Planning of the Mexican steel production, part I: Modelling

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1 Introduction

The background to this project comes from a study of the steel production in Mexico, performed jointly by Mexico and the IMF. All numerical data comes from a report by David Kendrick, Alex Meeraus and Jamie Alatorre. The material has been adapted to a smaller project by aggregating the original data into fewer, larger regions.

The original report treated six coal mines, eight ore mines, nine steel mills consisting of more than 30 different production facilities, approximately 20 different groups of steel products and more than 30 different groups of raw materials and intermediate products. The finished products where distributed to nine different market areas and it was possible to import and export raw materials as well as intermediate and finished products. In this assignment we have eliminated the smaller mills and mines and aggregated market areas and product groups. We are left with one coal mine, five ore mines, five mills with seven different production processes, two different kinds of raw materials, two different intermediate products, two consumer products and three different market areas.

The following sections give a short description of steel production, in particular the processes used in the year 1985, which is when the study was originally done. After this follows a short description of the raw materials, the different steel mills, the processes in those mills, which intermediate and finished products that are produced, and finally a short description of the different demand regions as well as the transportation system used in Mexico. The description includes prices, capacities, demand data and data regarding the efficiency of the different production processes.

2 Steel production

During the last two centuries, steel has been produced in a two-step process, first the reduction of ore to raw iron, after this the removal of carbon in order to produce steel.

In the reduction phase of the production the iron ore, consisting mainly of iron-oxides and coke, is poured into a blast-furnace, where some of the coke is burnt to heat the mixture. The production includes a surplus of coke and at high temperatures some of the coke reacts with the oxygen in the iron oxide reducing it to pure iron. In temperatures in excess of 800 degrees Celsius, coal tends to blend with the iron, hence the output from the blast furnace will be raw iron containing approximately 4% coal. A medium-sized blast-furnace may produce approximately 2000 tons of raw iron per day. The iron is tapped out every 3–9 hours, removing 300–900 tons of raw iron. Impurities in the ore and the coke form a layer of slag floating on the raw iron. Different substances are added to the slag (mainly limestone) to decrease its viscosity in order to make it possibly to tap it off as well.

Some of the raw iron is used directly as pig-iron. As pig-iron is fairly brittle, one need to reduce the carbon contents below 1% in order to produce steel, which is more tough. At the time of this study three different processes were used to reduce the level of carbon.

In the Bessemer process, named after its British inventor, the hot raw iron is poured into a large container through which air is blown. The carbon reacts with the oxygen in the air producing carbon oxide, reducing the level of carbon in the steel. Unfortunately the nitrogen in the air may react with the iron reducing the strength of the resulting steel. To prevent this some mills are switching to using pure oxygen in the Bessemer process, a method which shows great potential.

In the Martin oven, named after the Frenchman Pierre Martin, the raw iron is heated using large burners blowing hot air over large tubs of raw iron. An excess of oxygen in the hot air reacts with the carbon in the iron. An advantage of the Martin oven compared to the Bessemer process is the possibility to add extra iron ore directly to the raw iron. The oxygen in the raw iron reacts with the carbon, reducing the carbon contents of the raw iron, and a cooling of the raw iron is obtained by adding the extra mass. The Martin oven is also named Siemens-Martin oven after some improvements of the processes heat-economy made by the German Siemens. The steel from these ovens is called SM-steel.

The third tempering-process is done in electro-ovens. The raw iron is kept in a large tub, similar to the Martin oven. The heat is provided by large electrodes, forming electric arcs to the tub of hot iron. Around the arcs, the carbon reacts with the oxygen in the air and the resulting carbon dioxide is vented out. The process is comparatively expensive, but produces steel of a higher quality compared to the two processes described earlier.

The processes described above having raw iron as an intermediate product have been used for a long time, although the combination blast-furnace/electro-oven is no longer used. A newer process used in the more modern mills in Mexico consists of reducing the iron ore to sponge iron using natural gas. The sponge iron is turned to steel using electro-ovens described above.

The liquid steel produced by any of these methods is poured into large chill-moulds. When the steel is cold enough (but still hot), it is transported to the rolling-mill, where it is formed to its final form of reinforcing bars, plates, beams etc. During the rolling of the steel there is a need for periodic re-heating in order to keep it soft enough to process.

During the processing of the iron there is a certain waste of material. As an example the rolling produces scrap-metal when the products are cut to standard lengths. These parts are returned to the production. In order to account for this, the coefficients given below are compensated for this spillage. The usage of raw material and intermediate products given is hence the net consumption, and the capacities of the different processes are adjusted in a similar fashion to show net capacity.

