

A linear programming model for integrated steel production and distribution planning

Mingyuan Chen

University of Regina, Regina, Saskatchewan, Canada, and

Weimin Wang

Federated Co-Op, Saskatoon, Saskatchewan, Canada

Introduction

The ever increasing competitiveness of the world market is forcing a large number of manufacturing companies to optimize their operations to win business. Optimal production planning is one of the most useful tools for achieving this objective. Over the last two decades, researchers and practitioners have developed and implemented many optimal planning models and methods for material purchasing, shopfloor scheduling, capacity planning and other production functions (e.g. Beged-Dov, 1983; Gelders and Van Wassenhove, 1981; Hitomi, 1991; Kendall and Schniederjans, 1985; Martin *et al.*, 1993; Miller and Liberatore, 1988). Integrated production planning problems in the manufacturing industry were discussed by Tang *et al.* (1970) and Ware (1992). Steel production, a relatively simple production process, can be viewed as an integrated manufacturing process encompassing raw material procurement, semi-finished product supply, finished product making, and material distribution at different production stages. A number of researchers discussed and presented mathematical models for optimal steel production planning (including Bielefeld *et al.*, 1986; Lin and Moodie, 1989; Mohanty and Singh, 1992; Sasidhar and Achary, 1991).

In this paper, an integrated production planning problem in a major Canadian steel making company is discussed. The company has one central plant and several finishing factories in other locations. Different factories, material suppliers in various territories and customers in different geographic regions form an interactive material flow network. Production costs and throughput rates at different stages of production are considered in developing the model. Raw material and semi-finished product purchasing costs, product distribution and transportation costs are also taken into account. In order to find the optimal solution of such a complicated problem, an integrated planning

methodology was adopted and the problem was formulated as a linear programming model. Computations of example problems with practical production data were performed to test the model. Computation results and analysis show that high level financial benefit can be achieved through the use of the integrated planning methodology. Details of the production system, problem description and model development are presented in the following sections.

A modern steel production environment

We consider the following issues in developing the mathematical programming model for integrated steel production planning in the company:

- raw material purchasing;
- capacity allocation;
- semi-finished product provision and outside procurement;
- business and customer demands; and
- material supply and sales distribution.

The relationship of these factors is schematically shown in Figure 1.

The network shown in Figure 1 demonstrates that raw material suppliers (R), semi-finished product suppliers (S), factories (F) and customers (C) are interactively connected. Raw material suppliers provide the same type of materials (scrap steel) from different locations. The price of the scrap steel may be different from different suppliers.

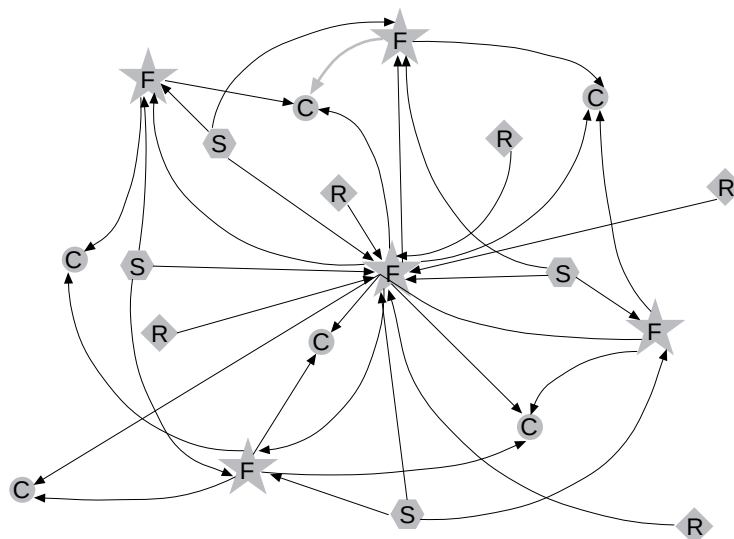


Figure 1.
Schematic
representation of
manufacturing network

Raw materials are shipped to the central steel plant and converted into semi-finished products (sheet, plate or coil products). Semi-finished products have different specifications corresponding to the types of end products (different types of steel pipes and other steel products) to be produced. During high demand seasons, purchasing semi-finished products may be necessary in order to satisfy business demands. Products are made according to business demands. Part of the demand is called “core business”. The amount of core business demand must be produced by the company to satisfy its long-term loyal customers. The rest of the demand is called “sales capacity” which is the forecasted demand in the current planning time period. Customers are located at different geographical regions, to where end products should be sent. Because of the wide variety of product types and different specifications, products are categorized into a number of groups. Each finishing factory concentrates on producing one or several product groups.

In each planning time period, available production capacities at the central steel mill and other finishing factories are limited. In good business seasons, the available production time at the central rolling mill is a critical factor. Because production rates are different for end products and semi-finished products, economical values of the scheduled periods of production time are different among products. Table I presents an example of production rates and profits in making two products, products A and B. It shows that product A can be produced at 31 tons per hour more than product B. However, the contribution margin (CM), or the net profit, of product A is \$1,553 less than that of product B.

