Creating a Green Supply Chain

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This paper presents a case study of a supply chain that is concerned with the distribution of aluminium metal, starting from raw material from a metal supplier to a casting plant, billets from the casting plant to the component producer, and, finally, die-cast components from the component producer to the market. The paper creates a green supply chain by integrating the concerns of transport pollution, marketing costs, time to market, recycling of scrap metal and energy conservation. Simulation and modelling tools are introduced to aid in the decision-making process of distance selections and choices of transportation in the case study. Based on a series of user-input selections, the simulation results are used to determine a range of optimal plant locations that will balance economic benefits (highest scrap values, least total costs, etc.) as well as environmental stewardship (least pollution).

- **Supply chain**
- **Simulation**
- **Transport pollution**
- **Marketing costs**
- **Decision-making**

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Introduction

BUSINESS ORGANISATIONS ARE FACING THE INCREASING PRESSURE OF BALANCING marketing and environmental (green) performance. This is an issue that is becoming more important to the public (Shultz and Holbrook 1999). In order to demonstrate good environmental management and sustainability, companies must learn to embrace a wide range of issues. Included are sustainable development, pollution and the community at large. The idea of green businesses forces the re-examination of the very purpose of a company's existence (Hick 2000). Adoption of greener management practices as part of an enterprise's policy is increasingly turning into a major strategic thrust in business organisations and is likely to carry on well into the 21st century (Stead and Stead 2000). This calls for a new approach to performing business, from merely achieving economic profit to developing ecologically sensitive strategic management policies. There are various approaches adopted by many enterprises in creating green enterprises, such as adopting eco-efficiency methods in the design of products (Hibbert 1998; Ottman 1999) or establishing industrial ecologies (Matthias 1999).

This paper looks at the creation of green enterprises from yet another perspective. We offer a unique approach by developing a simulation model for a supply chain that helps to achieve optimal performance (low marketing cost, fast delivery time, etc.) and least transport pollution. The conservation of energy and promotion of recycling scrap metal are also considered in the supply-chain case study.

Supply-chain management

Supply-chain management usually takes into consideration issues of minimising end cost (market cost), efficient logistical aspects and timely delivery of goods (Cox 1999). However, at the beginning of the 21st century, a shift in focus can be observed. For example, business chain partners were formed to participate in implementing environmentally friendly practices that reduce waste and pollution (Melnyk and Handfield 1996). In this paper, we take a look at the green or environmental concerns of a supply chain. One of the approaches adopted is by taking into consideration the levels of pollution from the various modes of transportation between plants.

Transport pollution

The transfer of raw material and goods from one plant to the next in a supply chain occurs by various modes of transportation: namely, by land, air or sea. The levels and types of transport pollution depend on the combination of two factors: the type of transportation and the distance travelled.

The pollution from diesel engine vehicles, such as heavy trucks, include gaseous pollutants such as carbon monoxide (CO), oxides of nitrogen (NO_x), particulate matter and volatile organic compounds (VOCs). Some hydrocarbons (including VOCs) from diesel emissions are carcinogenic. VOCs are known to affect, or are suspected of affecting, human health. NO_x are invisible, toxic gases that can form fine aerosol particles or salts that can contribute to acid rain or fog. Fuel from engines that are not highly efficient may be emitted as particulate matter. Toxic and cancer-causing chemicals can be carried by particulate matter into the lungs. Moreover, ozone and particulate matter are associated with adverse health and welfare effects, including respiratory illness, environmental damage and visibility problems, such as haze (US EPA 2000).

The impact of transport pollution can also be assessed in monetary terms: the cost of healthcare, the cost of days of work lost and the economic cost of premature deaths. In

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the UK , for example, environmental economists have estimated the cost of air pollution from road transport at £19.7 billion a year (Ashden Trust 1994). Many other researchers have discussed the problems of pollution in greater detail (e.g. Flachsbart 1999; Colvile *et al.* 2001).