3 The coal and ore mines of Mexico

As mentioned before, this project is limited to studying the largest of the coal and ore mines. Although there are several small coal mines in Mexico this project settles for studying only the mines in the Coahuila-province which supply the majority of Mexican coal. Relevant data for this province is given in Table 1.

Table 1: Data for the coal mines of Mexico.

Place	Capacity, Mton/Yr	Price, pesos/ton
Coahuila	13.2	500

Iron ore is produced mainly in five different areas. Data for the different areas is given in Table 2. The quality factor in the table gives the fraction that is effectively used in the production of iron. For example, a quality of 0.9 means that the production requires 1/0.9 times the amount of ore used if the ore had quality 1.0.

Table 2: Data for the ore mines of Mexico.

Place	Capacity, Mton/Yr	Quality	Price, pesos/ton
Penacol	6.60	0.91	140
Lastruchas	2.85	0.96	150
Laperla	3.47	0.96	150
Cerro-Mer	2.24	1.00	160
El-Encino	8.45	0.91	140

The capacities of the different mines, both coal and ore, are adjusted to include the capacity of the smaller mines left out of the study. The capacity of the mines left out are added to the closest mine still in the study.

4 Existing steel mills

Currently there are five large steel mills in Mexico. The three mills Ahmsa, Fundidora and Sicartsa use a traditional blast-furnace combined with tempering in Martin or oxygen ovens. The other mills, Hylsa and Hylsap, use reduction to sponge iron by using natural gas, followed by tempering in electro-ovens. Relevant data for the different processes is given in the Tables 3 and 4. The coefficients show input (−) and output (+) at unit production, and the relation between input/output and level of production is assumed to be linear. As an example we note that producing one ton of raw iron in a blast-furnace requires 2.3 tons of ore and 1.52 tons of coal.

Table 3: Input (−) and output (+) coefficients of the central products and processes of the mills in Ahmsa, Fundidora and Sicartsa.

Process / Product	Blast-furnace	Tempering in Martin oven	Tempering in oxygen oven
Iron ore, quality 1.00, ton	−2.30	–	–
Coal, ton	−1.52	–	–
Raw iron, ton	1.00	−1.06	−1.05
Steel, ton	–	1.00	1.00
Energy expenses, pesos	−63.5	−119.5	–
Other expenses, pesos	−720.0	−158.4	−179.6

Table 4: Input (−) and output (+) coefficients for the mills in Hylsa and Hylsap.

Process / Product	Reduction to sponge iron	Tempering in electro-oven
Ore, quality 1.00, ton	−2.11	–
Sponge iron, ton	1.00	−1.08
Steel, ton	–	1.00
Energy expenses, pesos	−187.0	−315.0
Other expenses, pesos	−5.5	−148.2

Only ore, coal, raw iron, sponge iron and steel are included in the tables. Other materials are aggregated in the entries energy expenses and other expenses. These entries cover the cost of natural gas, electricity, electrodes, salaries, and so forth. A division into energy cost and other cost is made, as the price of energy is expected to rise more rapidly than the prices of other materials and salaries in the near future.

Coal is given as the input to the blast-furnaces, although coke is used. The coal is processed to produce coke at the mill. By-products of this production, such as gas, are sold or used in other processes. In the costs given these differences have been accounted for. In the data given for the Martin oven we have ignored the possibility of mixing in extra iron ore, in order to simplify the problem. In addition we have ignored the possibility of including scrap-metal in the process, and adjusted the coefficients as described earlier.

The capacities of the different steel-producing processes at the different mills are given in Table 5. The costs for rolling the steel are given in Table 6.

Table 5: Capacity of the different processes, given in Mton output.

Steel mill / Process	Ahmsa	Fundidora	Sicartsa	Hylsa	Hylsap
Blast-furnace	4.30	2.40	1.20	–	–
Martin oven	1.95	0.95	–	–	–
Oxygen oven	2.17	1.60	1.40	–	–
Red. to sponge iron	–	–	–	1.08	1.10
Electro-oven	–	–	–	1.23	0.66
Plate production	3.50	2.20	1.40	1.30	1.00
Pipe production	1.50	1.20	0.55	0.20	–

Table 6: Costs for rolling 1 ton of steel.

Energy expenses, pesos	44.2
Other expenses, pesos	5.3

5 Demand

The demand is distributed over a large number of products, and it is neither practical nor possible to include all of them in a large-scale planning model. Hence the products have been aggregated to groups using approximately the same kind and amount of processing resources, making the products in a group interchangeable from a production perspective.

