 * d_{p,q_l} \qquad \forall p \in P, \forall l \in L \qquad (8)$$

Constraint (8) denotes that there is an obliged amount of inventory at end of the second period for each product.

$$k_c \sum_{p \in P} w_{pb}^2 = z_{cb} \qquad \forall c \in C, \forall b \in B \qquad (9)$$

Constraint (9) states the required amount of commodity for total production of steel in the future node b.

$$h_{ep}^1 w_{pb}^1 \leq y_{epb}^1 \leq g_{pe}^1 \, w_{pb}^1 \qquad \forall\, p \in P, \forall b \in B\,, \forall e \in E \qquad (10)$$

$$h_{ep}^2 w_{pb}^2 \leq y_{epb}^2 \leq g_{pe}^2 \, w_{pb}^2 + y_{epb}^3 \qquad \forall\, p \in P, \forall b \in B, \forall e \in E \qquad (11)$$

Constraints (10) states the obliged upper and lower bound percentages for each element obtained at the end of the first process in the future node b. Similarly, Constraints (11) states the obliged upper and lower bound percentages for each element obtained at the end of the second process in the future node b. As in deterministic model, the help variable y_{ept}^3 is used to show the reduced amount of Carbon and Silicon. Because the Carbon and Silicon amounts within the raw material input is more than that within the output. Furthermore this variable makes the model feasible.

$$x_{(DRI),p,n}^1 \geq m \sum_{j \in J} x_{jpn}^1 \qquad \forall\, p \in P, \forall n \in N/L \qquad (12)$$

Whole stochastic model is demonstrated in Appendix G.

12.3 Test and Analysis

We have tested the model by programming and solving it in AMPL. The program code is placed as Appendix H. We have used the same representatives for product types, Ferro-alloy types and commodities as we did in testing the first optimization model in Chapter 11. Data for constant parameters are the same as the ones used in Section 11.1 while testing the optimization model. We have generated the uncertain parameters for future nodes randomly by following functions in AMPL run file which can be found in Appendix H. Moreover, there is no correlation exist between any data.

- Loss parameters in both processes: 0.9 + 0.1*Uniform01()

The formula provided us with generated random numbers for all future event nodes between 0.9 and 1. It means that remained percentage of element can be from 90% to 100%. Because we have assumed that loss occurrence may be up to 10 percent of the material.

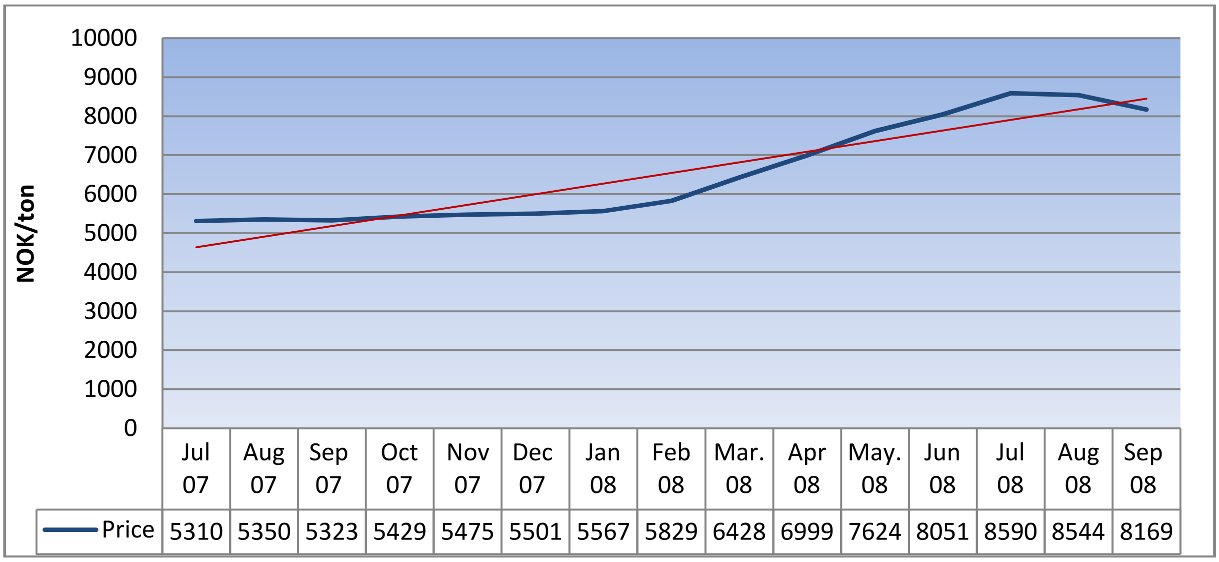
- Home scrap parameter: 0.1*Uniform01()

The formula provided us with generated random numbers between 0 and 0.1 for all future event nodes. Because we have assumed that scrap may occur up to 10 percent of the product.

- Price parameter: price[p, Pred[n]]*(0.8+0.6*Uniform01())

The formula generates price parameters for the future event nodes by multiplying the price of the predecessor node with a randomly generated number between 0.8 and 1.4. As explained before, price has a rising trend. However, we need to define the first price parameter which is in node 0. Then by using the formula above, we can generate random price parameters for the future nodes. To determine the first price value we have used the method that we have explained and used in Section 11.1.1.

Historical price data for several steel products are provided by SINTEF. The graphic and table below shows the prices for the selected Carbon Steel product.



Graphic 12-1 Historical price values for carbon steel

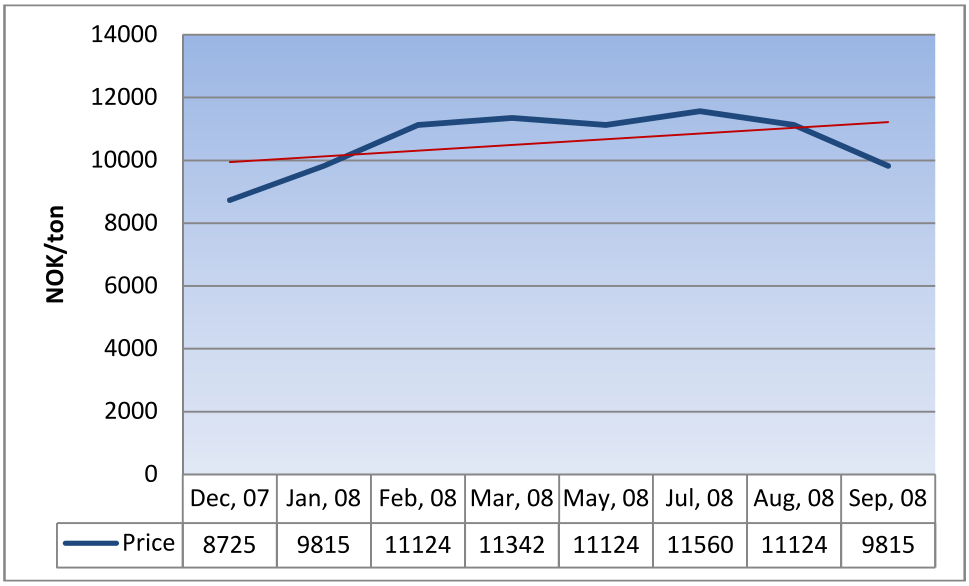
If we calculate the expected value of price differentiations, we find the following result:

$\Delta p_{\mu} = 0.0295$

Then; $p_{2009} = 8410$

$p_{2010-1} = \mathbf{8658\ NOK/ton}$

Following graph and table displays historical data for stainless steel.



Graphic 12-2 Historical price values for stainless steel

If we implement the same method then we find the following numbers:

$\Delta p_{\mu} = 0.0134$

$p_{2009} = 9946$

$p_{2010-1} = \mathbf{10079\ NOK/ton}$

$p_{2010-2} = \mathbf{10214\ NOK/ton}$

We would like to again lay stress on that accuracy of data and numbers found as a result are not crucially important since our aim is to see if the model works correctly.

When we run the program, we have obtained the following results. The table below displays the purchasing decision should be made at the beginning of each period by taking uncertainty into account.

	Period 1				
	Carbon Steel		Stainless Steel		
	DRI	Scrap_CS	DRI	Scrap_SS	Fe-Cr
Node 0	1122110	1683170	169496	254245	15018.9

	Period 2				
	Carbon Steel		Stainless Steel		
	DRI	Scrap_CS	DRI	Scrap_SS	Fe-Cr
Node 1	270041	1683170	49372.7	74059	2120.53
Node 2	312048	405061	53068.3	79602.4	1731.05
Node 3	235257	468071	44366.2	66549.4	2475.25
Node 4	226161	339242	43134.4	64701.6	1649.84

The solution given at root node (0) is the most important one. Because it is the first decision of the planning horizon and has to be given in accordance with uncertain parameters. The values given on table above for Node-0 are the optimal amount of raw materials and Ferro-alloys should be purchased in the beginning of the first period, considering the randomness. The values demonstrated under period-2 are the optimal purchased amount of raw materials and Ferro-alloys for each possible random scenario.

Variables representing the amount of product to be produced, amount of purchased commodities and inventory levels are all dependent on the solution found for purchasing decision of raw materials and Ferro-alloys along with the uncertain parameters. It means that purchasing of raw materials is the main decision that we give under uncertainty. We have also illustrated this issue in Figure 12-2. Moreover instead of results our major goal was to see the stochastic programming model's successfully working, as emphasized previous chapters. Thus, we think that it is not critically important to interpret the solutions for the other variables. However, the results for are shown in Appendix H by the solution file, if required.

Consequently, taking randomness into account, we have found the optimal purchasing decisions explained above and the maximized profit for the whole planning horizon under these circumstances will be 17,034,000,000 NOK.

13 CONCLUSIONS AND FUTURE WORKS

In the thesis, the handled research problem was optimizing operations of the future steel plant within the potential industrial cluster with respect to technical and operational characteristics. The problem was a part of the Gas-Mat which is large and very complicated research project and being carried out by SINTEF. It was difficult to define and delimitate the research problem space. High uncertainty levels in all fragments of the problem were the other major challenges that we confronted.

During the solution process of the problem, determined objectives were detailed literature research, mathematical formulation and description of the initial cluster code, demand forecasting, development of the optimization model and finally development of the stochastic programming model.

Firstly an extensive literature research was conducted to collect information and understand all aspects of the problem. In particular, in the beginning, knowledge about the potential actors of the industrial cluster was gained. Later on, steel characteristics and production were the focused areas to learn about these unfamiliar topics for us. In addition to literature research, theory research also helped us with estimating steel demand as well as developing optimization models both deterministic and stochastic. Especially the information gained through theoretical research on stochastic programming enabled us to implement stochastic programming to our optimization model. Both literature and theory review enlightened our way while trying to achieve the objectives that were determined initially.

After learning about the potential plants of the cluster, the initial code for whole industrial cluster were converted into mathematical programming model and described in details. So that, the cluster characteristics, all input and output flows and constraints were clarified. Then, reliable quantitative forecasting methods were implemented in order to estimate the demand for steel in Norway. This work was important in terms of providing reliable data for future demand which has to be satisfied as one of the goals of the Gas-Mat research project.

Afterwards, based on the gained information about steel production, the optimization model, which aimed on cost minimization, was developed for the steel plant of the cluster. Furthermore the optimization tool was created in AMPL language based on this model. The next step was to validate the model. Semi-artificial data were constructed in order to test the model. As a result, it worked efficiently and properly.

As a final step, in order to approximate the optimization model to real life and to gain the ability of making decisions under uncertainty, the problem were formulated as a stochastic program. Thus, the stochastic programming model was developed along with the stochastic programming tool in AMPL for optimization of operations in the steel plant, taking randomness into consideration. The objective of the model was maximizing the total profit.