Sustainable issues in aluminium production

In the aluminium production industry, cost-effective methods are needed to address issues arising from the scrap metal generated during the production stages. These issues involve the casting plant, which produces the aluminium billets, and the component producer, which produces die-cast or forged components. The locations of the plants have to be selected in a manner that will promote convenience—in terms of distance travelled and monetary returns—regarding the recycling of scrap metal.

Another issue concerning sustainable development is the conservation of energy. An increasingly deregulated power industry is scrambling to keep pace with strong customer demand. This has forced many manufacturers to have a vested interest in reducing the costs of energy, which often represent a substantial portion of the total operating expenses (Quinn 2001). This issue is especially addressed at the metal suppliers and in the casting plants, which each consume a huge amount of energy for the melting of metal. This necessitates the casting plant to be located close to the metal supplier so that molten metal may be supplied by the latter. (The theoretical amount of electricity required to melt 1 tonne of aluminium is 294 kWh; see Street 1986.)

Simulation and speed

Time and speed are crucial in today's fast-paced competitive markets. Owing to hypercompetition, enterprises that are not keeping pace with fluid marketing demands and changes may lose out to competitors that have the advantage of faster and speedier deliveries arising from well-planned plant locations and good marketplace selections. Therefore computer simulation is a useful tool offering a wide range of decision scenarios, saving time, energy and cost.

Simulation software

ProcessModel (ProcessModel 2000) is a simulation software package that is commercially available for designing and improving systems. This software combines flowchart technology and simulation to allow operations to be studied from a holistic view. It allows the testing of different options or 'what if' scenarios to aid managers, planners and decision-makers in assessing and analysing their company's processes or activities. By using activity charts to describe a sequence of actions (or decision-making processes), the outcome of each action or decision becomes more transparent. The software allows users to create simulation models by using simple programming and mathematical formulae (also known as model logic).

The advantage of the simulation software and its application to improving industrial processes to achieve more sustainable business results have been presented by various researchers. As a first example, it has been demonstrated how the 'tragedy of the commons' (Hardin 1986) was 'reinvented' by companies that did not consider resource preservation and recycling activities a part of their business plan (Spedding *et al.* 1999). In a second example, simulation tools have been used to track production costs, pollution and waste levels, and a smelter company's performance was measured based on two decisions—the first to allow the system to 'run as usual', and second to implement

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more sustainable operations (Khoo *et al.* 2001). In a third case, suggestions were made as to how simulation could be developed to integrate sustainable efforts or environmental management into a complete business model (Taplin *et al.* 2001). These examples demonstrated how simulation tools have facilitated the dissemination of information and the visual verification of making the right decisions while saving time and costs.

Objectives and layout

This paper offers a unique simulation approach to aid the creation of a green supply chain, consisting of four plants, to achieve:

- A balance of low total market cost and low transport pollution
- Fast deliveries between plants
- Promotion of recycling of scrap metal
- Conservation of energy
- The use and application of simulations in decision-making and for creating greener business practices

The paper is laid out as follows. The following section introduces the case study and the four plants of the supply chain. The cost and pollution variables of the plants are also described. Next, the details of the boundary distances of the plants, the location settings and the transport types within the supply chain are presented. Four types of location are designed for the simulation study. We go on to present the simulation results, followed by a section on final results, with discussion. Finally, we provide a conclusion.

Case study of a supply chain

The supply-chain case study involves the distribution of metal, starting with metal ingots from the supplier to the casting plant, billets from the casting plant (or pilot plant) to the component producer and, finally, finished (die-cast or forged) components to the market or end-user. The casting plant produces billets made of aluminium mixed with various types of alloy. The billets are produced to fill a marketing niche where the demand for weight reduction in material is sought. This type of light metal provides a sustainable and environmentally friendly solution to improving energy efficiency in the aerospace, electronics and automotive industry. The component producer is a typical die-casting company that produces small precision components, with specialised design, tooling and net-shaped production processes for the die-cast components. The supply chain, including the transport pollution and recycling activities, is shown in Figure 1.