	Production rate (tons/hour)	Unit CM ^a (\$/ton)	CM per hour (\$/hour)
Product A	125	53	6,625
Product B	94	87	8,178

^aCM, contribution margin – marginal profit excluding certain costs

Table I.
An example for product
comparison

This example illustrates that when planning production capacity, a planner must consider not only production rate, but also cost and profit. In a complicated steel manufacturing environment with a large volume of information on a wide variety of products and facilities, it is desirable to use properly developed mathematical models and computer information systems for optimal production planning.

The production planning framework

It is obvious that customers' demands are the driving force of production planning. In the company, the central plant production capacity is a critical factor in satisfying customers' demand. Capacity plans for the central rolling mill dominate semi-finished product purchasing and transportation. Sales

distribution is also of major concern in the integrated production planning. Figure 2 presents a framework of the traditional production planning process in the company. Under this system, the sales department provides business information and decides business satisfaction. The production operation division deals with facility allocation at different factories. Purchasing departments are responsible for raw material and semi-finished product purchasing.

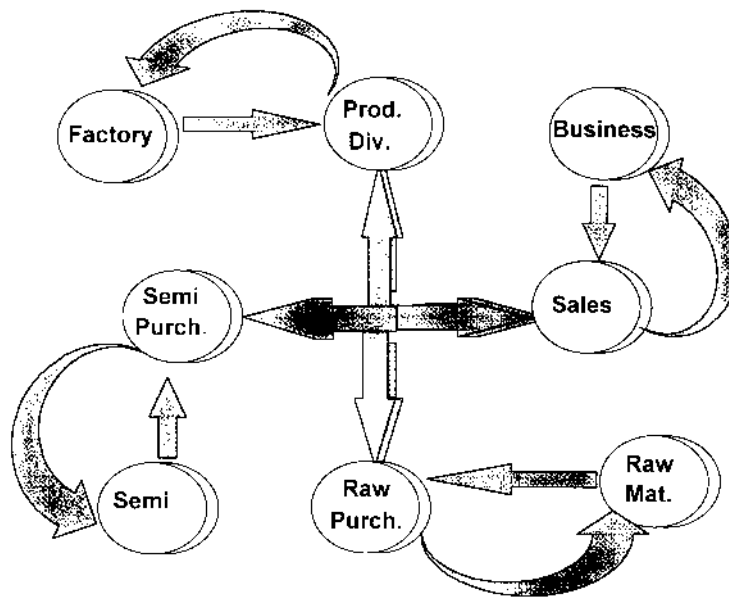


Figure 2.
Existing production
planning framework

Existing production planning framework

With this traditional approach, production planning is done separately by each department. Since market and production information change rapidly, this non-integrated planning approach faces certain difficulties in performing the planning work. Some of the disadvantages are:

- At each planning stage or in an individual department, planning work is performed separately. The planners use different information processing and presentation methods. Most of the planning work is done manually, including data input and alternative plan analysis.
- Information from other departments may not be used directly. This can cause information redundancy and time delay. On the other hand, a large volume of information exchange between departments is difficult and time consuming.
- The dynamic and fast-changing production situations may cause difficulties for planners to keep information up to date.

To address the above problems associated with the traditional planning practice, an integrated production planning procedure was developed. The general framework of this approach is shown in Figure 3. One of the important features of this framework is the planning kernel. Information from raw material purchasing, semi-finished product supply, and production and sales departments can be transmitted to this central planning programme. Optimal production plans are also generated from this programme. The generated optimal plans will then be disassembled and carried out at the lower operational levels in the system.

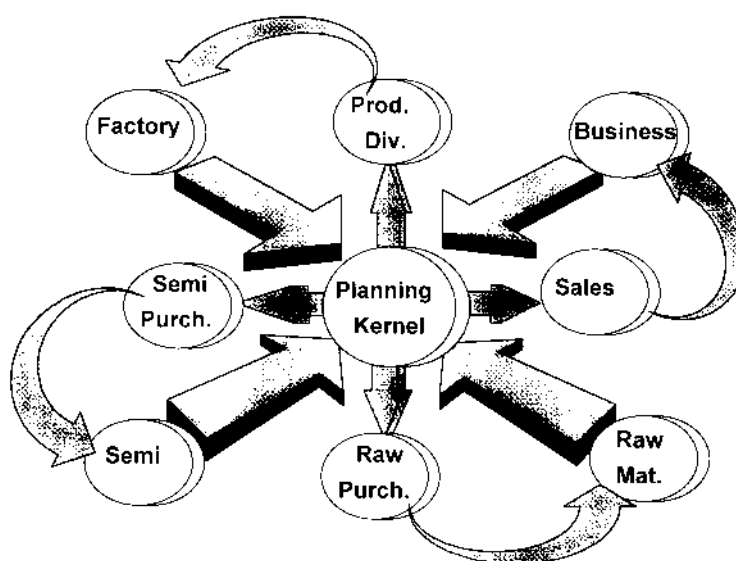


Figure 3.
Integrated production
planning framework

An integrated production and distribution planning model

In this section, the integrated production planning model based on the practical production conditions in the company is discussed in more detail.