Due to the time constraint, developed optimization models were not integrated into the cluster model in this thesis. Thus, the very first future work is the integration of the optimization models into the industrial cluster model. This work primarily needs further discussions with the SINTEF research team. Then improvements for the other plants should be performed with respect to their own technical and operational characteristics. In order to achieve this, detailed research should be conducted regarding the plants and data should be collected. Later on, applicability of improvements, which are done in the steel plant, to the other plants should be analyzed. Afterwards a comprehensive deterministic model for the whole industrial cluster can be developed. Finally, regarding uncertainties within each plant, a stochastic programming model can be developed by explained method in our thesis.

There is a minor further research can be conducted on lower and upper bound generation for the first and second processes of steelmaking. In the thesis, a simple method was implemented to generate the bounds and to test the model. However, more scientific research can be performed and methods can be formulated in order to assign feasible bounds for the processes with respect to the element composition percentages within raw materials and final product composition.

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15 APPENDICES

Appendix A: Initial Xpress Code Supplied By SINTEF

```
model 'WGMO_Operational'
uses 'mmxprs','mmodbc','mmsystem';

!Comments model version
!New formulation of the flow variables (general wrt commodity). KM 06.10.2008
!Also a general price parameter (distinction of prices in and out of market?)

!Added result report for income and costs. KM 25.11.2008

! ***************************
! * Setting some parameters *
! ***************************
	writeln("Setting some default parameters");
	setparam("xprs_verbose",true); ! optimize with a lot of output
	setparam("xprs_loadnames",true); ! load names into optimizer - output with
meaningful names
	setparam("xprs_maxiis",1); ! max 1 set of iis during getiis
	setparam("SQLdebug",true); ! for debugging the SQL queries
	! default length might be to short - 8 characters
	setparam("SQLcolsize",255); ! string size for transfer between Mosel and ODBC
! *********************************
! * END -  Setting some parameters *
! *********************************

forward procedure writeResultsProfits
forward procedure writeResultsFlow
forward procedure writeResultsPlants


!The sets in the model
declarations
	TIME:				set of integer	!The set of all time periods in the model
	PLANTS:					set of string	!The set of all plants in the
model
	COMMODITIES:	set of string		!The set of all commodities in the model
end-declarations

SQLconnect('DSN=Excel Files; DBQ=Gassmat_Input.xls')
SQLexecute("SELECT * FROM TimePeriods", TIME)
SQLexecute("SELECT * FROM PlantsInCluster", PLANTS)
SQLexecute("SELECT * FROM Commodities", COMMODITIES)

finalize(TIME)
finalize(PLANTS)
finalize(COMMODITIES)


!Parameters used in the cluster model
declarations
	!The prices of the commodities in the model
		PURCH_PRICE:		dynamic array(COMMODITIES,TIME) of real	!Price
paid for the commodities
		SALES_PRICE:		dynamic array(COMMODITIES,TIME) of real !Price
obtained for the commodities
	!The seperator
```

```
			WET_GAS:				real
		! fraction of the incoming gas that is wet gas
		!The ASU
			AIR_OXY:				real
		! fraction of the incoming gas that is oxygen
		!The POX
		!The methanol plant
		!The DRI plant
			UTILIZATION_H2:		real					!
percentage of h2 used in the dri production
			UTILIZATION_CO:				real
		! percentage of co used in the dri productin
		!The steel plant
			DRI_MIX_STEEL:		real					!
portion of dri in the steel production
		!The gas fired power plant
			EFFICIENCY_POWER:	real					!
power efficiency in the power plant

		!Network description  - we add flow variables and description of the links in the
network
			LINKS:					dynamic
array(PLANTS,PLANTS,COMMODITIES) of integer
			INV_COST_LINKS:				dynamic
array(PLANTS,PLANTS,COMMODITIES) of integer

		!Capacity limitations in the plants, per unit investment cost, operation cost
			CAP_MAX:				array(PLANTS) of real
			CAP_MIN:				array(PLANTS) of real
			INV_UNIT_COST:		array(PLANTS) of real
			INV_FIXED_COST:				array(PLANTS) of real
			PROD_MIN:				array(PLANTS) of real
			COMM_INV:				array(PLANTS) of string
		!Commmodities which determine the investment costs in the plants
			OPER_UNIT_COST:				array(PLANTS) of real
			OPER_FIXED_COST:	array(PLANTS) of real
			COMM_OPER:				array(PLANTS) of string
		!Commmodities which determine the operational costs in the plants
end-declarations

!Reading data from Excel
!Data for the Seperator
		WET_GAS:= SQLreadreal('SELECT Wet_gas FROM Seperator_Data')
!Data for the ASU
		AIR_OXY:= SQLreadreal('SELECT Oxygen_air FROM ASU_Data')
!Data for the POX
!Data for the DRI
		UTILIZATION_H2:= SQLreadreal('SELECT Utilization_H2 FROM DRI_Data')
		UTILIZATION_CO:= SQLreadreal('SELECT Utilization_CO FROM DRI_Data')
!Data for the Power Plant
		EFFICIENCY_POWER:= SQLreadreal('SELECT Efficiency FROM PP_Data')
!Data for the Steel plant
		DRI_MIX_STEEL:= SQLreadreal('SELECT DRI_fraction FROM Steel_Data')
!Data for the Methanol plant

!Links in the cluster
		SQLexecute("SELECT From_plant, To_plant, Commodity, Link FROM Links_Cluster",
LINKS)
		SQLexecute("SELECT From_plant, To_plant, Commodity, Inv_Cost FROM
Links_Cluster", INV_COST_LINKS)
```

```
!Prices of the commodities in the cluster
	SQLexecute("SELECT Commodities, Time, Purch_price FROM Price_Data",
PURCH_PRICE)
	SQLexecute("SELECT Commodities, Time, Sale_price FROM Price_Data",
SALES_PRICE)

!Investment input (capacity and costs)
	SQLexecute("SELECT Plant, Max_Capacity FROM Investment", CAP_MAX)
	SQLexecute("SELECT Plant, Min_Capacity FROM Investment", CAP_MIN)
	SQLexecute("SELECT Plant, Cost_Par FROM Investment", INV_UNIT_COST)
	SQLexecute("SELECT Plant, Fixed_Cost FROM Investment", INV_FIXED_COST)
	SQLexecute("SELECT Plant, Min_Production FROM Investment", PROD_MIN)
	SQLexecute("SELECT Plant, Det_Comm FROM Investment", COMM_INV)

!Operation input (fixed and variable costs)
	SQLexecute("SELECT Plant, Cost_Par FROM Operation", OPER_UNIT_COST)
	SQLexecute("SELECT Plant, Fixed_Cost FROM Operation", OPER_FIXED_COST)
	SQLexecute("SELECT Plant, Det_Comm FROM Operation", COMM_OPER)

SQLdisconnect

bigM:=9999999999999999


!Decision variables used in the cluster model
declarations
	!Network variables
		capacity:			array(PLANTS) of mpvar	!Installed capacity in
the different plants
		flow:				dynamic
array(PLANTS,PLANTS,COMMODITIES,TIME) of mpvar		!Flow commodities between the
plants (and the market)
		inv_plant:			dynamic array(PLANTS) of mpvar	!binary
variable to indicate whether or not the plant is installed
		inv_link:		dynamic array(PLANTS,PLANTS,COMMODITIES) of mpvar
!binary variable for investment in infrastructure

	!The seperator
		gas_sep:			array(TIME) of mpvar		! natural gas that
enters the seperator
		ch4_sep:			array(TIME) of mpvar		! dry gas from the
seperator
		lpg_sep:		array(TIME) of mpvar		! wet gas from the seperator
	!The ASU
		air_asu:		array(TIME) of mpvar		! air that enters the ASU
		o2_asu:			array(TIME) of mpvar		! oxygen from the ASU
		n2_asu:		array(TIME) of mpvar		! nitrogen from the ASU
		kwh_asu:			array(TIME) of mpvar		! total usage of kwh in
the ASU
	!The POX
		ch4_pox:			array(TIME) of mpvar		! methane that enters
the pox
		o2_pox:			array(TIME) of mpvar		! oxygen that enters the
pox
		h2_pox:			array(TIME) of mpvar		! hydrogen produced in
the pox
		co_pox:		array(TIME) of mpvar		! carbonmonoksid produced in
the pox
```

```
			syngas_pox:			array(TIME) of mpvar		! syngas produced in the pox
		!The methanol plant
			ch3oh_met:			array(TIME) of mpvar		! methanol produced in the plant
			h2_met:			array(TIME) of mpvar		! hydrogen that enters the plant
			co_met:		array(TIME) of mpvar		! carbonmonoksid that enters the plant
			syngas_met:		array(TIME) of mpvar		! syngas that enters the plant
		!The DRI plant
			fe_h2_dri:			array(TIME) of mpvar		! dri produced in the plant by using h2
			fe_co_dri:			array(TIME) of mpvar		! dri produced in the plant by using co
			ore_dri:		array(TIME) of mpvar		! ore input to the dri plant
			ore_h2_dri:			array(TIME) of mpvar		! iron ore that enters the plant (pellets) used by h2
			ore_co_dri:			array(TIME) of mpvar		! iron ore that enters the plant (pellets) used by co
			h2_dri:			array(TIME) of mpvar		! hydrogen that enters the plant
			co_dri:		array(TIME) of mpvar		! carbonmonoksid that enters the plant
			syngas_dri:		array(TIME) of mpvar		! syngas that enters the plant
			h20_dri:		array(TIME) of mpvar		! h20 produced in the dri
			co2_dri:		array(TIME) of mpvar		! co2 produced in the dri
			kwh_dri:		array(TIME) of mpvar		! total usage of kwh in the dri plant
		!The steel plant
			prod_steel:			array(TIME) of mpvar		! steel production in the plant
			dri_steel:			array(TIME) of mpvar		! dri used in the steel production
			scrap_steel:		array(TIME) of mpvar		! scrap used in the steel production
			kwh_steel:			array(TIME) of mpvar		! power used in the steel production
		!The gas fired power plant
			prod_kwh:			array(TIME) of mpvar		! total production of kwh in the power plant (adjusted for efficiency)
			o2_power:			array(TIME) of mpvar		! input of oxygen to the power plant
			co2_power:			array(TIME) of mpvar		! output of co2 from the power plant
			kwh_power:			array(TIME) of mpvar		! output of kwh from the power plant
			prod_ch4_kwh:	array(TIME) of mpvar		! power production in the plant
			prod_h2_kwh:	array(TIME) of mpvar		! power production in the plant
			prod_co_kwh:	array(TIME) of mpvar		! power production in the plant

			ch4_power:			array(TIME) of mpvar		! methane used in the power production
			h2_power:		array(TIME) of mpvar		! hydrogen used in the power production
			co_power:			array(TIME) of mpvar		! co used in the power production
			syngas_power:	array(TIME) of mpvar		! syngas used in the power production
```

```
                    o2_ch4_power:   array(TIME) of mpvar        ! o2 used in the power
production
                    o2_h2_power:    array(TIME) of mpvar        ! o2 used in the power
production
                    o2_co_power:    array(TIME) of mpvar        ! o2 used in the power
production
                    h20_ch4_power:  array(TIME) of mpvar        ! h20 produced in the power
production
                    h20_h2_power:   array(TIME) of mpvar        ! h20 produced in the power
production
                    co2_ch4_power:  array(TIME) of mpvar        ! co2 produced in the power
production
                    co2_co_power:   array(TIME) of mpvar        ! co2 produced in the power
production
          !The carbon black plant
                    prod_cb_c:              array(TIME) of mpvar        ! total production of
carbon in the carbon black plant
                    kwh_cb:                 array(TIME) of mpvar        ! total usage of kwh in
the carbon black plant
                    ch4_cb:                 array(TIME) of mpvar        ! usage of methane in
the carbon black plant
                    prod_cb_h2:             array(TIME) of mpvar        ! production of
hydrogen in the carbon black plant
end-declarations

forall(i in PLANTS, j in PLANTS, c in COMMODITIES, t in TIME) do
          if LINKS(i,j,c)=1 then
                    create(flow(i,j,c,t))
          end-if
end-do

forall(i in PLANTS, j in PLANTS, c in COMMODITIES) do
          if LINKS(i,j,c)=1 then
                    create(inv_link(i,j,c))
                    inv_link(i,j,c) is_binary
          end-if
end-do

forall(i in PLANTS-{'MARKET'}) do
          create(inv_plant(i))
          inv_plant(i) is_binary
end-do


!*****************************************************************************************************************
!*********************************
!*** INVESTMENT COSTS**** ********
!*********************************
!In this section, the formulation for the capacity investments are given as well as the
associated costs

!Capacity investments
forall(p in PLANTS) do
          MAX_CAPACITY(p):= capacity(p) <= CAP_MAX(p)
          MIN_CAPACITY(p):= capacity(p) >= CAP_MIN(p)

          PLANT_INVESTMENT(p):= capacity(p) <= bigM * inv_plant(p)
end-do

forall(i in PLANTS, j in PLANTS, c in COMMODITIES, t in TIME) do
```

```
!		LINK_INVESTMENT2(i,j,c):= flow(i,j,c,t) <= bigM * inv_plant(i)
!		LINK_INVESTMENT3(i,j,c):= flow(i,j,c,t) <= bigM * inv_plant(j)
		LINK_INVESTMENT1(i,j,c):= flow(i,j,c,t) <= bigM * inv_link(i,j,c)
end-do



forall(p in PLANTS) do
		INVESTMENT_COST_PLANT(p):= inv_plant(p) * INV_FIXED_COST(p) + capacity(p) *
INV_UNIT_COST(p)
end-do

INVESTMENT_COST:= sum(p in PLANTS) INVESTMENT_COST_PLANT(p) +
						sum(i in PLANTS, j in PLANTS, c in
COMMODITIES) INV_COST_LINKS(i,j,c) * inv_link(i,j,c)

!***************************************
!*** END - INVESTMENT COSTS**** ********
!***************************************


!*************************************************************************************************************
!*********************************
!*** OPERATION COSTS**** ********
!*********************************
!In this section, the formulation of the operational costs are given

forall(p in PLANTS) do
		forall (t in TIME)do