Marketing time, cost and pollution variables

The pollution and costing factors (inventory, scrap metal values and total costs) of the four plants within the chain are dependent on the following:

- Distances between plants
- Types or modes of transport between plants

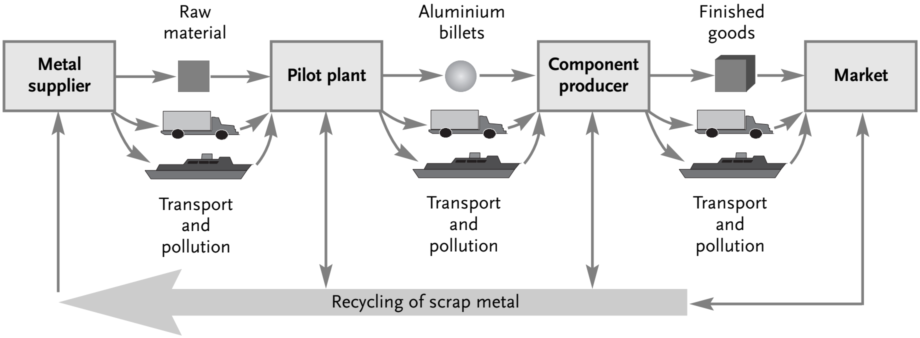

Figure 1 SUPPLY-CHAIN CASE STUDY

- ▶ Amount of metal processed and transferred between the plants
- ▶ The choice of location to which to send the scrap metal

All calculated results of total transport cost, inventory cost and scrap metal values are performed according to the data displayed in Table 1. The transport pollution data used for the case study is displayed in Table 2.

Cost or value	*Distance between plants (km)*			
	0.5	500	500–1,500	1,500–5,000
Scrap value (as a percentage of metal tonnage value)				
Casting plant	10	2	2	2
Component producer	10	2	2	2
Inventory costs (as a percentage of production costs)				
Casting plant	1	5	8	10
Component producer	1	5	8	10
Transportation costs (in Australian dollars per tonne per kilometre)*				
Forklift truck	1.00	n/a	n/a	n/a
Truck	n/a	0.15	0.13	0.12
Rail	n/a	0.10	0.09	0.08
Ship	n/a	n/a	n/a	0.05

* Speed of transport: forklift truck, 10–25 kmh; truck, 70–80 kmh; train, approximately 50 kmh; ship, approximately 18 kmh.

Table 1 SCRAP VALUES, INVENTORY COSTS AND TRANSPORTATION COSTS

Except for the metal supplier, the total accumulative cost of each plant is calculated according to the plant's respective distances from the previous member of the supply chain (i.e. the distance of the casting plant from the supplier, the distance of the component producer from the casting plant and so on). The final total costs for the various plants are calculated as follows.

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Vehicle (g/l)	***Pollutant (g/l)***			
	NO_x	VOCs	CO	PM
Trucks*	11.4	3.7	6.7	4.2
Rail**	59.75	4.315	9.1	4.315
Ship†	18,761.3	126.4	2.362	200
Forklift truck‡	37.6	0	20.3	1.6

* Capacity up to 20 tonnes and fuel consumption 50 l per 100 km

** Capacity up to 1,500 tonnes and fuel consumption 400–500 l per 100 km

† Generator power approximately 600 kW

‡ Capacity up to 4 tonnes and fuel consumption 5–6 l per 18 km

Note: NO_x = nitrogen oxides; VOCs = volatile organic compounds; CO = carbon monoxide; PM = particulate matter

Table 2 VEHICLE POLLUTION STATISTICS

Source for figures on trucks and ships: QEPA 1999
Source for figures on rail transport and forklift trucks: US EPA 2000

For the metal supplier, the total cost per tonne, $C^{\mathrm{MS}}(\text{total})$, is:

$$C^{\mathrm{MS}}(\text{total}) = C(\text{metal}) \qquad [1]$$

where $C(\text{metal})$ is the cost of metal per tonne.