A brief description of the production environment

Raw material supplies are limited within each supplier's territory and the price may vary with different territories. Raw material transportation cost depends mainly on the distance between the territory and the central plant. Each finished product corresponds to a certain type of semi-finished product. The production cost of a semi-finished product is usually lower than the purchasing cost of the same semi-finished product. Purchased semi-finished products may introduce an extra cost in finished goods production due to the slight difference in specifications usually associated with purchased semi-finished products. This extra cost is termed lowered production efficiency cost. The purchasing cost of a semi-finished product is also different from territory to territory. Finished product purchasing is not considered because the company would not

buy any product from other companies and sell it directly to its customers. Each semi-finished product has a unique production rate in the central plant. This rate is called rolling tons per hour. The yield from raw materials to semi-finished product is also an attribute of a semi-finished product. The yield value is usually an estimate and may not be very accurate. Different finished products have different production throughput rates. The yield from a semi-finished product to a finished product is determined by the processing procedure for each product. Each factory has a production capacity measured in total available production time. Total finishing production capacity of the company can normally satisfy total customers' demand but semi-finishing production capacity of the company may not satisfy the total demand. Selling prices of finished products depend on customer regions so that the same product may have different selling prices in different regions. Each finishing factory is dedicated to a certain number of product groups. Semi-finished products from any supplier's territory can be transported directly to these factories with different freight costs. Similarly, finished products from finishing factories are normally shipped to customers directly.

Modelling the system

We developed a linear programming formulation to solve the integrated production planning problems of purchasing, production and distribution. The model is intended to integrate the planning sub-functions into a single planning operation. Since the central steel making plant is the only one to produce semi-finished products in the company, all purchased raw materials are transported to this central plant. Semi-finished products are either provided by the central plant or obtained by the finishing factories directly from outside suppliers. In the latter case, the semi-finished products will be shipped directly from the suppliers to the demanding factories. The linearity of the cost function in the planning model is consistent with the business practice in the company. Raw material, semi-finished product or finished product inventory is not included in the model, since the company is more interested in a one time integrated planning model at this stage.

Model presentation

In presenting the mathematical programming model, the following notations are used.

Indices

- i = index of factories, $i \in \{0, \dots, I\}$. $i = 0$ refers to the central plant;
- j = index of raw material supplying territories, $j \in \{1, \dots, J\}$;
- k = index of territories of semi-finished product purchasing, $k \in \{1, \dots, K\}$;
- l = index of customer regions, $l \in \{1, \dots, L\}$;
- m = index of product groups, $m \in \{1, \dots, M\}$; and
- n_m = index of product items in group m , $n_1 \in \{1, \dots, N_j\}, \dots, n_m \in \{1, \dots, N_m\}$.

Parameters

(1) Raw material supply:

- Costs:
 RC_j = unit raw material purchasing cost from territory j .
- Capacities:
 L_j = supply capacity in raw material territory j .

(2) Production:

- Production costs:
 FC_{nm}^c = fixed cost in steel making at the central plant for product n_m (product item n in group m). Fixed costs are estimated consumption values of the company's fixed facility by different products. They actually work in the same way as variable costs;
 VC_{nm}^c = unit variable cost in steel making at the central plant for product n_m ;
 FF_{nm} = fixed cost of product n_m for finished good production; and
 VF_{nm} = unit variable cost of product n_m for finished good production.
- Production rates:
 PS_{nm} = production rate of semi-finished product, which will be used for producing finished product n_m ;
 PF_{nm} = production rate of finished product n_m ;
 YR_{nm} = yield percentage from raw materials to semi-finished product of product n_m ;
 YS_{nm} = yield percentage from semi-finished product to finished product n_m .
- Production capacity:
 τ^c = available production time for steel making at the central plant;
 τ_{im}^f = available production time for finished product group m at factory i .

(3) Semi-finished product purchasing cost:

$CS_{k,nm}$ = unit purchasing cost of semi-finished product corresponding to finished product n_m in territory k .

(4) Sales:

- Price:
 $PR_{l,nm}$ = unit selling price of product n_m in customer region l .

- Customer demand:

$DC_{l,nm}$ = amount of core business for product n_m in customer region l ;

$DF_{l,nm}$ = amount of sales forecast for product n_m in customer region l .

- (5) Transportation cost:

TR_j^c = unit transportation cost of raw materials from territory j to the central plant;

TS_i^c = unit transportation cost of semi-finished products from the central plant to factory i ;

$TS_{i,k}^f$ = unit transportation cost of semi-finished products from supplier's territory k to factory i ;

TF_{il} = unit transportation cost of finished products from factory i to customer region l .

Decision variables

$x_{il,nm}$ = amount of product n_m produced in factory i for customers in region l by using semi-finished product from the central plant;

$y_{il,nm}$ = amount of product n_m produced in factory i for customers in region l by using purchased semi-finished product;

$u_{ik,nm}$ = amount of semi-finished product purchased from territory k and used in factory i for producing product n_m ; and

w_j = amount of raw materials to purchase from territory j .

Additional terms used in presenting the objective and constraint functions of the model are introduced as needed. To determine an integrated optimal production plan, the following constraint conditions in the system are considered.