			OPERATION_COST_PLANT(p,t):=sum(i in PLANTS, c in COMMODITIES | c =
COMM_OPER(p)) (flow(i,p,c,t) + flow(p,i,c,t)) * OPER_UNIT_COST(p)
		end-do
end-do

OPERATION_COST:= sum(p in PLANTS, t in TIME) ( inv_plant(p) * OPER_FIXED_COST(p) ) +
sum(p in PLANTS, t in TIME) OPERATION_COST_PLANT(p,t)

!***************************************
!*** END - OPERATION COSTS**** ********
!***************************************


!*************************************************************************************************************
!*********************************
!*** INPUT TO THE CLUSTER ********
!*********************************
!Description:	External input to the cluster. Also connection to the different parts in the
cluster is given:
		!The resource is on the left hand side in the constraints, while the right hand side
		!gives the usage in the different plants

COST_OF_INPUT:= sum(c in COMMODITIES, t in TIME) PURCH_PRICE(c,t) * sum(p in PLANTS)
flow('MARKET',p,c,t)

forall(t in TIME) do
		COST_INPUT_PERIOD(t):= sum(c in COMMODITIES) PURCH_PRICE(c,t) * sum(p in
PLANTS) flow('MARKET',p,c,t)
end-do
!***************************************
!*** END - INPUT TO THE CLUSTER ********
```

```
!****************************************

!*************************************************************************************************************
!**********************
!*** SEPERATOR ********
!**********************
!Description:	Seperates dry and wet gas from the incoming natural gas
		!The left hand side gives the incoming resource, and the right hand side the
usage in the plant

!Input balance
forall(t in TIME) do
	IB_SEP(t):= sum(p in PLANTS) flow(p,'SEPERATOR','Natural gas',t) = gas_sep(t)
end-do

!Mass balance
forall(t in TIME) do
	MB_SEP1(t):= lpg_sep(t) = WET_GAS * gas_sep(t)
	MB_SEP2(t):= ch4_sep(t) = (1 - WET_GAS) * gas_sep(t)
end-do

!Production limits
forall(t in TIME) do
	PROD_SEP_CONSTR1(t):= gas_sep(t) <= capacity('SEPERATOR')
	PROD_SEP_CONSTR2(t):= gas_sep(t) >= PROD_MIN('SEPERATOR')
end-do

!Output balance
forall(t in TIME) do
	OB_SEP1(t):= lpg_sep(t) = sum(i in PLANTS) flow('SEPERATOR',i,'LPG',t)
	OB_SEP2(t):= ch4_sep(t) = sum(i in PLANTS) flow('SEPERATOR',i,'CH4',t)
end-do
!****************************
!***   END - SEPERATOR    ***
!****************************


!*************************************************************************************************************
!**********************
!***   ASU        ***
!**********************
!Description:	Seperate the oxygen from the air

!Input balance
forall(t in TIME) do
	IB_ASU1(t):= air_asu(t) = sum(p in PLANTS) flow(p,'ASU','Air',t)
	IB_ASU2(t):= kwh_asu(t) = sum(p in PLANTS) flow(p,'ASU','kWh',t)
end-do

!Mass balance
forall(t in TIME) do
	MB_ASU1(t):= (1/32) * o2_asu(t) = (1/144) * air_asu(t)
	MB_ASU2(t):= (1/112) * n2_asu(t) = (1/144) * air_asu(t)
	MB_ASU3(t):= o2_asu(t) = (1/770) * kwh_asu(t)				!assumes 770
kwh per tonn o2

end-do

!Production limits
forall(t in TIME) do
```

```
		PROD_ASU_CONSTR1(t):= o2_asu(t) <= capacity('ASU')
		PROD_ASU_CONSTR2(t):= o2_asu(t) >= PROD_MIN('ASU')
end-do

!Output balance
forall(t in TIME) do
		OB_ASU1(t):= o2_asu(t) = sum(i in PLANTS) flow('ASU',i,'O2',t)
end-do
!****************************
!***   END - ASU        ***
!****************************


!****************************************************************************************************
!**********************
!***   POX        ***
!**********************
!Description:	Creates syntheses gas from methane

!Input balance
forall(t in TIME) do
		IB_POX1(t):= ch4_pox(t) = sum(i in PLANTS) flow(i,'POX','CH4',t)
		IB_POX2(t):= o2_pox(t) = sum(i in PLANTS) flow(i,'POX','O2',t)
end-do

!Mass balance
forall(t in TIME) do
		MB_POX1(t):= (1/8) * h2_pox(t) = (1/32) * ch4_pox(t)
		MB_POX2(t):= (1/8) * h2_pox(t) = (1/32) * o2_pox(t)
		MB_POX3(t):= (1/56) * co_pox(t) = (1/32) * ch4_pox(t)
		MB_POX4(t):= (1/56) * co_pox(t) = (1/32) * o2_pox(t)
		MB_POX5(t):= syngas_pox(t) = h2_pox(t) + co_pox(t)
end-do

!Production limits
forall(t in TIME) do
		PROD_POX_CONSTR1(t):= h2_pox(t)+ co_pox(t)<= capacity('POX')
		PROD_POX_CONSTR2(t):= h2_pox(t)+ co_pox(t)>= PROD_MIN('POX')
end-do

!Output balance
forall(t in TIME) do
		!OB_POX1(t):= h2_pox(t) = sum(i in PLANTS) flow('POX',i,'H2',t)
		!OB_POX2(t):= co_pox(t) = sum(i in PLANTS) flow('POX',i,'CO',t)
		OB_POX1(t):= syngas_pox(t) = sum(i in PLANTS) flow('POX',i,'Syngas',t)
end-do
!****************************
!***   END - POX        ***
!****************************

!****************************************************************************************************
!**********************
!***   METHANOL    ***
!**********************
!Description:	produces methanol from syntheses gas

!Input balance
forall(t in TIME) do
		!IB_MET1(t):= h2_met(t) = sum(i in PLANTS) flow(i,'METHANOL','H2',t)
		!IB_MET2(t):= co_met(t) = sum(i in PLANTS) flow(i,'METHANOL','CO',t)
```

```
        IB_MET1(t):= syngas_met(t) = sum(i in PLANTS) flow(i,'METHANOL','Syngas',t)
        IB_MET2(t):= h2_met(t) = (1/8) * syngas_met(t) + sum(i in PLANTS)
flow(i,'METHANOL','H2',t)
        IB_MET3(t):= co_met(t) = (7/8) * syngas_met(t) + sum(i in PLANTS)
flow(i,'METHANOL','CO',t)
end-do

!Mass balance
forall(t in TIME) do
        MB_MET1(t):= (1/32) * ch3oh_met(t) = (1/4) * h2_met(t)
        MB_MET2(t):= (1/32) * ch3oh_met(t) = (1/28) * co_met(t)
end-do

!Production limits
forall(t in TIME) do
        PROD_MET_CONSTR1(t):= ch3oh_met(t) <= capacity('METHANOL')
        PROD_MET_CONSTR2(t):= ch3oh_met(t) >= PROD_MIN('METHANOL')
end-do

!Output balance
forall(t in TIME) do
        OB_MET(t):= ch3oh_met(t) = sum(i in PLANTS) flow('METHANOL',i,'Methanol',t)
end-do
!****************************
!***   END - METHANOL    ***
!****************************


!********************************************************************************************************************
!**********************
!***   DRI PLANT   ***
!**********************
!Description:      The DRI plant produces DRI from iron ore (pellets) by using reducing gas

!Input balance
forall(t in TIME) do
        !IB_DRI1(t):= h2_dri(t) = sum(i in PLANTS) flow(i,'DRI','H2',t)
        !IB_DRI2(t):= co_dri(t) = sum(i in PLANTS) flow(i,'DRI','CO',t)
        IB_DRI3(t):= ore_dri(t) = sum(i in PLANTS) flow(i,'DRI','Iron Ore',t)          !Input from an
external market
        IB_DRI4(t):= ore_dri(t) = ore_h2_dri(t) + ore_co_dri(t)
        !Balance between ore used by H2 and CO
        IB_DRI5(t):= syngas_dri(t) = sum(i in PLANTS) flow(i,'DRI','Syngas',t)
        IB_DRI6(t):= h2_dri(t) = (1/8) * syngas_dri(t) + sum(i in PLANTS) flow(i,'DRI','H2',t)
        IB_DRI7(t):= co_dri(t) = (7/8) * syngas_dri(t) + sum(i in PLANTS) flow(i,'DRI','CO',t)
        IB_DRI8(t):= kwh_dri(t) = sum(i in PLANTS) flow(i,'DRI','kWh',t)

end-do

!Mass balance
forall(t in TIME) do
        MB_DRI1(t):= (1/112) * fe_h2_dri(t) = (1/160) * ore_h2_dri(t)
        MB_DRI2(t):= (1/112) * fe_h2_dri(t) = (1/6) * h2_dri(t) * UTILIZATION_H2
        MB_DRI3(t):= (1/112) * fe_h2_dri(t) = (1/54) * h20_dri(t)

        MB_DRI4(t):= (1/112) * fe_co_dri(t) = (1/160) * ore_co_dri(t)
        MB_DRI5(t):= (1/112) * fe_co_dri(t) = (1/84) * co_dri(t) * UTILIZATION_CO
        MB_DRI6(t):= (1/112) * fe_co_dri(t) = (1/132) * co2_dri(t)
```

```
        MB_DRI7(t):= fe_h2_dri(t) + fe_co_dri(t) = (1/95) * kwh_dri(t)
        !assumes 95 kwh per tonn dri
end-do

!Production limits
forall(t in TIME) do
        FE_DRI_CONSTR1(t):= fe_h2_dri(t) + fe_co_dri(t) <= capacity('DRI')
        FE_DRI_CONSTR2(t):= fe_h2_dri(t) + fe_co_dri(t) >= PROD_MIN('DRI')
end-do

!Output balance
forall(t in TIME) do
        OB_DRI1(t):= fe_h2_dri(t) + fe_co_dri(t) = sum(j in PLANTS) flow('DRI',j,'DRI',t)
        OB_DRI2(t):= (1-UTILIZATION_H2) * h2_dri(t) = sum(j in PLANTS) flow('DRI',j,'H2',t)
        OB_DRI3(t):= (1-UTILIZATION_CO) * co_dri(t) = sum(j in PLANTS) flow('DRI',j,'CO',t)
        OB_DRI4(t):= co2_dri(t) = sum(j in PLANTS) flow('DRI',j,'CO2',t)
end-do
!****************************
!***   END - DRI PLANT   ***
!****************************




!***********************
!***   STEEL PLANT   ***
!***********************
!Description:      use the DRI to produce steel
        !steel scrap comes from an external market
        !steel is sent to a market place

!Input balance
forall(t in TIME) do
        IB_STEEL1(t):= kwh_steel(t) = sum(i in PLANTS) flow(i,'STEEL','kWh',t)
        IB_STEEL2(t):= scrap_steel(t) = sum(i in PLANTS) flow(i,'STEEL','Steel scrap',t)
        IB_STEEL3(t):= dri_steel(t) = sum(i in PLANTS) flow(i,'STEEL','DRI',t)

end-do

!Mass balance
forall(t in TIME) do
        MB_STEEL1(t):= prod_steel(t) = (1/400) * kwh_steel(t)                    !assumes 400
kwh per tonn steel
        MB_STEEL2(t):= prod_steel(t) = dri_steel(t) + scrap_steel(t)
end-do

!Production limits
forall(t in TIME) do
        PROD_STEEL_CONSTR1(t):= prod_steel(t) <= capacity('STEEL')
        PROD_STEEL_CONSTR2(t):= prod_steel(t) >= PROD_MIN('STEEL')
end-do

!DRI content
        !fraction of input that should be dri: DRI_MIX_STEEL = dri / (dri + scrap)
forall(t in TIME) do
        DR_STEEL(t):= dri_steel(t) = DRI_MIX_STEEL * (dri_steel(t) + scrap_steel(t))
end-do

!Output balance
forall(t in TIME) do
```

```
		OB_STEEL(t):= prod_steel(t) = sum(j in PLANTS) flow('STEEL',j,'Steel',t)
end-do
!*****************************
!***   END - STEEL PLANT   ***
!*****************************

!prod_steel(1) = (1/400) * kwh_steel(1)

!*********************************
!***   GAS FIRED POWER PLANT   ***
!*********************************
!Description:	produce power from natural gas (methane, hydrogen and co)

!Input balance
forall(t in TIME) do
		IB_PP1(t):= o2_ch4_power(t) + o2_h2_power(t) + o2_co_power(t) = sum(i in PLANTS)
flow(i,'POWER','O2',t)
		IB_PP2(t):= ch4_power(t) = sum(i in PLANTS) flow(i,'POWER','CH4',t)
		!IB_PP3(t):= h2_power(t) = sum(i in PLANTS) flow(i,'POWER','H2',t)
		!IB_PP4(t):= co_power(t) = sum(i in PLANTS) flow(i,'POWER','CO',t)
		IB_PP3(t):= syngas_power(t) = sum(i in PLANTS) flow(i,'POWER','Syngas',t)
		IB_PP4(t):= h2_power(t) = (1/8) * syngas_power(t) + sum(i in PLANTS)
flow(i,'POWER','H2',t)
		IB_PP5(t):= co_power(t) = (7/8) * syngas_power(t) + sum(i in PLANTS)
flow(i,'POWER','CO',t)
end-do

!Mass balance
forall(t in TIME) do
		MB_POWER_CH4_1(t):= (1/0.24448) * prod_ch4_kwh(t) = (1/16) * ch4_power(t) *
1000000
		MB_POWER_CH4_2(t):= (1/0.24448) * prod_ch4_kwh(t) = (1/64) * o2_ch4_power(t) *
1000000
		MB_POWER_CH4_3(t):= (1/44) * co2_ch4_power(t) = (1/16) * ch4_power(t)
		MB_POWER_CH4_4(t):= (1/36) * h20_ch4_power(t) = (1/16) * ch4_power(t)

		MB_POWER_H2_1(t):= (1/0.158888) * prod_h2_kwh(t) = (1/4) * h2_power(t) * 1000000
		MB_POWER_H2_2(t):= (1/0.158888) * prod_h2_kwh(t) = (1/32) * o2_h2_power(t) *
1000000
		MB_POWER_H2_3(t):= (1/36) * h20_h2_power(t) = (1/4) * h2_power(t)

		MB_POWER_CO_1(t):= (1/0.1555688) * prod_co_kwh(t) = (1/56) * co_power(t) * 1000000
		MB_POWER_CO_2(t):= (1/0.1555688) * prod_co_kwh(t) = (1/32) * o2_co_power(t) *
1000000
		MB_POWER_CO_3(t):= (1/88) * co2_co_power(t) = (1/56) * co_power(t)
end-do

!Energy efficiency and total production
forall(t in TIME) do
		EE_PP(t):= prod_kwh(t) = EFFICIENCY_POWER * (prod_ch4_kwh(t) + prod_h2_kwh(t)
+ prod_co_kwh(t))
end-do

!Production limits
forall(t in TIME) do
		PROD_POWER_CONSTR1(t):= prod_kwh(t) <= capacity('POWER')
		PROD_POWER_CONSTR2(t):= prod_kwh(t) >= PROD_MIN('POWER')
end-do

!Output balance
```

```
forall(t in TIME) do
	OB_PP1(t):= prod_kwh(t) = sum(j in PLANTS) flow('POWER',j,'kWh',t)
	OB_PP2(t):= co2_ch4_power(t) + co2_co_power(t) = sum(j in PLANTS)
flow('POWER',j,'CO2',t)
end-do
!***************************************
!***   END - GAS FIRED POWER PLANT   ***
!***************************************


!*********************************
!***   CARBON BLACK          ***
!*********************************
!Description:	produce carbon (and hydrogen) from methane

!Input balance
forall(t in TIME) do
	IB_CB1(t):= ch4_cb(t) = sum(i in PLANTS) flow(i,'CARBON BLACK','CH4',t)
	IB_CB2(t):= kwh_cb(t) = sum(i in PLANTS) flow(i,'CARBON BLACK','kWh',t)
end-do

!Mass balance
forall(t in TIME) do
	MB_CB1(t):= prod_cb_c(t) = (12/16) * ch4_cb(t)
	MB_CB2(t):= prod_cb_h2(t) = (4/16) * ch4_cb(t)
	MB_CB3(t):= prod_cb_c(t) = (1/1700) * kwh_cb(t)			!assumes
1700 kwh per tonn carbon black

end-do

!Production limits
forall(t in TIME) do
	PROD_CB_CONSTR1(t):= prod_cb_c(t) <= capacity('CARBON BLACK')
	PROD_CB_CONSTR2(t):= prod_cb_c(t) >= PROD_MIN('CARBON BLACK')
end-do

!Output balance
forall(t in TIME) do
	OB_CB1(t):= prod_cb_c(t) = sum(j in PLANTS) flow('CARBON BLACK',j,'Carbon',t)
	OB_CB2(t):= prod_cb_h2(t) = sum(j in PLANTS) flow('CARBON BLACK',j,'H2',t)
end-do
!***************************************
!***   END - CARBON BLACK          ***
!***************************************


!**************************************************************************************************************
!*********************************
!*** OUTPUT FROM THE CLUSTER *****
!*********************************
!Description:	Output from the cluster that can go to different markets
	!The product is on the left hand side in the constraints, while the right hand side
	!gives the production in the different plants
REVENUE_FROM_OUTPUT:= sum(c in COMMODITIES, t in TIME) SALES_PRICE(c,t) * sum(p in
PLANTS) flow(p,'MARKET',c,t)
```