For the casting plant, the total cost, $C^{\mathrm{CP}}(\text{total})$, is:

$$\begin{aligned} C^{\mathrm{CP}}(\text{total}) = {} & C^{\mathrm{MS}}(\text{total}) + C^{\mathrm{CP}}(\text{inventory}) - R^{\mathrm{CP}}(\text{scrap}) + C^{\mathrm{MS-CP}}(\text{transport}) \\ & + C^{\mathrm{CP}}(\text{scrap}) + C^{\mathrm{CP}}(\text{process}) \qquad [2] \end{aligned}$$

where $C^{\mathrm{CP}}(\text{inventory})$ is the cost of the casting-plant inventory, $R^{\mathrm{CP}}(\text{scrap})$ is the return on casting-plant scrap value, $C^{\mathrm{MS-CP}}(\text{transport})$ is the total cost of transport from the metal supplier to the casting plant, $C^{\mathrm{CP}}(\text{scrap})$ is the total cost of transport to send scrap from the casting plant and $C^{\mathrm{CP}}(\text{process})$ is the total metal process cost at the casting plant.

For the component producer (component maker), the total cost, C^{CM}, is:

$$\begin{aligned} C^{\mathrm{CM}}(\text{total}) = {} & C^{\mathrm{CP}}(\text{total}) + C^{\mathrm{CM}}(\text{inventory}) - R^{\mathrm{CM}}(\text{scrap}) + C^{\mathrm{CP-CM}}(\text{transport}) \\ & + C^{\mathrm{CM}}(\text{scrap}) + C^{\mathrm{CM}}(\text{process}) \qquad [3] \end{aligned}$$

where $C^{\mathrm{CM}}(\text{inventory})$ is the cost of the component-producer inventory, $R^{\mathrm{CM}}(\text{scrap})$ is the return on component-producer scrap value, $C^{\mathrm{CP-CM}}(\text{transport})$ is the total cost of transport from the casting plant to the component producer, $C^{\mathrm{CM}}(\text{scrap})$ is the total cost of transport to send scrap from the component producer and $C^{\mathrm{CM}}(\text{process})$ is the total metal process cost at the component producer.

For the market (end-user), the total cost, $C^{\mathrm{m}}(\text{total})$, is:

$$C^{\mathrm{m}}(\text{total}) = C^{\mathrm{CM}}(\text{total}) + C^{\mathrm{CM-m}}(\text{transport}) \qquad [4]$$

where $C^{\mathrm{CM-m}}(\text{transport})$ is the total cost of transport from the component producer to market.

The possible modes of transportation are by truck (type 1), by truck and rail (type 2) or by truck and ship (type 3). It was decided that the mode of transport for a distance of 0.5 km is a forklift truck (type 4). The reason for this decision is based on the actual situation; a great deal of time may be saved at the loading and unloading of material onto trucks.

The trucks used in the model are assumed to have a carrying capacity of 20 tonnes and the forklift trucks are assumed to have a carrying capacity of 4 tonnes. This means that the number of trucks and forklifts travelling in the model depends on the amount of metal travelling through the system. In selecting transport types 2 and 3, the truck travelling distance to the rail or seaport is assumed to be 10 km. The sample calculations for the four transportation selections are as follows.

The total transport cost for transport types 1 and 4, $C_v(\text{transport})$, is:

$$C_v(\text{transport}) = d_v \times C_v(w, d) \times w \times n_v \qquad [5]$$

where d_v is the distance travelled by vehicle v (here, v = truck or forklift truck), $C_v(w, d)$ is the cost of vehicle v per tonne per distance, w is the amount of metal in tonnes and n_v is the number of vehicles used.