Model constraints

- (1) Raw material supply:

Amount of raw materials w_j purchased from territory j should not exceed the supplier's capacity L_j in that territory. This can be expressed by:

$$w_j \leq L_j, \quad \forall j. \quad (1)$$

Let $\bar{w}_{il,nm}$ be the amount of raw materials used to produce $x_{il,nm}$ tons of product n_m . Thus:

$$\bar{w}_{il,nm} = \frac{x_{il,nm}}{YR_{nm}YS_{nm}}.$$

Total amount of raw materials purchased for production cannot exceed those purchased from all territories. This is expressed by:

$$\sum_{i=0}^I \sum_{l=1}^L \sum_{m=1}^M \sum_{n=1}^{N_m} \bar{w}_{il,nm} \leq \sum_{j=1}^J w_j ,$$

i.e.

$$\sum_{i=0}^I \sum_{l=1}^L \sum_{m=1}^M \sum_{n=1}^{N_m} \frac{x_{il,nm}}{YR_{nm} YS_{nm}} \leq \sum_{j=1}^J w_j . \quad (2)$$

(2) Steel making capacity in the central plant:

Let $\bar{x}_{il,nm}$ be the amount of semi-finished products to produce $x_{il,nm}$ tons of finished product n_m , then:

$$\bar{x}_{il,nm} = \frac{x_{il,nm}}{YS_{nm}} .$$

The time required to produce semi-finished products $\bar{x}_{il,nm}$ at the central plant is:

$$\frac{\bar{x}_{il,nm}}{PS_{nm}} = \frac{x_{il,nm}}{YS_{nm} \cdot PS_{nm}} .$$

The amount of semi-finished products produced at the central plant is limited by its rolling capacity τ^c . This is expressed by:

$$\sum_{i=0}^I \sum_{l=1}^L \sum_{m=1}^M \sum_{n=1}^{N_m} \frac{x_{il,nm}}{YS_{nm} \cdot PS_{nm}} \leq \tau^c . \quad (3)$$

(3) Semi-finished product purchasing and production:

Let $\bar{y}_{il,nm}$ be the corresponding amount of semi-finished products to produce $y_{il,nm}$ tons of finished products. Then:

$$\bar{y}_{il,nm} = \frac{y_{il,nm}}{YS_{nm}} .$$

The total amount $\sum_{il=1}^L \bar{y}_{il,nm}$ should be less than the corresponding purchased amount, i.e.:

$$\sum_{l=1}^L \frac{y_{il,nm}}{YS_{nm}} \leq \sum_{k=1}^K u_{ik,nm} , \quad \forall i, \quad \forall n, \quad \forall m . \quad (4)$$

(4) Production capacities for finished products:

Let $\bar{\tau}_{,nm}$ be the corresponding finishing production time. Since $\sum_{il=1}^L (x_{il,nm} + y_{il,nm})$ is the amount of product n_m produced at factory i , then:

$$\bar{\tau}_{i, nm} = \sum_{l=1}^L \frac{(x_{il, nm} + y_{il, nm})}{YS_{nm}}.$$

The planned production amount of product n_m is subject to the available production time at factory i . Thus the constraint is:

$$\sum_{l=1}^L \sum_{n=1}^{N_m} \frac{(x_{il, nm} + y_{il, nm})}{YS_{nm}} \leq \tau_{im}^f, \forall i, \forall m. \quad (5)$$

601

(5) Customer demands:

Core business demands must be satisfied. In other words, the total amount of products n_m produced for customer region l must be greater than or equal to the corresponding core business, i.e.:

$$\sum_{i=0}^I (x_{il, nm} + y_{il, nm}) \geq DC_{l, nm}, \quad \forall l, \quad \forall n, \quad \forall m. \quad (6)$$

On the other hand, total production should not exceed forecasted total demand, i.e.:

$$\sum_{i=0}^I (x_{il, nm} + y_{il, nm}) \leq DF_{l, nm}, \quad \forall l, \quad \forall n, \quad \forall m \quad (7)$$

Objective function

The objective in solving the planning problem is to maximize the total net profit, which can be generally expressed as:

Total net profit = Total revenue – Total cost.

In this model, the total revenue is simply the total selling income:

$$\sum_{l=1}^L \sum_{m=1}^M \sum_{n=1}^{N_m} RP_{l, nm} \cdot \sum_{i=0}^I (x_{il, nm} + y_{il, nm})$$

Total cost contains more factors as discussed below:

- Raw material purchasing cost:

$$\sum_{j=1}^J RC_j \cdot w_j$$

- Fixed cost:

$$\sum_{i=0}^I \sum_{l=1}^I \sum_{m=1}^M \sum_{n=1}^{N_m} \{(FC_{nm}^c + FF_{nm}) \cdot x_{il, nm} + FF_{nm} \cdot y_{il, nm}\}$$

- Variable cost:

$$\sum_{i=0}^I \sum_{l=1}^L \sum_{m=1}^M \sum_{n=1}^{N_m} \{ (VC_{nm}^c + VF_{nm}) \cdot x_{il,nm} + VF_{nm} \cdot y_{il,nm} \}$$