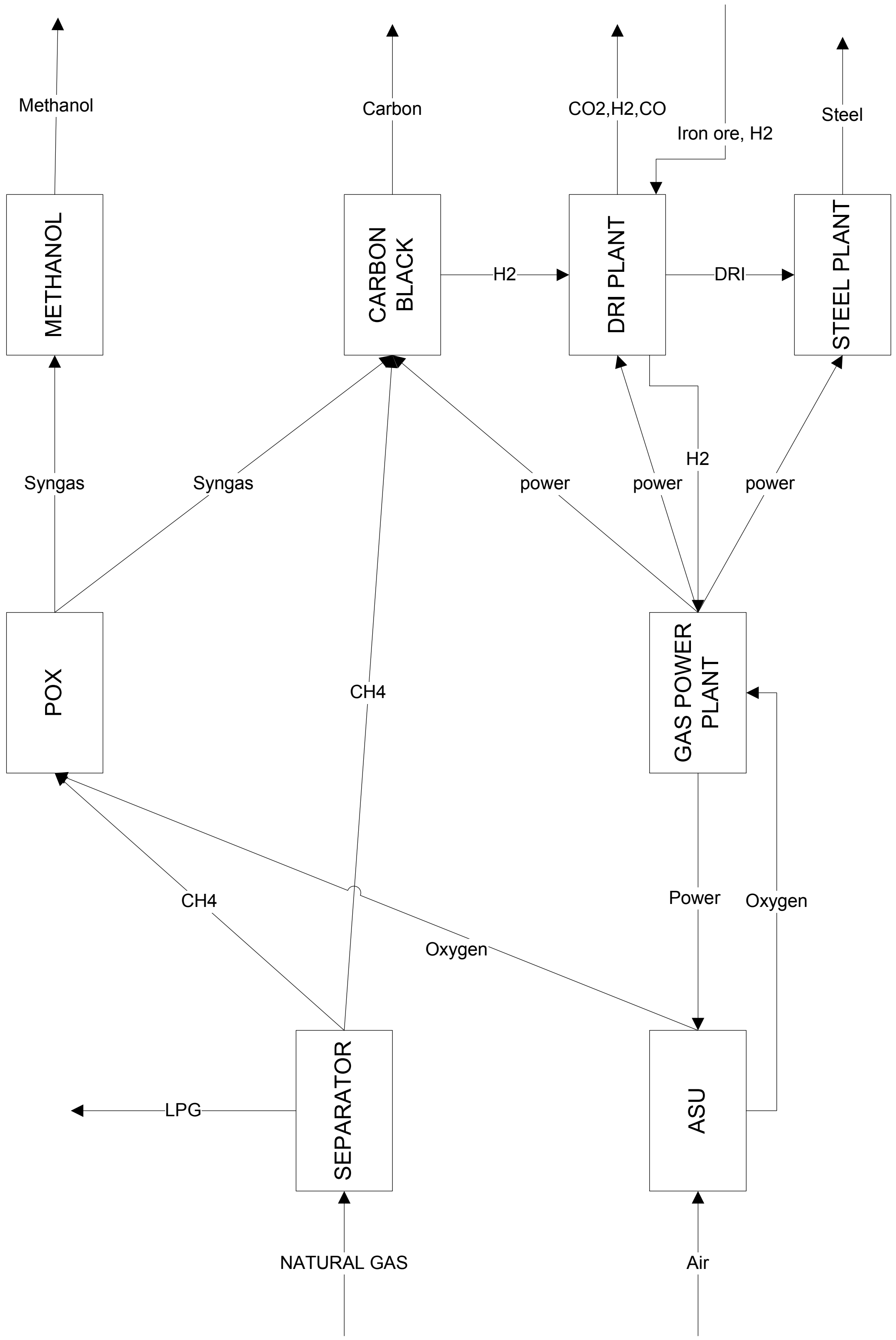
```
forall(t in TIME) do
	REVENUE_PERIOD(t):= sum(c in COMMODITIES) SALES_PRICE(c,t) * sum(p in
PLANTS) flow(p,'MARKET',c,t)
end-do
!***************************************
!*** END - INPUT TO THE CLUSTER ********
!***************************************


GOAL:= REVENUE_FROM_OUTPUT - COST_OF_INPUT - INVESTMENT_COST -
OPERATION_COST

maximize(GOAL)
writeln(getsol(GOAL))
writeln(getsol(REVENUE_FROM_OUTPUT))
writeln(getsol(COST_OF_INPUT))
writeln(getsol(INVESTMENT_COST))
writeln(getsol(OPERATION_COST))

writeResultsProfits
writeResultsFlow
writeResultsPlants


procedure writeResultsProfits
	declarations
		investment_s:	array(PLANTS) of string
		cost_s:			dynamic array(COMMODITIES) of string
		income_s:		dynamic array(COMMODITIES) of string
		profit_s:		string

		statistics_s:	array(PLANTS, TIME, 1..3) of string
	end-declarations


forall(p in PLANTS) do
	investment_s(p) += ";" + p + ";" +
		string(getsol(inv_plant(p)) * INV_FIXED_COST(p) + getsol(capacity(p)) *
INV_UNIT_COST(p)) + ";" + " "
end-do

forall(c in COMMODITIES) do
	test_link(c):= sum(i in PLANTS, t in TIME | LINKS('MARKET',i,c) = 1)
getsol(flow('MARKET',i,c,t))
end-do

forall(c in COMMODITIES | test_link(c) > 0) do
	forall(t in TIME) do
		cost_s(c) += string(PURCH_PRICE(c,t) * sum(p in PLANTS)
getsol(flow('MARKET',p,c,t))) + ";"
	end-do
end-do


forall(c in COMMODITIES) do
	test_link2(c):= sum(i in PLANTS, t in TIME | LINKS(i,'MARKET',c) = 1)
getsol(flow(i,'MARKET',c,t))
end-do

forall(c in COMMODITIES | test_link2(c) > 0) do
```

```
		forall(t in TIME) do
			income_s(c) += string(SALES_PRICE(c,t) * sum(p in PLANTS)
getsol(flow(p,'MARKET',c,t))) + ";"
		end-do
end-do


forall(t in TIME) do
		if t = 1 then
			profit_s += "Profit" + ";" + ";" + string(getsol(REVENUE_PERIOD(t)) -
getsol(COST_INPUT_PERIOD(t)) - getsol(INVESTMENT_COST))
		else
			profit_s += ";" + string(getsol(REVENUE_PERIOD(t)) -
getsol(COST_INPUT_PERIOD(t)))
		end-if
end-do




count:=1
count2:=1
count3:=1
fopen("WGMO_Profits.sol",F_OUTPUT)
		writeln(";" + ";" + "Time period")
		writeln(";" + ";" + "1" + ";" + "2")
		forall(p in PLANTS) do
			if count=1 then
				writeln("Investments" + investment_s(p))
			else
				writeln(investment_s(p))
			end-if
			count+=1
		end-do

!writeln(";;;;;;;;;;;;")
!writeln(";;;;;;;;;;;;")

		forall(c in COMMODITIES | test_link(c)>0) do
			if count2=1 then
				writeln("Cost of commodities" + ";" + c + ";" + cost_s(c))
			else
				writeln(";" + c + ";" + cost_s(c))
			end-if
			count2+=1
		end-do

!writeln(";;;;;;;;;;;;")
!writeln(";;;;;;;;;;;;")

		forall(c in COMMODITIES | test_link2(c)>0) do
			if count3=1 then
				writeln("Income from commodities" + ";" + c + ";" + income_s(c))
			else
				writeln(";" + c + ";" + income_s(c))
			end-if
			count3+=1
		end-do

!writeln(";;;;;;;;;;;;")
```

```
!writeln(";;;;;;;;;;;;")

        writeln(profit_s)

fclose(F_OUTPUT)


end-procedure


procedure writeResultsFlow
        declarations
                heading1:               string
                heading2:               string
                flow_s:                 dynamic array(PLANTS,PLANTS,COMMODITIES)
of string
        end-declarations

heading1:= "Flow pattern in the cluster"
heading2:= "From plant" + ";" + "To plant" + ";" + "Commodity" + ";"
        forall(t in TIME) do
                heading2+= "Flow in period " + t + ";"
        end-do


forall(i in PLANTS, j in PLANTS, c in COMMODITIES | LINKS(i,j,c)=1) do
        flow_s(i,j,c):= i + ";" + j + ";" + c + ";"
                forall(t in TIME) do
                        flow_s(i,j,c)+= string(getsol(flow(i,j,c,t)))
                        flow_s(i,j,c)+= ";"
                end-do
end-do


fopen("WGMO_Flow.sol",F_OUTPUT)
        writeln(heading1)
        writeln(heading2)
        forall(i in PLANTS, j in PLANTS, c in COMMODITIES | LINKS(i,j,c)=1) do
                writeln(flow_s(i,j,c))
        end-do
fclose(F_OUTPUT)

end-procedure


procedure writeResultsPlants
        declarations
                heading1:                       string
                heading2:                       string
                capacity_s:                     array(PLANTS) of string
                production_s:           array(PLANTS,COMMODITIES) of string
                resource_s:                     array(PLANTS,COMMODITIES) of string
        end-declarations

heading1:= "Results from the plants"
heading2:= "Plant" + ";" + "Category" + ";"
        forall(t in TIME) do
                heading2+= "Period" + t + ";"
        end-do
```

```
forall(p in PLANTS) do
	capacity_s(p) += p + ";" + "Installed capacity" + ";" + string(getsol(capacity(p))) + ";" +
string(getsol(capacity(p)))
end-do

forall(p in PLANTS, c in COMMODITIES | LINKS(p,'MARKET',c)=1) do ! |
exists(flow(p,'MARKET',c,1))) do
	production_s(p,c) += p + ";" + "Production of " + c + ";"
	forall(t in TIME) do
		production_s(p,c) += string(sum(i in PLANTS) getsol(flow(p,i,c,t))) + ";"
	end-do
end-do

forall(p in PLANTS, c in COMMODITIES | LINKS('MARKET',p,c)=1) do ! |
exists(flow(p,'MARKET',c,1))) do
	resource_s(p,c) += p + ";" + "Use of " + c + ";"
	forall(t in TIME) do
		resource_s(p,c) += string(sum(j in PLANTS) getsol(flow(j,p,c,t))) + ";"
	end-do
end-do


fopen("WGMO_Plants.sol",F_OUTPUT)
	writeln(heading1)
	writeln(heading2)
	forall(p in PLANTS) do
		writeln(capacity_s(p))
	end-do
	forall(p in PLANTS, c in COMMODITIES | LINKS(p,'MARKET',c)=1) do ! |
exists(flow(p,'MARKET',c,1))) do
		writeln(production_s(p,c))
	end-do
	forall(p in PLANTS, c in COMMODITIES | LINKS('MARKET',p,c)=1) do ! |
exists(flow('MARKET',p,c,1))) do
		writeln(resource_s(p,c))
	end-do
fclose(F_OUTPUT)

end-procedure




end-model
```