The total transport cost for transport type 2, $C_2(\text{transport})$, is:

$$C_2(\text{transport}) = [d_{\text{truck}} \times C_{\text{truck}}(w, d) \times w \times n_{\text{truck}}] + [d_{\text{rail}} \times C_{\text{rail}}(w, d) \times w] \qquad [6]$$

where d_{truck} and d_{rail} is the distance travelled by truck and rail, respectively, $C_{\text{truck}}(w, d)$ and $C_{\text{rail}}(w, d)$ is the cost of truck per tonne per distance and the cost of train per tonne per distance, respectively, and n_{truck} is the number of trucks used. Similarly, for transport type 3, the total cost is:

$$C_2(\text{transport}) = [d_{\text{truck}} \times C_{\text{truck}}(w, d) \times w \times n_{\text{truck}}] + [d_{\text{ship}} \times C_{\text{ship}}(w, d) \times w] \qquad [7]$$

The 'time to deliver' is the amount of travel time spent in delivering the goods between the plants. The total time to deliver, $t(\text{total})$, is:

$$t(\text{total}) = [s_v \times d^{\text{MS–CP}}] + [s_w \times d^{\text{CP– CM}}] + [s_x \times d^{\text{CM–m}}] \qquad [8]$$

where s_v, s_w and s_x are the travel speeds of vehicles v, w and x, respectively (v, w, x = truck, forklift truck, train or ship); $d^{\text{MS–CP}}$ is the distance between the metal supplier and the casting plant; $d^{\text{CP–CM}}$ is the distance between the casting plant and the component producer; and $d^{\text{CM–m}}$ is the distance between the component producer and the market.

Boundary distances and location cases

The boundary distance of the supply chain is defined as the approximate distance between the metal supplier and potential market (end-user). These distances are selected on the basis of a country such as Australia with a number of major cities. Within a city the distance between two plants is not likely to exceed 50 km. If, for example, some plants are in one city and some in another, then the distance between the cities is approximated to be 1,000–2,500 km. If one (or more) of the plants is (are) located offshore, or in another country, then the condition may be stretched to 5,000 km or to 10,000 km. It is most practical that the locations of at least two consecutive plants be situated side by side, in order to:

- Promote scrap metal recycling activities. The scrap metal is generated from both the casting plant and the component producer and yields the highest value when being sent to the next-closest plant; scrap metal may be sent only to the supplier, casting plant or market.
- Save on transportation costs and minimise pollution. In the case where two plants are located at a 'close' distance of approximately 0.5 km, forklifts may be selected as the transport mode between the plants; otherwise, alternative transport types may be selected.

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Therefore, the distances and transport selections that are tested for the simulation runs are designed according to the four location settings shown in Figure 2: location cases A, B, C and D.

Simulation model

Computer simulation is used to provide a fast and efficient method of capturing the outcomes of decisions. The function and purpose of the simulation model is to trace and compute the costing and pollution variables (from Tables 1 and 2) throughout the supply chain from beginning to end. The simulation model accepts the distances between plants as user input values and generates the cumulative total costs and pollution levels, based on the distances entered.

It is designed first to establish the location of the casting plant with reference to the metal supplier. The next user input selections determine the location of the component producer with reference to the casting plant, and, finally, the location of the market with reference to the component producer. If 'far' distances are selected, user input choices are also made for the different types (1, 2 or 3) of transportation.

The simulation model is shown in Figure 3. An example of the user input pop-up menu provided by the model is displayed in Figure 4.

Simulation runs

Based on user input selections, the simulation model generates sets of results. A total of 40 simulation runs are performed, all taking into account the four location cases and transport types. The simulation entries are shown in Table 3. In each simulation run, the amount of metal entered into the system is 1,000 tonnes.

Simulation results

Figures 5 and 6 display the total transport costs and total pollution, respectively. Figure 7 displays the total marketing costs of the supply chain. The total time to deliver is displayed in Figure 8.

From the simulation results, a margin is selected for 'low' values of total cost and pollution. The final assessment of the best range of locations from the simulation runs is based on the following.