In this project we settle for only two groups, plates and pipes (including beams and bars). The rationale behind this division is that the newer mills almost exclusively produce plates, whereas the older mills have a more versatile production capacity.

The demand prognosis is given as a total demand for all of Mexico, given in Table 7, which is divided among the regions according to Table 8. The demand distribution is assumed to be equal for the two groups of products. As an example we note that Mexico City has a demand of $0.5 * 3.28 = 1.64$ tons of pipes per year.

Table 7: Demand of the two product groups.

Product group	Demand, Mton
Plates	5.08
Pipes	3.28

Table 8: Regional distribution of demand.

Area	%
Mexico City	50
Monterey	31
Guadalajara	19

6 Export and import

There is, of course, also a possibility to export and import raw material, intermediate products, plates, and pipes. However, as the cost of transportation is rather high, only import and export of plates and pipes will be of interest. You may assume that exporting goods (i.e., plates and pipes) will yield 2700 pesos per ton when delivered to a Mexican harbour, and importing goods will cost 3000 pesos per ton when delivered to a Mexican harbour. Hence, only domestic transportation costs need to be regarded.

In the following description of the transportation system, "Import" is included as an additional producer, and the distance given is the distance between the demand area and the closest harbour. In the same fashion "Export" is included as a consumer, and the distance given is the distance between each mill and the closest harbour.

7 The transportation system

The coal, the ore and the finished products are all transported by railway, and we assume that the transport capacity present is enough to serve the demand. Hence the transport system does not impose any restriction on the production, but the transportation costs will of course affect the optimal solution.

The transportation costs are divided into two parts. There is a starting cost for loading the goods and running the terminal. In addition to this there is a running cost proportional to the transportation distance. The distances between the mines and the mills are given in Table 9, and the distances from the mills to the demand areas are given in Table 10. Finally, the transportation costs are given in Table 11.

Table 9: Distances by rail from mines to mills (km).

Steel mill Mine	Ahmsa	Fundidora	Sicartsa	Hylsa	Hylsap
Coahuila	120	400	1500	400	1420
Penacol	1490	1396	337	1376	1116
Lastruchas	1416	1322	10	1312	995
Laperla	403	621	1797	626	1595
Cerro-Mer	677	636	1275	640	1245
El-Encino	1401	1307	965	1300	1033

Table 10: Distances by rail from producers (including import) to consumers (including export) (km).

Steel mill Dem. area	Ahmsa	Fundidora	Sicartsa	Hylsa	Hylsap	Import
Mexico City	1204	929	819	920	185	428
Monterey	218	10	1305	17	1085	521
Guadalajara	1125	1030	704	1033	760	300
Export	739	521	10	520	315	–

Table 11: Fixed and proportional transportation costs for raw materials and products.

Product group	Fixed costs, pesos/ton	Proportional cost, pesos/(ton*km)
Coal, ore	17.46	0.106
Plates	57.16	0.194
Pipes	57.16	0.204

8 Assignment

Your task is to write a report that describes a linear programming model for minimizing the total cost for supplying the demand of steel in Mexico. The linear program should be based on the data given in the Sections 3–7 (Section 2 is mainly intended as a general introduction to steel production).

An advantage of linear programming models is that they are quite easy to understand even for people with just basic knowledge of mathematics. This requires, however, that the variables, the objective function, and the constraints of the model are clearly defined. For the problem given in this paper it is appropriate to illustrate the flows of the different materials in a figure and then introduce a variable for each flow.

In the industry it is more likely that your model will be used if the managers understand it. One of the purposes of this assignment is that you should learn how to formulate a complex problem as an easily understandable linear program. Therefore we have the following requirements on your report:

- it shall include a figure illustrating the material flows of the problem;
- the variables must be clearly defined and connected to the figure;
- the objective function and the constraints should be clearly described;
- it must be written with a text formatting tool (e.g., LaTeX, Word, or FrameMaker); and
- it should look professional!

Before starting the modelling work you should read Section 8.1 in the course notes and Example 8.1 in particular. This example considers a small transportation problem and contains a figure that illustrates the material flows.

Since there is a lot of data in the problem you do not need to give explicit values of the coefficients in the model; on the contrary, we encourage the use of general notation, such as d_{ij} for the distance from mine i to mill j (see the compact formulation of Example 8.1). However, every coefficient introduced must be clearly defined!

The report should be written in *groups of two* (preferable) or *individually*. Names and personal code numbers of the group members as well as the account number (aopt-XX) should be given on the front page of the report. **Deadline for handing in the model report is January 28!**

To the groups that have delivered an accepted model report, we will later distribute a version of the model, implemented in AMPL, which will be used to answer questions in the second part of the project.

Good luck!