Appendix B: Graphical View of Whole Industrial Cluster



Whole Industrial Cluster and Material Flows

Appendix C: Moving Average Method Results

		3-Period Moving Average				
Inital Data	Consump.	Forecast	No. Obs	|Error|	|Error^2|	|Error/Con.|
1997	1880					
1998	1995					
1999	1230					
2000	1260	1701,67	1	441,67	195069	0,3505
2001	1260	1495,00	2	235,00	55225	0,1865
2002	1300	1250,00	3	50,00	2500	0,0385
2003	1301	1273,33	4	27,67	765	0,0213
2004	1812	1287,00	5	525,00	275625	0,2897
2005	1388	1471,00	6	83,00	6889	0,0598
2006	1656	1500,33	7	155,67	24232	0,0940
2007	1620	1618,67	8	1,33	2	0,0008
2008	1550	1554,67	9	4,67	22	0,0030
2009	1610	1608,67	10	1,33	2	0,0008
2010		1593,33				
Sum :	19862		55	1.525,33	560331	1,0450

		5-Period Moving Average				
Inital Data	Consump.	Forecast	No. Obs	|Error|	|Error^2|	|Error/Con.|
1997	1880					
1998	1995					
1999	1230					
2000	1260					
2001	1260					
2002	1300	1525,00	1	225,00	50625	0,1731
2003	1301	1409,00	2	108,00	11664	0,0830
2004	1812	1270,20	3	541,80	293547	0,2990
2005	1388	1386,60	4	1,40	2	0,0010
2006	1656	1412,20	5	243,80	59438	0,1472
2007	1620	1491,40	6	128,60	16538	0,0794
2008	1550	1555,40	7	5,40	29	0,0035
2009	1610	1605,20	8	4,80	23	0,0030
2010		1564,80				
Sum :	19862		36	1.258,80	431867	0,7892

Appendix D: Linear Regression Method Results

2007:

	Initial Data		Forecast					
2	x	y (Consumption)	No. Observation	y*No.Observation	Forecast	|Error|	|Error^2|	|Error/Consumption|
3	1997	1880	1	1880	1595,25	284,75	81079,97	0,15
4	1998	1995	2	3990	1575,91	419,09	175637,19	0,21
5	1999	1230	3	3690	1556,56	326,56	106643,81	0,27
6	2000	1260	4	5040	1537,22	277,22	76849,92	0,22
7	2001	1260	5	6300	1517,87	257,87	66498,34	0,20
8	2002	1300	6	7800	1498,53	198,53	39413,08	0,15
9	2003	1301	7	9107	1479,18	178,18	31748,76	0,14
10	2004	1812	8	14496	1459,84	352,16	124019,23	0,19
11	2005	1388	9	12492	1440,49	52,49	2755,30	0,04
12	2006	1656	10	16560	1421,15	234,85	55156,66	0,14
13	2007		11		1401,80			
14	Sum	15082		81355		2582	759.802	1,72
15	Average	1508						
16								
17					Where:			
18					n =	10		
19					Sxy =	-15960		
20					Sxx =	825		
21					b =	-19,3455		
22					a =	1614,6		

2008:

	Initial Data		Forecast					
2	x	y (Consumption)	No. Observation	y*No.Observation	Forecast	|Error|	|Error^2|	Error/Consumption|
3	1997	1880	1	1880	1595,23	284,77	81095,51	0,15
4	1998	1995	2	3990	1575,89	419,11	175652,43	0,21
5	1999	1230	3	3690	1556,55	326,55	106637,87	0,27
6	2000	1260	4	5040	1537,22	277,22	76849,92	0,22
7	2001	1260	5	6300	1517,88	257,88	66503,03	0,20
8	2002	1300	6	7800	1498,55	198,55	39420,30	0,15
9	2003	1301	7	9107	1479,21	178,21	31758,48	0,14
10	2004	1812	8	14496	1459,87	352,13	123993,62	0,19
11	2005	1388	9	12492	1440,54	52,54	2760,07	0,04
12	2006	1656	10	16560	1421,20	234,80	55131,04	0,14
13	2007	1402	11	15422	1401,86	0,14	0,02	0,00
14	2008		12		1382,53			
15	Sum	16484		96777		2582	759.802	1,72
16	Average	1499						
17								
18					Where:			
19					n =	11		
20					Sxy =	-23397		
21					Sxx =	1210		
22					b =	-19,3364		
23					a =	1614,564		