The runs giving 'low' values of total transport pollution are:

1, 2, 3, 5, 8, 9, 10, 12, 15, 16, 17, 19, 22, 23, 24, 25, 26, 28

The runs giving 'low' values of total market cost are:

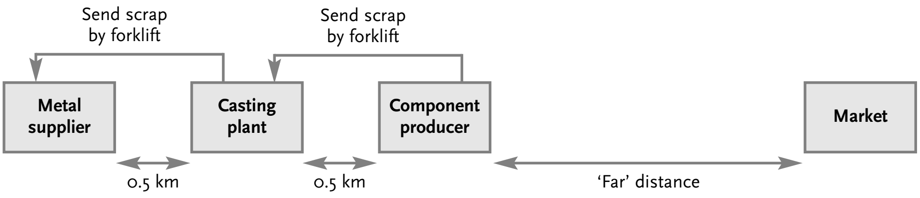
1, 3, 5, 8, 10, 12, 15, 17, 19, 24, 26, 28, 33

The matching numbers for balancing minimum costs and pollution are thus:

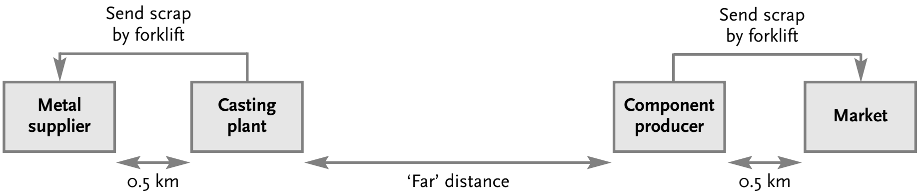
1, 3, 5, 8, 10, 12, 15, 17, 19, 24, 26, 28

With reference to Table 3, run 1 is a case A location setting with a distance of 625 km between the component producer and market. The transportation selected between the last two plants is of type 1 (trucks only).

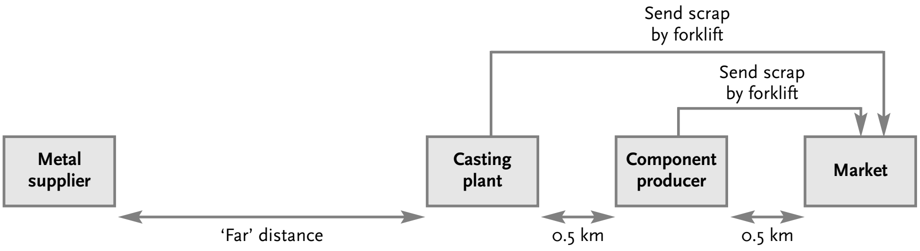
Runs 3 and 5 refer to a Case A location setting with a type 2 (trucks and rail) transportation mode between the 'far distance' plants. Runs 8, 10 and 12 are for Case B location