- Semi-finished product purchasing cost:

$$\sum_{k=1}^K \sum_{m=1}^M \sum_{n=1}^{N_m} CS_{k,nm} \sum_{i=0}^I u_{ik,nm}$$

- Raw material transportation cost:

$$\sum_{j=1}^J TR_j^c \cdot w_j$$

- Semi-finished product transportation cost from central plant to other factories:

$$\sum_{i=1}^I TS_i^c \cdot \sum_{l=1}^L \sum_{m=1}^M \sum_{n=1}^{N_m} \frac{x_{il,nm}}{YS_{nm}}$$

- Semi-finished product transportation cost from supplier's territories to other factories:

$$\sum_{i=0}^I \sum_{k=1}^K TS_{i,k}^f \cdot \sum_{m=1}^M \sum_{n=1}^{N_m} u_{ik,nm}$$

- Finished product transportation cost:

$$\sum_{i=0}^I \sum_{l=1}^L TF_{i,l} \cdot \sum_{m=1}^M \sum_{n=1}^{N_m} (x_{il,nm} + y_{il,nm})$$

Summarizing the above discussed constraint and objective functions, the complete linear programming model can be expressed by:

$$\begin{aligned} \text{Maximize } Z = & \sum_{l=1}^L \sum_{m=1}^M \sum_{n=1}^{N_m} RP_{l,nm} \cdot \sum_{i=0}^I (x_{il,nm} + y_{il,nm}) - \sum_{j=1}^J RC_j \cdot w_j \\ & - \sum_{i=0}^I \sum_{l=1}^L \sum_{m=1}^M \sum_{n=1}^{N_m} \{ (FC_{nm}^c + FF_{nm}) \cdot x_{il,nm} + FF_{nm} \cdot y_{il,nm} \} \\ & - \sum_{i=0}^I \sum_{l=1}^L \sum_{m=1}^M \sum_{n=1}^{N_m} \{ (VC_{nm}^c + VF_{nm}) \cdot x_{il,nm} + VF_{nm} \cdot y_{il,nm} \} \end{aligned}$$

$$\begin{aligned}
 & - \sum_{i=1}^I TS_i^c \cdot \sum_{l=1}^L \sum_{m=1}^M \sum_{n=1}^{N_m} \frac{x_{il,nm}}{YS_{nm}} - \sum_{i=0}^I \sum_{k=1}^K TS_{i,k}^f \cdot \sum_{m=1}^M \sum_{n=1}^{N_m} u_{ik,nm} \\
 & - \sum_{i=0}^I \sum_{l=1}^L TF_{i,l} \cdot \sum_{m=1}^M \sum_{n=1}^{N_m} (x_{il,nm} + y_{il,nm})
 \end{aligned}$$

Subject to:

$$w_j \leq L_j, \forall j \quad (1)$$

$$\sum_{i=0}^I \sum_{l=1}^L \sum_{m=1}^M \sum_{n=1}^{N_m} \frac{x_{il,nm}}{YR_{nm} YS_{nm}} \leq \sum_{j=1}^J w_j \quad (2)$$

$$\sum_{i=0}^I \sum_{l=1}^L \sum_{m=1}^M \sum_{n=1}^{N_m} \frac{x_{il,nm}}{YS_{nm} \cdot PS_{nm}} \leq \tau^c \quad (3)$$

$$\sum_{l=1}^L \frac{y_{il,nm}}{YS_{nm}} \leq \sum_{k=1}^K u_{ik,nm}, \quad \forall i, \quad \forall n, \quad \forall m \quad (4)$$

$$\sum_{l=1}^L \sum_{n=1}^{N_m} \frac{(x_{il,nm} + y_{il,nm})}{YS_{nm}} \leq \tau_{im}^f, \forall i, \forall m \quad (5)$$

$$\sum_{i=0}^I (x_{il,nm} + y_{il,nm}) \leq DF_{l,nm}, \quad \forall l, \quad \forall n, \quad \forall m \quad (6)$$

$$\sum_{i=0}^I (x_{il,nm} + y_{il,nm}) \leq DF_{l,nm}, \quad \forall l, \quad \forall n, \quad \forall m \quad (7)$$

$$x_{il,nm}, y_{il,nm}, u_{ik,nm} \geq 0, \forall i, l, k, n, m \quad (8)$$

Example and analysis

The example problem

In this section, we present a numerical example to illustrate the integrated production planning model. Consider an example problem with three factories ($i = 3$) including the central plant that produces both semi-finished products and certain types of finished products. Raw material purchasing is from five territories ($j = 5$) and semi-finished product suppliers are located in two major territories ($k = 2$). Customers are in three different regions ($l = 3$). There are three principal product groups ($m = 3$), which consist of three, five and four finished product items respectively ($N_1 = 3$, $N_2 = 5$, and $N_3 = 4$). The available total

production time at the central plant τ^c is 1,200 hours which is the capacity of a two-month production period, not including machine maintenance time. Details of the data used in this example problem are given in Tables AI-AVII in the Appendix. The size of this linear programming example problem is relatively small with 227 variables and 124 constraints.

Computation results

Data in Tables AI-AVII in the Appendix were input into the linear programming model. An optimal solution was found for raw material purchasing, semi-finished product purchasing and production, as well as finished product production. The optimal solution was generated by a linear programming algorithm from the IMSL package residing in a VAX machine. The results are presented in Tables AVIII-AXI, also in the Appendix. The optimal solution of this example problem indicates that \$41.3840 million of revenue and \$7.8953 million of profit can be generated from the two months of production. Total cost is \$33.4887 million.