2009:

	Initial Data		Forecast					
2	x	y (Consumption)	No. Observation	y*No.Observation	Forecast	|Error|	|Error^2|	Error/Consumption|
3	1997	1880	1	1880	1595,17	284,83	81130,03	0,1515
4	1998	1995	2	3990	1575,85	419,15	175687,99	0,2101
5	1999	1230	3	3690	1556,53	326,53	106622,04	0,2655
6	2000	1260	4	5040	1537,21	277,21	76846,56	0,2200
7	2001	1260	5	6300	1517,89	257,89	66509,28	0,2047
8	2002	1300	6	7800	1498,58	198,58	39432,33	0,1528
9	2003	1301	7	9107	1479,26	178,26	31775,76	0,1370
10	2004	1812	8	14496	1459,94	352,06	123946,67	0,1943
11	2005	1388	9	12492	1440,62	52,62	2768,99	0,0379
12	2006	1656	10	16560	1421,30	234,70	55082,67	0,1417
13	2007	1402	11	15422	1401,98	0,02	0,00	0,0000
14	2008	1383	12	16596	1382,67	0,33	0,11	0,0002
15	2009		13		1363,35			
16	Sum	17867		113373		2582	759.802	1,7157
17	Average	1489						
18								
19					Where:			
20					n =	12		
21					Sxy =	-33150		
22					Sxx =	1716		
23					b =	-19,3182		
24					a =	1614,485		

2010:

Initial Data				Forecast			
x	y (Consumption)	No. Observation	y*No.Observation	Forecast	|Error|	|Error^2|	|Error/Consumption|
1997	1880	1	1880	1595,21	284,79	81106,03	0,1515
1998	1995	2	3990	1575,88	419,12	175662,31	0,2101
1999	1230	3	3690	1556,55	326,55	106634,54	0,2655
2000	1260	4	5040	1537,22	277,22	76850,81	0,2200
2001	1260	5	6300	1517,89	257,89	66507,31	0,2047
2002	1300	6	7800	1498,56	198,56	39426,25	0,1527
2003	1301	7	9107	1479,23	178,23	31766,21	0,1370
2004	1812	8	14496	1459,90	352,10	123973,64	0,1943
2005	1388	9	12492	1440,57	52,57	2763,76	0,0379
2006	1656	10	16560	1421,24	234,76	55111,43	0,1418
2007	1402	11	15422	1401,91	0,09	0,01	0,0001
2008	1383	12	16596	1382,58	0,42	0,17	0,0003
2009	1363	13	17719	1363,25	0,25	0,06	0,0002
2010		14		1343,92			
Sum	19230		131092		2583	759.803	1,7160
Average	1479						
				Where:			
				n =	13		
				Sxy =	-45734		
				Sxx =	2366		
				b =	-19,3297		
				a =	1614,538		

Excel Analysis Toolpack Results

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0,317170333
R Square	0,10059702
Adjusted R Square	0,025646772
Standard Error	251,6284516
Observations	14

ANOVA

	df	SS	MS	F	Significance F
Regression	1	84982,8967	84982,8967	1,342183946	0,269185819
Residual	12	759802,5319	63316,87766		
Total	13	844785,4286			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	40192,16264	33424,06526	1,202491747	0,25236392	-32632,61948	113016,9448	-32632,6195	113016,94
X Variable 1	-19,32747253	16,68280389	-1,158526627	0,269185819	-55,67617964	17,02123459	-55,6761796	17,021235

RESIDUAL OUTPUT

Observation	Predicted Y	Residuals	Standard Residuals
1	1595,2	284,8	1,178043407
2	1575,872527	419,1274725	1,733674001
3	1556,545055	-326,5450549	-1,350717166
4	1537,217582	-277,2175824	-1,146679583
5	1517,89011	-257,8901099	-1,06673365
6	1498,562637	-198,5626374	-0,821332183
7	1479,235165	-178,2351648	-0,737249862
8	1459,907692	352,0923077	1,456390525
9	1440,58022	-52,58021978	-0,217492209
10	1421,252747	234,7472527	0,971005805
11	1401,925275	0,074725275	0,000309093
12	1382,597802	0,402197802	0,001663646
13	1363,27033	-0,27032967	-0,001118189
14	1343,942857	0,057142857	0,000236365

Appendix E: Deterministic Mathematical Model

Minimize:

$$\sum_{j\in J}\sum_{p\in P}\sum_{t\ in\ 1..T} c_{jt}x^1_{jpt} + \sum_{f\in F}\sum_{p\in P}\sum_{t\ in\ 1..T} f_{ft}x^2_{fpt} + \sum_{c\in C}\sum_{t\ in\ 1..T} e_{ct}z_{ct} +$$

$$\sum_{p\in P}\sum_{t\ in\ 1..T} u\, w^2_{pt} + \sum_{p\in P}\sum_{t\ in\ 1..T} i\, I_{pt}$$

Subject to:

$$\sum_{j\in J} l^1_e\ x^1_{jpt}\ a^1_{je}\ +\ s_p\ w^2_{pt}\ a^3_{ep} =\ y^1_{ept} \qquad \forall\ e\in E, \forall p\in P, t\ in\ 1..T \qquad (1)$$

$$y^1_{ept}\ + \sum_{f\in F} l^2_e\ x^2_{fpt}\ a^2_{fe} = y^2_{ept} \qquad \forall\ e\in E, \forall p\in P, t\ in\ 1..T \qquad (2)$$

$$\sum_{e\in E} y^1_{ept} = w^1_{pt} \qquad \forall p\in P, t\ in\ 1..T \qquad (3)$$

$$\sum_{e\in E} y^2_{ept} =\ w^2_{pt} \qquad \forall p\in P, t\ in\ 1..T \qquad (4)$$

$$w^1_{pt}\ \geq b_p \qquad \forall p\in P, t\ in\ 1..T \qquad (5)$$

$$I_{p,t-1} + (1-s_p)w^2_{pt} =\ d_{pt} + I_{pt} \qquad \forall p\in P, \quad t\ in\ 1..T \qquad (6)$$

$$I_{p,0} = 0 \qquad \forall p\in P \qquad (7)$$

$$I_{p,T} = 0.2 * d_{p,T} \qquad \forall p\in P \qquad (8)$$

$$k_c\sum_{p\in P} w^2_{pt} = z_{ct} \qquad t\ in\ 1..T, \forall c\in C \qquad (9)$$

$$h^1_{ep}w^1_{pt} \leq y^1_{ept} \leq g^1_{ep}\ w^1_{pt} \qquad \forall\ p\in P, t\ in\ 1..T, \forall e\in E \qquad (10)$$

$$h^2_{ep}w^2_{pt} \leq y^2_{ept} \leq g^2_{ep}\ w^2_{pt} + y^3_{ept} \qquad \forall\ p\in P, t\ in\ 1..T, \forall e\in E \qquad (11)$$

$$x^1_{'DRI',p,t}\ \geq m\sum_{j\in J} x^1_{jpt} \qquad \forall\ p\in P, \quad t\ in\ 1..T \qquad (12)$$

$$x^1_{jpt} \geq 0, x^2_{fpt} \geq 0, y^1_{ept} \geq 0, y^2_{ept} \geq 0, w^1_{pt} \geq 0, w^2_{pt} \geq 0, z_{ct} \geq 0, I_{pt} \geq 0$$

$$\forall\ e\in E, \forall\ t\in T, \forall c\in C, \forall j\in J, \forall f$$

Appendix F: AMPL Code of Deterministic Mathematical Model

Model file:

```
set Raw_Materials;
set FeAl;
set Elements;
set Commodities;
set Products;

param T > 0;
param cost1{j in Raw_Materials, t in 1..T}>= 0;
param cost2{f in FeAl, t in 1..T} >= 0;
param cost3{c in Commodities, t in 1..T} >= 0;
param hold_cost ;
param attribute1{e in Elements,j in Raw_Materials} >=0;
param attribute2{e in Elements,f in FeAl} >=0;
param coef{c in Commodities} ;
param unitcost >= 0;
param loss1{e in Elements};
param loss2{e in Elements};
param min_weight{p in Products};
param demand {p in Products, t in 1..T};
param lower_perc1{e in Elements, p in Products};
param upper_perc1{e in Elements, p in Products};
param lower_perc2{e in Elements, p in Products};
param upper_perc2{e in Elements, p in Products};
param DRI_mix_steel;
param home_scrap{p in Products};
param scrap_attribute {e in Elements, p in Products};

var x1 {j in Raw_Materials, p in Products, t in 1..T} >=0;
var x2 {f in FeAl,p in Products, t in 1..T} >=0;
var y1 {e in Elements, p in Products, t in 1..T} >= 0;
var y2 {e in Elements, p in Products, t in 1..T} >= 0;
var y3 {e in Elements, p in Products, t in 1..T} >= 0;
var w1 {p in Products, t in 1..T} ;
var w2 {p in Products, t in 1..T} ;
var z {c in Commodities, t in 1..T} >= 0 ;
var I{p in Products, t in 0..T}>=0;
```

```
minimize Total_cost:  sum{j in Raw_Materials, p in Products, t in 1..T} cost1[j,t]*x1[j,p,t] + sum{f in FeAl, p in Products, t in 1..T}cost2[f,t]*x2[f,p,t]+ sum{c in Commodities, t in 1..T} cost3[c,t]*z[c,t] + sum{p in Products, t in 1..T}unitcost*w2[p,t] + sum{p in Products, t in 1..T}hold_cost*I[p,t] ;

subject to y1_value{e in Elements,p in Products, t in 1..T}: sum{j in Raw_Materials} loss1[e]*x1[j,p,t]*attribute1[e,j] + home_scrap[p]*w2[p,t]*scrap_attribute[e,p] = y1[e,p,t];

subject to y2_value{e in Elements,p in Products, t in 1..T}: y1[e,p,t] + sum{f in FeAl} loss2[e]*x2[f,p,t]*attribute2[e,f] = y2[e,p,t];

subject to w1_value{p in Products, t in 1..T} : sum{e in Elements} y1[e,p,t] = w1[p,t] ;

subject to w2_value{p in Products, t in 1..T} : sum{e in Elements} y2[e,p,t] = w2[p,t] ;

subject to w1_bound{p in Products, t in 1..T} : w1[p,t] >= min_weight[p];

subject to Inv_balance{p in Products, t in 1..T} : I[p,t-1] + w2[p,t] - home_scrap[p]*w2[p,t] = I[p,t] + demand[p,t];

subject to Initial_inv{p in Products}: I[p,0] = 0;

subject to Final_inv{p in Products}: I[p,T] >= 0.2*demand[p,T];

subject to commodity{c in Commodities,t in 1..T}: coef[c] * sum{p in Products}w2[p,t] = z[c,t];

subject to lower_bound1 {e in Elements,p in Products,t in 1..T} : y1[e,p,t] >= lower_perc1[e,p]*w1[p,t] ;

subject to upper_bound1 {e in Elements,p in Products, t in 1..T}: y1[e,p,t] <= upper_perc1[e,p]*w1[p,t] ;

subject to lower_bound2 {e in Elements,p in Products, t in 1..T}: y2[e,p,t] >= lower_perc2[e,p]*w2[p,t] ;

subject to upper_bound2 {e in Elements,p in Products, t in 1..T}: y2[e,p,t] <= upper_perc2[e,p]*w2[p,t] + y3[e,p,t];

subject to DRI_usage{p in Products, t in 1..T}: x1['DRI',p,t] >= DRI_mix_steel* sum{j in Raw_Materials} x1[j,p,t];
```