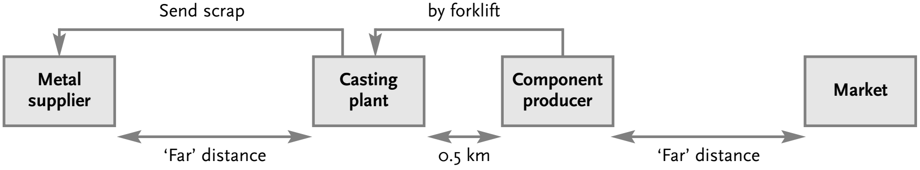
LOCATION CASE A



LOCATION CASE B



LOCATION CASE C



LOCATION CASE D

Figure 2 LOCATION CASES A–D

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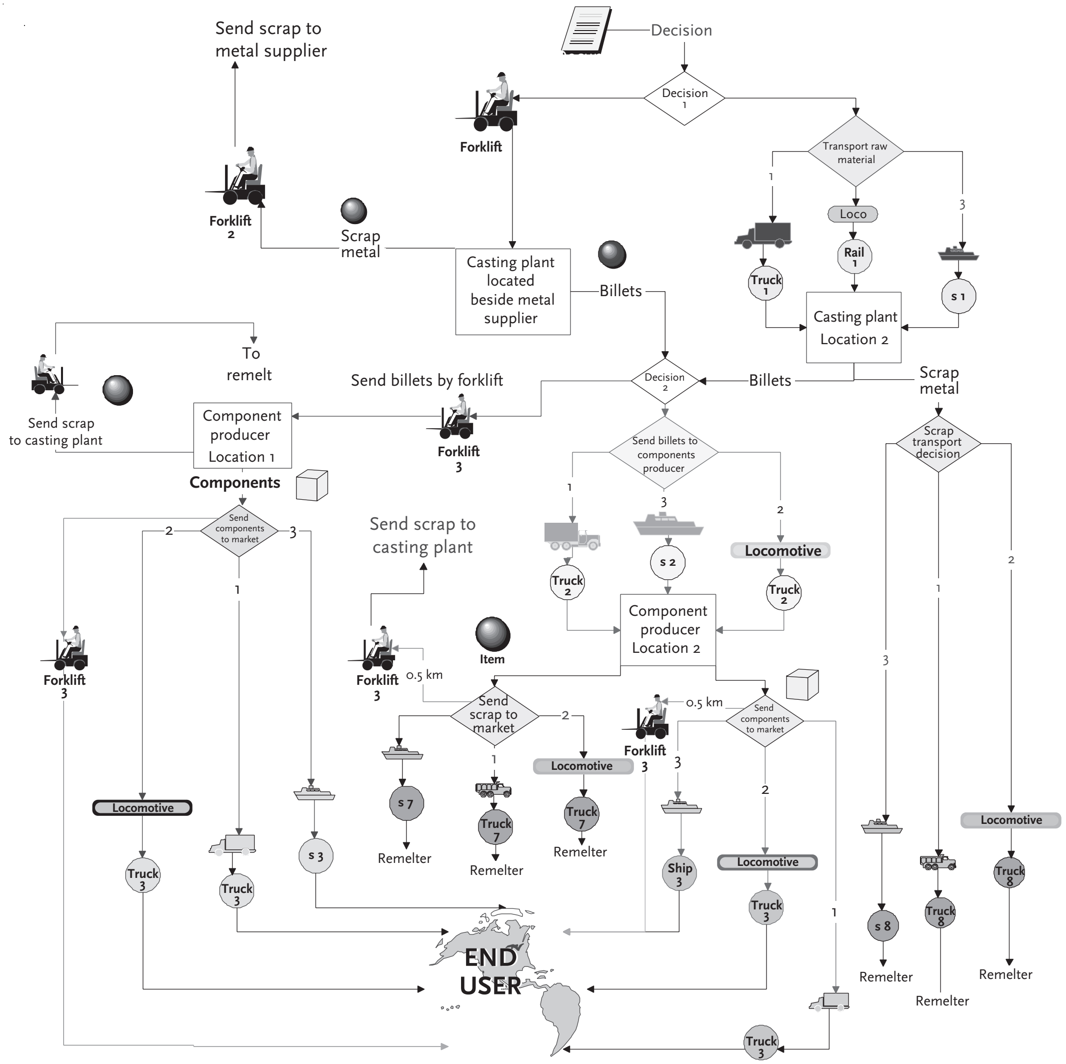
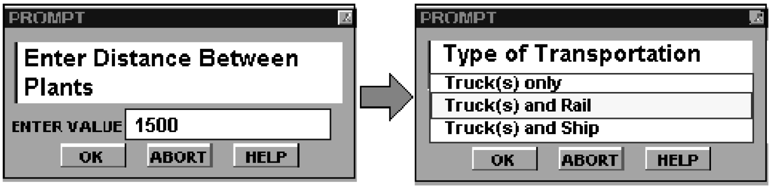