Result analysis

Sensitivity analysis and shadow price analysis were performed with the example problem. These analyses provide more information on the optimal solution. Such analyses are useful in a dynamic production and market environment.

Sensitivity analysis

Sensitivity analysis was carried out to investigate the impact of the input parameters on the optimality of the solution. It provides the information regarding individual (not combined) impacts on the result when some parameters of the model vary. In this model, production cost, production capacity and product selling prices are among the most important parameters. Specifically, the following input factors were considered in the analysis:

- fixed costs;
- variable costs;
- purchasing costs of raw materials;
- purchasing costs of semi-finished products;
- selling prices of finished products;
- transportation costs;
- business amount; and
- capacity of central steel making plant.

The IMSL program also output sensitivity analysis results of the linear programming model. However, the output needs to be converted to the real cost

terms and properly interpreted. After conversion and some routine calculations, we observe from the analysis that:

- Purchasing costs of semi-finished products and product selling prices have more significant impact on total revenue and cost than have transportation costs and raw material purchasing cost.
- Changes of fixed cost have significant impact on total profit.
- Total profit will be significantly increased if variable costs can be lowered.

The chart in Figure 4 shows the change ranges of these factors in which the optimal plan remains valid.

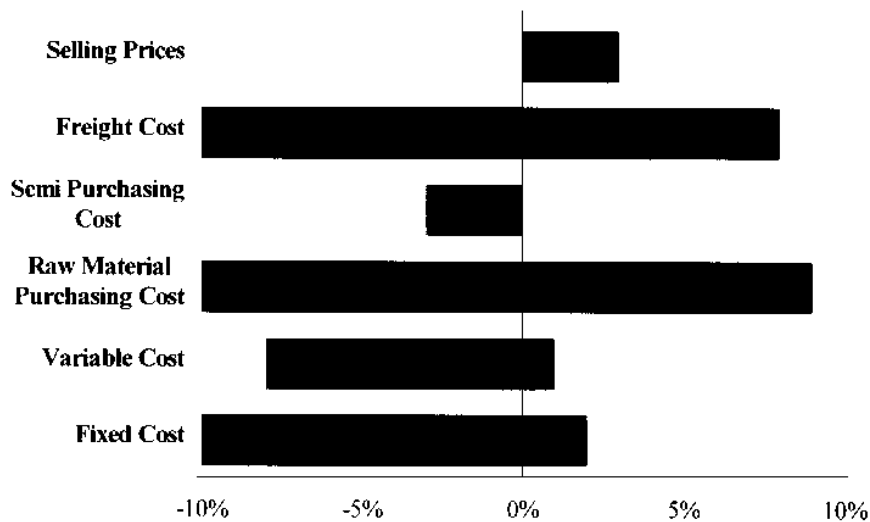


Figure 4.
Sensitivity analysis
observation summary

Shadow price analysis

Shadow price gives the net impact of additional units of resources on the optimal profit. The analysis is carried out on the following resources:

- available production time τ^c at central steel making plant;
- available production time τ_{im}^f for finished product making;
- capacity of raw material supply in each territory;
- core business requirement; and
- forecasted sales capacity.

Shadow price of available finished product making time is shown in Table II. As can be seen from this table, an extra hour of production time for making product group 2 in factory 0 can increase profit by \$91.09. An extra hour of production time for making product group 3 in factory 0 can increase profit by \$285.74. In factory 1, profit can be increased by \$189.41 if an extra hour is

available to produce product group 3. The increase of production time in factory 2 will not increase the profit. Similar phenomena have been observed from shadow price analysis on other resources.

Computation results of this example problem with the size of 124×227 were generated by the VAX machine in less than 100 seconds under a VMS time-sharing operating system. A realistic problem of a larger size (196×509) was also calculated using the same model. Similar results were obtained and similar analyses were conducted. It took about 230 seconds to find the optimal solution for this larger example on the same computer. This shows that the integrated planning approach is practical and can be used to solve real world production planning problems.

Table II.
Shadow prices of
capacity in finishing
production

	Product group 1 (\$)	Product group 2 (\$)	Product group 3 (\$)
Factory 0	0.00	91.09	285.74
Factory 1	0.00	0.00	189.41
Factory 2	0.00	0.00	0.00

Summary and conclusions

In this paper, an integrated approach for planning steel production in a major Canadian steel making company was discussed. A linear programming model was developed to formulate the production and transportation planning problem based on the company's system structure and production practice. The model was illustrated by a smaller sized example and tested by large sized realistic problems. Critical analysis was conducted to obtain in-depth knowledge of the system.

In conducting this research project in the company, real data were acquired and used with the help of the company's planning managers and staff. In the example problem presented in the previous section, typical and representative (not actual) data were used to calculate the results. A separate internal report of this project was submitted to the company and was highly evaluated and praised by the company's planning managers. As the authors are aware, the suggestions proposed in the report were taken by the company to set up detailed planning models using the same approach as discussed in this paper.

With the integrated planning approach, many benefits can be expected in planning large scale steel production. These can be highlighted as follows:

- More profit could be achieved under the current internal and external production conditions. Cross-functional operations can be optimized and overall optimality can be obtained.