Data file:

```
set Raw_Materials:= DRI SCRAP_SS SCRAP_CS;
set FeAl:= FCH FNI FMN FMO;
set Elements:= F C Cr Ni Mo Mn Si;
set Commodities:= E;
set Products:= SS CS;
param T:= 2;
param cost1(tr): DRI  SCRAP_SS  SCRAP_CS:=
               1 3520  2018       2018
               2 3632  2019       2019;
param cost2(tr): FCH  FNI  FMN   FMO :=
               1 6120 9200 12200 104745
               2 6150 9250 12300 104800 ;
param cost3(tr):  E :=
                1 0.5
                2 0.563 ;
param hold_cost:= 100;
param DRI_mix_steel:= 0.4;
param attribute1: DRI SCRAP_SS SCRAP_CS :=
            F      0.94  0.80      0.903
            C      0.04  0.01      0.003
            Cr     0     0.16      0
            Ni     0     0.02      0
            Mo     0     0.01      0
            Mn     0     0         0.004
            Si     0.02  0         0           ;
param attribute2: FCH  FNI    FMN    FMO :=
             F     0.45  0.62   0.25   0.35
             C     0     0      0      0
             Cr    0.55  0      0      0
             Ni    0     0.38   0      0
             Mo    0     0      0      0.65
             Mn    0     0      0.75   0
             Si    0     0      0      0  ;
param scrap_attribute:  SS     CS     :=
             F         0.78   0.93
             C         0.001  0.0005
             Cr        0.105  0
             Ni        0      0
             Mo        0.002  0
             Mn        0      0.001
             Si        0      0      ;
param loss1:= F 0.95 C 0.95 Cr 1 Ni 1 Mo 1 Mn 1 Si 1;
param loss2:= F 1 C 1 Cr 0.99 Ni 0.98 Mo 0.98 Mn 0.99 Si 1;
param coef:= E 400;
param min_weight:= SS 100000 CS 500000 ;
param demand: 1 2 :=
          SS 234720 250000
          CS 1330080 1500000    ;
param unitcost:= 400;
param home_scrap:= SS 0.1 CS 0.05;
param lower_perc1:   SS     CS    :=
            F          0.75   0.936
            C          0      0
            Cr         0      0
            Ni         0      0
            Mo         0      0
            Mn         0      0
            Si         0      0      ;
param upper_perc1:   SS     CS     :=
            F          1      1
            C          0.04   0.04
            Cr         0.18   0
            Ni         0.02   0
            Mo         0.01   0
            Mn         0      0.004
            Si         0.02   0.02         ;
param lower_perc2:   SS      CS      :=
             F         0.78    0.93
             C         0.001   0.0005
             Cr        0.105   0
             Ni        0       0
             Mo        0.002   0
             Mn        0       0.001
             Si        0       0        ;
param upper_perc2:   SS        CS   :=
             F         0.892   0.99
             C         0.01    0.003
             Cr        0.18    0
             Ni        0.02    0
             Mo        0.01    0
             Mn        0       0.004
             Si        0       0            ;
```

Run file:

```
model final.mod ;
data final.dat;
option solver cplex;
option cplex_options 'sensitivity';
solve;
display Total_cost > final.sol;
display x1, x2 > final.sol;
display y1, y2, y3 > final.sol;
display w1, w2 > final.sol;
display z > final.sol;
display I > final.sol;
display x1.down, cost1, x1.up > final.sol;
exit;
```

Solution file:

```
Total_cost = 13175200000

:                     x1          x2        :=
DRI       CS  1    593793          .
DRI       CS  2    803581          .
DRI       SS  1     98686.8        .
DRI       SS  2    126133          .
FCH       CS  1       .            0
FCH       CS  2       .            0
FCH       SS  1       .         1764.49
FCH       SS  2       .         2255.22
FMN       CS  1       .            0
FMN       CS  2       .            0
FMN       SS  1       .            0
FMN       SS  2       .            0
FMO       CS  1       .            0
FMO       CS  2       .            0
FMO       SS  1       .            0
FMO       SS  2       .            0
FNI       CS  1       .            0
FNI       CS  2       .            0
FNI       SS  1       .            0
FNI       SS  2       .            0
SCRAP_CS  CS  1    890689          .
SCRAP_CS  CS  2   1205370          .
SCRAP_CS  SS  1         0          .
SCRAP_CS  SS  2         0          .
SCRAP_SS  CS  1         0          .
SCRAP_SS  CS  2         0          .
SCRAP_SS  SS  1    148030          .
SCRAP_SS  SS  2    189200          .
;


:         w1         w2        :=
CS  1   1400080    1400080
CS  2   1894740    1894740
SS  1    259045     260800
SS  2    331091     333333
;
```

```
z :=
E 1    664354000
E 2    891228000
;

I :=
CS 0        0
CS 1        0
CS 2    3e+05
SS 0        0
SS 1        0
SS 2    50000
;

x1.down :=
DRI       CS 1    3468.92
DRI       CS 2    2220.5
DRI       SS 1    3462.79
DRI       SS 2     301.914
SCRAP_CS  CS 1    1983.95
SCRAP_CS  CS 2   -3553.42
SCRAP_CS  SS 1       0
SCRAP_CS  SS 2       0
SCRAP_SS  CS 1       0
SCRAP_SS  CS 2       0
SCRAP_SS  SS 1    1979.86
SCRAP_SS  SS 2   -3754.68
;

cost1 :=
DRI       1   3520
DRI       2   3632
SCRAP_CS  1   2018
SCRAP_CS  2   2019
SCRAP_SS  1   2018
SCRAP_SS  2   2019
;


x1.up :=
DRI       CS 1   10807.2
DRI       CS 2    3683.08
DRI       SS 1   11682.2
DRI       SS 2    3689.21
SCRAP_CS  CS 1    3200.57
SCRAP_CS  CS 2    2053.05
SCRAP_CS  SS 1       0
SCRAP_CS  SS 2       0
SCRAP_SS  CS 1       0
SCRAP_SS  CS 2       0
SCRAP_SS  SS 1    4268.15
SCRAP_SS  SS 2    2057.14
;
```

Appendix G: Stochastic Programming Model

Maximize

$$\sum_{p\in P}\sum_{b\in B} t_b\, p_{pb}\, d_{p,(q_b)} - \sum_{j\in J}\sum_{p\in P}\sum_{b\in B} t_b\, c_{j,(q_b)}\, x^1_{j,p,(q_b)}$$

$$-\sum_{f\in F}\sum_{p\in P}\sum_{b\in B} t_b\, f_{f,(q_b)}\, x^2_{f,p,(q_b)} - \sum_{c\in C}\sum_{b\in B} t_b\, e_{c,(q_b)} z_{cb}$$

$$-\sum_{p\in P}\sum_{b\in B} t_b\, u\, w^2_{pb} - \sum_{p\in P}\sum_{n\in N} i\, I_{pn}$$

Subject to

$$\sum_{j\in J} l^1_{eb}\ x^1_{j,p,(q_b)}\, a^1_{je} + s_{pb}\, w^2_{pb}\, a^3_{pe} = y^1_{epb} \qquad \forall\, e\in E, \forall p\in P, \forall b\in B \qquad (1)$$

$$y^1_{epb} + \sum_{f\in F} l^2_{eb}\, x^2_{f,p,(q_b)}\, a^2_{fe} = y^2_{epb} \qquad \forall\, e\in E, \forall p\in P, \forall b\in B \qquad (2)$$

$$\sum_{e\in E} y^1_{epb} = w^1_{pb} \qquad \forall p\in P, \forall b\in B \qquad (3)$$

$$\sum_{e\in E} y^2_{epb} = w^2_{pb} \qquad \forall p\in P, \forall b\in B \qquad (4)$$

$$w^1_{pb} \geq o_p \qquad \forall p\in P, \forall b\in B \qquad (5)$$

$$I_{p,(q_b)} + (1-s_{pb})w^2_{pb} = d_{p,q_b} + I_{pb} \qquad \forall p\in P,\ \forall b\in B \qquad (6)$$

$$I_{p,0} = 0 \qquad \forall p\in P \qquad (7)$$

$$I_{pl} = 0.2 * d_{p,q_l} \qquad \forall p\in P, \forall l\in L \qquad (8)$$

$$k_c \sum_{p\in P} w^2_{pb} = z_{cb} \qquad \forall c\in C, \forall b\in B \qquad (9)$$

$$h^1_{ep} w^1_{pb} \leq y^1_{epb} \leq g^1_{pe}\, w^1_{pb} \qquad \forall\, p\in P, \forall b\in B, \forall e\in E \qquad (10)$$

$$h^2_{ep} w^2_{pb} \leq y^2_{epb} \leq g^2_{pe}\, w^2_{pb} + y^3_{epb} \qquad \forall\, p\in P, \forall b\in B, \forall e\in E \qquad (11)$$

$$x^1_{(DRI),p,n} \geq m \sum_{j\in J} x^1_{jpn} \qquad \forall\, p\in P, \forall n\in N/L \qquad (12)$$

Appendix H: AMPL Code of the Stochastic Programming Model

Model file:

```
# The scenario tree
param Last_node;
set Nodes := 0..Last_node;
param Root in Nodes default 0;
set Future_Nodes := Nodes diff {Root};
param Child_of_per_node default 4;
param Pred{n in Future_Nodes} default (n-1) div Child_of_per_node;
param First_leaf;
set Leaves := First_leaf..Last_node;
param Prob{n in Nodes} default if n in Leaves then 1/(Last_node - First_leaf + 1) else sum{cn in
Future_Nodes:Pred[cn]=n}Prob[cn];

# Deterministic sets
set Raw_Materials;
set FeAl;
set Elements;
set Commodities;
set Products;

param cost1{j in Raw_Materials,n in Nodes diff Leaves}>= 0;
param cost2{f in FeAl, n in Nodes diff Leaves} >= 0;
param cost3{c in Commodities, n in Nodes diff Leaves} >= 0;
param price{p in Products, n in Nodes} ;
param hold_cost ;
param attribute1{e in Elements,j in Raw_Materials} >=0;
param attribute2{e in Elements,f in FeAl} >=0;
param coef{c in Commodities} ;
param unitcost >= 0;
param loss1{e in Elements, n in Future_Nodes};
param loss2{e in Elements, n in Future_Nodes};
param min_weight{p in Products};
param demand {p in Products, n in Nodes diff Leaves};
param lower_perc1{e in Elements, p in Products};
param upper_perc1{e in Elements, p in Products};
param lower_perc2{e in Elements, p in Products};
param upper_perc2{e in Elements, p in Products};
```

```
param DRI_mix_steel;
param home_scrap{p in Products, n in Future_Nodes};
param scrap_attribute {e in Elements, p in Products};

var x1 {j in Raw_Materials, p in Products, n in Nodes diff Leaves} >=0;
var x2 {f in FeAl, p in Products, n in Nodes diff Leaves} >=0;
var y1 {e in Elements, p in Products, n in Future_Nodes} >= 0;
var y2 {e in Elements, p in Products, n in Future_Nodes} >= 0;
var y3 {e in Elements, p in Products, n in Future_Nodes} >= 0;
var w1 {p in Products, n in Future_Nodes} >= 0 ;
var w2 {p in Products, n in Future_Nodes} >= 0 ;
var z {c in Commodities,n in Future_Nodes} >= 0 ;
var I {p in Products, n in Nodes} >= 0;

maximize Total_profit: sum{p in Products, n in Future_Nodes}Prob[n]* price[p,n]* demand[p,Pred[n]] - sum{j in Raw_Materials,p in Products, n in Future_Nodes} Prob[n]*cost1[j,Pred[n]]*x1[j,p,Pred[n]] - sum{f in FeAl,p in Products, n in Future_Nodes}Prob[n]*cost2[f,Pred[n]]*x2[f,p,Pred[n]] - sum{c in Commodities,n in Future_Nodes} Prob[n]*cost3[c,Pred[n]]*z[c,n] - sum{p in Products,n in Future_Nodes}Prob[n]*unitcost*w2[p,n] - sum{p in Products,n in Nodes}Prob[n]*hold_cost*I[p,n];

subject to y1_value{e in Elements,p in Products,n in Future_Nodes}: sum{j in Raw_Materials} loss1[e,n]*x1[j,p,Pred[n]]*attribute1[e,j] + home_scrap[p,n]*w2[p,n]*scrap_attribute[e,p] = y1[e,p,n];

subject to y2_value{e in Elements,p in Products,n in Future_Nodes}: y1[e,p,n] + sum{f in FeAl} loss2[e,n]*x2[f,p,Pred[n]]*attribute2[e,f] = y2[e,p,n];

subject to w1_value{p in Products,n in Future_Nodes} : sum{e in Elements} y1[e,p,n] = w1[p,n] ;

subject to w1_bound{p in Products, n in Future_Nodes} : w1[p,n] >= min_weight[p];

subject to w2_value{p in Products,n in Future_Nodes} : sum{e in Elements} y2[e,p,n] = w2[p,n] ;

subject to Inv_balance{p in Products,n in Future_Nodes} : I[p,Pred[n]] + (1-home_scrap[p,n]) * w2[p,n] =
I[p,n] + demand[p,Pred[n]];

subject to Initial_inv{p in Products}: I[p,0] = 0;

subject to Final_inv{p in Products, n in Leaves}: I[p,n] >= 0.2*demand[p,Pred[n]];

subject to electricity{c in Commodities,n in Future_Nodes}: coef[c] * sum{p in Products}w2[p,n] = z[c,n];

subject to lower_bound1 {e in Elements,p in Products, n in Future_Nodes}: y1[e,p,n] >=
lower_perc1[e,p]*w2[p,n] ;

subject to upper_bound1 {e in Elements,p in Products, n in Future_Nodes}: y1[e,p,n] <=
upper_perc1[e,p]*w2[p,n] ;

subject to lower_bound2 {e in Elements,p in Products, n in Future_Nodes}: y2[e,p,n] >=
lower_perc2[e,p]*w2[p,n] ;
```

subject to upper_bound2 {e in Elements,p in Products, n in Future_Nodes}: y2[e,p,n] <= upper_perc2[e,p]*w2[p,n] + y3[e,p,n] ;

subject to DRI_usage{p in Products,n in Nodes diff Leaves}: x1['DRI',p,n] >= DRI_mix_steel* sum{j in Raw_Materials}x1[j,p,n];

Data file:

```
set Raw_Materials:= DRI SCRAP_SS SCRAP_CS;
set FeAl:= FCH FNI FMN FMO;
set Elements:= F C Cr Ni Mo Mn Si;
set Commodities:= E;
set Products:= SS CS;
param Last_node:= 20;
param First_leaf:= 5;
param cost1(tr): DRI SCRAP_SS SCRAP_CS:=
                0 3520  2018         2018
                1 3632  2019         2019
                2 3632  2019         2019
                3 3632  2019         2019
                4 3632  2019         2019    ;
param cost2(tr): FCH   FNI  FMN   FMO :=
                0 6120 9200 12200 104745
                1 6150 9250 12300 104800
                2 6150 9250 12300 104800
                3 6150 9250 12300 104800
                4 6150 9250 12300 104800   ;
param cost3(tr):  E :=
                 0 0.5
                 1 0.563
                 2 0.563
                 3 0.563
                 4 0.563 ;
param hold_cost:= 100;
param DRI_mix_steel:= 0.4;
param attribute1: DRI SCRAP_SS SCRAP_CS :=
           F      0.94    0.80      0.903
           C      0.04    0.01      0.003
           Cr     0       0.16      0
           Ni     0       0.02      0
           Mo     0       0.01      0
           Mn     0       0         0.004
           Si     0.02    0         0          ;
```

```
param attribute2: FCH   FNI    FMN    FMO :=
          F      0.45  0.62   0.25   0.35
          C      0     0      0      0
          Cr     0.55  0      0      0
          Ni     0     0.38   0      0
          Mo     0     0      0      0.65
          Mn     0     0      0.75   0
          Si     0     0      0      0  ;
param scrap_attribute:  SS    CS    :=
          F         0.78   0.93
          C         0.001  0.0005
          Cr        0.105  0
          Ni        0      0
          Mo        0.002  0
          Mn        0      0.001
          Si        0      0     ;
param coef:= E 400;
param min_weight:= SS 100000 CS 500000 ;
param demand : 0       1        2         3        4    :=
        SS 234720  250000   250000    250000   250000
        CS 1330080 1500000  1500000   1500000  1500000  ;
param unitcost:= 400;
param lower_perc1:   SS    CS   :=
         F          0.75  0.936
         C          0     0
         Cr         0     0
         Ni         0     0
         Mo         0     0
         Mn         0     0
         Si         0     0    ;
param upper_perc1:   SS    CS   :=
         F          1     1
         C          0.04  0.04
         Cr         0.18  0
         Ni         0.02  0
         Mo         0.01  0
         Mn         0     0.004
         Si         0.02  0.02     ;

param lower_perc2:   SS     CS  :=
          F         0.78   0.93
          C         0.001  0.0005
          Cr        0.105  0
          Ni        0      0
          Mo        0.002  0
          Mn        0      0.001
          Si        0      0     ;
param upper_perc2:   SS     CS  :=
          F         0.892  0.99
          C         0.01   0.003
          Cr        0.18   0
          Ni        0.02   0
          Mo        0.01   0
          Mn        0      0.004
          Si        0      0       ;
```

Run file:

```
model stochastic.mod ;
data stochastic.dat;
let {e in Elements, n in Future_Nodes} loss1[e,n] := 0.9 + 0.1*Uniform01();
let {e in Elements, n in Future_Nodes} loss2[e,n] := 0.9 + 0.1*Uniform01();
let {p in Products, n in Future_Nodes} home_scrap[p,n] := 0.1*Uniform01();
let price['CS',0] := 8658;
let price['SS',0] := 10079;
let {p in Products, n in Future_Nodes} price[p,n]:= price[p,Pred[n]]*(0.8+0.6*Uniform01());
option solver cplexamp;
solve;
display Prob >stochastic.sol;
display loss1,loss2 > stochastic.sol;
display home_scrap > stochastic.sol;
display price > stochastic.sol;
display Total_profit > stochastic.sol;
display x1, x2 > stochastic.sol;
display y1, y2, y3 > stochastic.sol;
display w1, w2 > stochastic.sol;
display z > stochastic.sol;
display I > stochastic.sol;
```

Solution file:

```
Total_profit = 17034000000

:                   x1          x2        :=
DRI      CS 0    1122110          .
DRI      CS 1     270041          .
DRI      CS 2     312048          .
DRI      CS 3     235257          .
DRI      CS 4     226161          .
DRI      SS 0     169496          .
DRI      SS 1      49372.7        .
DRI      SS 2      53068.3        .
DRI      SS 3      44366.2        .
DRI      SS 4      43134.4        .
FCH      CS 0        .            0
FCH      CS 1        .            0
FCH      CS 2        .            0
FCH      CS 3        .            0
FCH      CS 4        .            0
FCH      SS 0        .        15018.9
FCH      SS 1        .         2120.53
FCH      SS 2        .         1731.05
FCH      SS 3        .         2475.25
FCH      SS 4        .         1649.84
FMN      CS 0        .            0
FMN      CS 1        .            0
FMN      CS 2        .            0
FMN      CS 3        .            0
FMN      CS 4        .            0
FMN      SS 0        .            0
FMN      SS 1        .            0
FMN      SS 2        .            0
FMN      SS 3        .            0
FMN      SS 4        .            0
FMO      CS 0        .            0
FMO      CS 1        .            0
FMO      CS 2        .            0
FMO      CS 3        .            0
FMO      CS 4        .            0
FMO      SS 0        .            0
FMO      SS 1        .            0
FMO      SS 2        .            0
```

```
FMO        SS 3        .            0
FMO        SS 4        .            0
FNI        CS 0        .            0
FNI        CS 1        .            0
FNI        CS 2        .            0
FNI        CS 3        .            0
FNI        CS 4        .            0
FNI        SS 0        .            0
FNI        SS 1        .            0
FNI        SS 2        .            0
FNI        SS 3        .            0
FNI        SS 4        .            0
SCRAP_CS   CS 0   1683170           .
SCRAP_CS   CS 1    405061           .
SCRAP_CS   CS 2    468071           .
SCRAP_CS   CS 3    352885           .
SCRAP_CS   CS 4    339242           .
SCRAP_CS   SS 0         0           .
SCRAP_CS   SS 1         0           .
SCRAP_CS   SS 2         0           .
SCRAP_CS   SS 3         0           .
SCRAP_CS   SS 4         0           .
SCRAP_SS   CS 0         0           .
SCRAP_SS   CS 1         0           .
SCRAP_SS   CS 2         0           .
SCRAP_SS   CS 3         0           .
SCRAP_SS   CS 4         0           .
SCRAP_SS   SS 0    254245           .
SCRAP_SS   SS 1     74059           .
SCRAP_SS   SS 2     79602.4         .
SCRAP_SS   SS 3     66549.4         .
SCRAP_SS   SS 4     64701.6         .
;

:          w1         w2        :=
CS 1     2700340    2700340
CS 2     2635730    2635730
CS 3     2788280    2788280
 CS 4     2880540    2880540
 CS 5      632032     632032
 CS 6      641191     641191
 CS 7      615761     615761
 CS 8      612075     612075
 CS 9      765331     765331
 CS 10     767691     767691
 CS 11     781948     781948
 CS 12     772251     772251
 CS 13     555957     555957
 CS 14     559710     559710
 CS 15     506116     506116
 CS 16     600350     600350
 CS 17     552242     552242
 CS 18      5e+05      5e+05
 CS 19     529006     529006
 CS 20     531142     531142
 SS 1      406884     421271
 SS 2      426851     441434
 SS 3      419591     433560
 SS 4      423891     438462
 SS 5      113520     115538
 SS 6      133148     135127
 SS 7      126200     128220
 SS 8      119282     121322
 SS 9      124803     126500
 SS 10     138378     139986
 SS 11     139930     141602
 SS 12     137969     139598
 SS 13     122324     124644
 SS 14     115488     117848
 SS 15     111871     114285
 SS 16     115783     118254
 SS 17     109779     111398
 SS 18      1e+05     101489
 SS 19     106938     108485
 SS 20     115539     117102
 ;
```

```
z :=
E 1     1248640000
E 2     1230870000
E 3     1288740000
E 4     1327600000
E 5      299028000
E 6      310527000
E 7      297592000
E 8      293359000
E 9      356732000
E 10     363071000
E 11     369420000
E 12     364739000
E 13     272240000
E 14     271023000
E 15     248160000
E 16     287442000
E 17     265456000
E 18     240595000
E 19     254996000
E 20     259297000
;
```

```
I [*,*] (tr)
:       CS          SS        :=
0           0         0
1     1218330   184581
2     1109600   173689
3     1298290   195658
4     1308550   198902
5       3e+05    50000
6      337460    57362.5
7      327846    54921.1
8      310764    52279.8
9       3e+05    50000
10     304080    51338.8
11     322249    54625.4
12     315413    53094.6
13     350719    58477.4
14     319617    53571.1
15      3e+05    50000
16     340321    57068.7
17     313679    53161.8
18      3e+05    50000
19     331791    56198.7
20     334556    57515.8
;
```