- Planning following the integrated approach will result in improved efficiency and less information redundancy.
- It will strengthen management capability since production plans are supported by well developed mathematical models and various analyses can be easily performed.

In order to implement the integrated planning approach properly, a company must involve all major planning operations in model construction and data processing. The company must have a comprehensive and well maintained central database to interface with the model so that the results can be generated quickly and reliably. We believe that the same generic approach can be extended and used to solve planning problems in other similar systems. In the next stage of our research, we plan to develop a more comprehensive model to solve multiple time period planning problems following the same integrated production planning approach.

References

- Beged-Dov, A.G. (1983), "Determination of optimal product mix by marginal analysis", *International Journal of Production Research*, Vol. 21, pp. 909-18.
- Bielefeld, F.W., Walter, K.D. and Wartmann, R. (1986), "A computer-based strategic planning system for steel production", *Interfaces*, Vol. 16, pp. 41-6.
- Gelders, L.F. and Van Wassenhove, L.N. (1981), "Production planning: a review", *European Journal of Operational Research*, Vol. 7, pp. 101-10.
- Hitomi, K. (1991), "Strategic integrated manufacturing systems: the concept and structures", *International Journal of Production Economics*, Vol. 25, pp. 5-12.
- Kendall, K.E. and Schniederjans, M.J. (1985), "Multi-product production planning: a goal programming approach", *European Journal of Operational Research*, Vol. 20, pp. 83-91.
- Lin, C.W. and Moodie, C.L. (1989), "Hierarchical production planning for a modern steel manufacturing system", *International Journal of Production Research*, Vol. 27, pp. 613-28.
- Martin, C.H., Dent, C. and Eckhart, J.C. (1993), "Integrated production, distribution, and inventory planning at Libbey-Owens-Ford", *Interfaces*, Vol. 23, pp. 68-78.
- Miller, T. and Liberatore, M. (1988), "Implementing integrated production and distribution planning systems", *International Journal of Production & Operations Management*, Vol. 8, pp. 31-41.
- Mohanty, R.P. and Singh, R. (1992), "A hierarchical production planning approach for a steel manufacturing system", *International Journal of Operations & Production Management*, Vol. 12, pp. 69-78.
- Sasidhar, B. and Achary, K.K. (1991), "A multiple arc network model of production planning in a steel mill", *International Journal of Production Economics*, Vol. 22, pp. 195-202.
- Tang, J.C.S., Adulbhan, P. and Zubair, T. (1979), "An aggregate production planning for a heavy manufacturing industry", *European Journal of Operational Research*, Vol. 3, pp. 22-9.
- Ware, N. (1992), "Integrated manufacturing planning", *Industrial Management & Data Systems*, Vol. 2, pp. 24-6.

Appendix: input and output data of the example problem

Product group	1			2					3			
Product item	1	2	3	1	2	3	4	5	1	2	3	4
Rate 1 (tons/hr)	56	75	65	47	47	52	56	60	50	54	45	45
Rate 2 (tons/hr)	75	114	85	95	87	87	115	110	105	92	92	88
Yield 1 (%)	45	40	38	40	34	42	39	44	52	41	46	46
Yield 2 (%)	85	80	80	75	75	85	85	90	80	85	90	85

Notes:

Rate 1 = Production efficiency rate in semi-finished product making

Rate 2 = Production efficiency rate in finishing process

Yield 1 = Yield percentage from raw material to semi-finished product

Yield 2 = Yield percentage from semi-finished product to finished goods

Table AI.
Production rate

Product group	1			2					3			
Product item	1	2	3	1	2	3	4	5	1	2	3	4
Fixed cost 1	40	30	33	50	42	44	39	47	36	34	40	43
Fixed cost 2	50	54	45	52	57	49	44	50	43	47	50	45
Variable cost 1	121	135	125	142	145	150	133	142	129	130	132	141
Variable cost 2	105	110	106	120	112	96	115	110	124	118	104	95
Semi cost $k = 1$	196	235	238	215	243	305	310	235	224	263	281	274
Semi cost $k = 2$	205	254	245	232	237	305	293	250	231	245	258	270
Product price $l = 1$	410	440	461	496	412	487	492	502	515	520	508	530
Product price $l = 2$	425	425	423	514	454	490	513	491	502	506	516	519
Product price $l = 3$	433	452	440	530	461	512	520	486	522	515	522	527

Notes:

Fixed cost 1 = Fixed cost in steel making process

Fixed cost 2 = Fixed cost in finished goods production process

Variable cost 1 = Variable cost in steel making process

Variable cost 2 = Variable cost in finished goods production process

Table AII.
Production cost

Product group	1			2					3			
Product item	1	2	3	1	2	3	4	5	1	2	3	4
$l = 1$	2,450	1,850	2,200	3,100	2,540	1,800	2,200	1,620	3,500	1,750	3,600	2,950
$l = 2$	2,100	3,420	1,000	2,550	1,950	950	3,620	2,850	3,750	3,200	4,160	1,150
$l = 3$	1,550	1,650	2,450	3,250	2,750	1,100	3,600	1,650	3,540	2,100	3,500	1,950

Table AIII.
Sales capacity forecast

Product group	1			2					3			
Product item	1	2	3	1	2	3	4	5	1	2	3	4
$l = 1$	1,100	1,500	1,250	950	1,450	850	1,400	1,620	2,100	1,750	1,620	1,350
$l = 2$	1,540	1,250	1,000	1,500	1,220	950	1,600	1,320	1,400	1,640	1,270	1,150
$l = 3$	980	1,240	1,200	1,450	1,350	1,100	1,750	850	1,360	1,050	960	840

Table AIV.
Core business demand

						Linear programming model 609							
<i>Raw material</i>													
Territory	<i>j</i> = 1	<i>j</i> = 2	<i>j</i> = 3	<i>j</i> = 4	<i>j</i> = 5								
Unit cost	8.0	10.0	15.0	21.0	27.0								
	Factory 0		Factory 1		Factory 2								
<i>Semi freight cost 1</i>													
Unit cost	0.0		14.0		23.0								
<i>Semi freight cost 2</i>													
Territory 1	25.0		29.0		18.0								
Territory 2	21.0		24.0		28.0								
<i>Freight cost of finished product</i>													
<i>l</i> = 1	15.0		22.0		18.0								
<i>l</i> = 2	25.0		16.0		21.0								
<i>l</i> = 3	19.0		27.0		29.0								
	Factory 1		Factory 2		Factory 3								
Product group 1	0		620		390								
Product group 2	740		0		540								
Product group 3	820		570		0								
Territory	<i>j</i> = 1	<i>j</i> = 2	<i>j</i> = 3	<i>j</i> = 4	<i>j</i> = 5								
Amount (tons)	63,000	47,000	55,000	60,000	50,000								
Note: The available production time at the central steel making plant $\tau^c = 1,200$ hours, which represents a two-month planning horizon excluding machine maintenance time													
Territory	1	2	3	4	5	Total							
Amount (tons)	65,000	47,000	36,741	0	0	148,741							
Unit cost (\$/tons)	12	16	19	23	28								
Sub-total cost (\$)	780,000	752,000	698,078	0	0	2,230,079							
From	<i>m</i> = 1			<i>m</i> = 2			<i>m</i> = 3			To			
Territory	<i>n</i> = 1	<i>n</i> = 2	<i>n</i> = 3	<i>n</i> = 1	<i>n</i> = 2	<i>n</i> = 3	<i>n</i> = 4	<i>n</i> = 5	<i>n</i> = 1	<i>n</i> = 2	<i>n</i> = 3	<i>n</i> = 4	factory
<i>k</i> = 1	1,824	0	0	0	0	0	0	0	0	0	0	0	<i>i</i> = 0
	0	0	0	0	1,933	0	0	0	0	0	0	0	<i>i</i> = 1
	0	0	0	0	0	0	0	0	0	0	0	0	<i>i</i> = 2
<i>k</i> = 2	0	0	0	0	3,427	0	0	0	0	0	0	0	<i>i</i> = 0
	5,353	0	0	11,867	0	0	0	6,800	6,618	0	0	0	<i>i</i> = 1
	0	0	0	0	0	0	0	0	0	0	0	0	<i>i</i> = 2
Table AIX. Optimal semi-finished product purchasing plan (tons)													

IJOPM
17,6

610

Table AX.
Optimal end product
production plan

Product group	1					2					3				Customer
Product item	1	2	3	1	2	3	4	5			1	2	3	4	region
Factory 0	0	1,850	2,200	0	1,450	1,800	2,200	0			0	1,064	0	0	$l=1$
	0	1,250	1,000	0	0	704	3,620	0			1,955	282	0	0	$l=2$
	1,550	1,650	2,450	0	0	1,100	3,600	0			3,540	2,100	3,500	1,950	$l=3$
Factory 1	0	0	0	0	0	0	0	0			0	0	0	0	$l=1$
	0	0	0	0	1,220	246	0	0			0	2,918	4,160	1,150	$l=2$
	0	0	0	0	1,350	0	0	0			0	0	0	0	$l=3$
Factory 2	2,450	0	0	3,100	0	0	0	1,620			3,500	686	3,600	2,950	$l=1$
	2,100	0	0	2,550	0	0	0	2,850			1,795	0	0	0	$l=2$
	0	0	0	3,250	0	0	0	1,650			0	0	0	0	$l=3$

Note: The amount is obtained by $X_{il,nm} + y_{il,nm}$

Table AXI.
Production plan of
semi-finished products
in the central plant

Product group	$m = 1$			$m = 2$					$m = 3$			
Product item	$n = 1$	$n = 2$	$n = 3$	$n = 1$	$n = 2$	$n = 3$	$n = 4$	$n = 5$	$n = 1$	$n = 2$	$n = 3$	$n = 4$
Factory 0	0	5,938	7,060	0	0	4,240	11,082	0	6,869	4,036	3,889	2,167
Factory 1	0	0	0	0	0	289	0	0	0	3,433	4,622	1,353
Factory 2	0	0	0	0	0	0	0	0	0	807	4,000	3,471

Note: The amount is obtained by $\sum_{l=1}^L \frac{X_{il,nm}}{YR_{nm}}$