Figure 3 THE SUPPLY-CHAIN SIMULATION MODEL



Enter Distance Between Plants

ENTER VALUE 1500

Type of Transportation

Truck(s) only
Truck(s) and Rail
Truck(s) and Ship

Figure 4 USER POP-UP SIMULATION MENUS

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Run	Distance			Transport		
	1	2	3	1	2	3
Location case A						
1	0.5	0.5	625	4	4	1
2	0.5	0.5	1,250	4	4	1
3	0.5	0.5	1,250	4	4	2
4	0.5	0.5	2,500	4	4	1
5	0.5	0.5	2,500	4	4	2
6	0.5	0.5	5,000	4	4	2
7	0.5	0.5	5,000	4	4	3
Location case B						
8	0.5	625	0.5	4	1	4
9	0.5	1,250	0.5	4	1	4
10	0.5	1,250	0.5	4	2	4
11	0.5	2,500	0.5	4	1	4
12	0.5	2,500	0.5	4	2	4
13	0.5	5,000	0.5	4	2	4
14	0.5	5,000	0.5	4	3	4
Location case C						
15	625	0.5	0.5	1	4	4
16	1,250	0.5	0.5	1	4	4
17	1,250	0.5	0.5	2	4	4
18	2,500	0.5	0.5	1	4	4
19	2,500	0.5	0.5	2	4	4
20	5,000	0.5	0.5	2	4	4
21	5,000	0.5	0.5	3	4	4
Location case D						
22	625	0.5	625	1	4	1
23	625	0.5	1,250	1	4	1
24	625	0.5	1,250	1	4	2
25	1,250	0.5	625	2	4	1
26	1,250	0.5	625	1	4	1
27	625	0.5	2,500	1	4	1
28	625	0.5	2,500	1	4	2
29	2,500	0.5	625	2	4	1
30	2,500	0.5	625	1	4	1
31	1,250	0.5	1,250	1	4	1
32	2,500	0.5	2,500	2	4	2
33	1,250	0.5	2,500	1	4	1
34	1,250	0.5	2,500	2	4	2
35	2,500	0.5	1,250	1	4	1
36	2,500	0.5	1,250	1	4	1
37	2,500	0.5	5,000	1	4	2
38	2,500	0.5	5,000	2	4	2
39	5,000	0.5	5,000	2	4	3
40	5,000	0.5	5,000	3	4	3

Distance 1 = metal supplier to casting plant; Distance 2 = casting plant to component producer;
Distance 3 = component producer to market
Transport 1 = metal supplier to casting plant; Transport 2 = casting plant to component producer
Transport 3 = component producer to market

Note: for an illustration of location cases A–D, see Figure 2.

Table 3 USER SELECTION OF 40 SIMULATION ENTRIES

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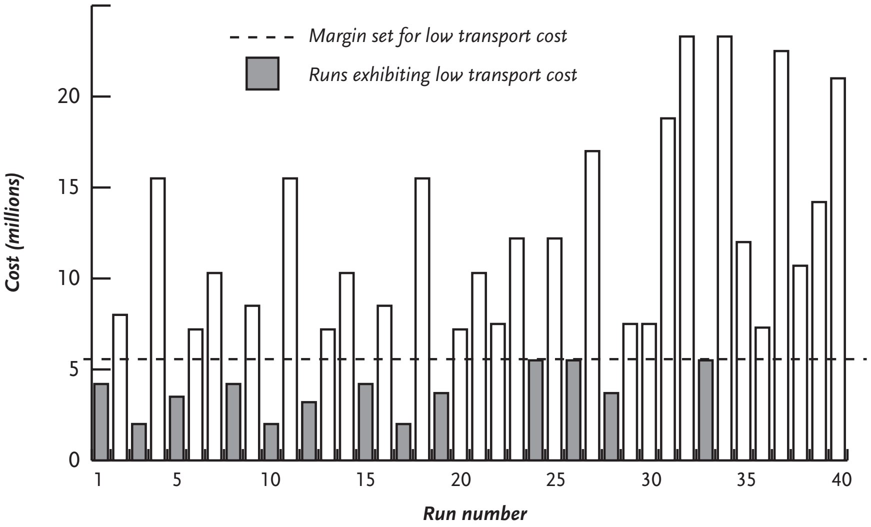

Figure 5 TOTAL SUPPLY-CHAIN TRANSPORT COST

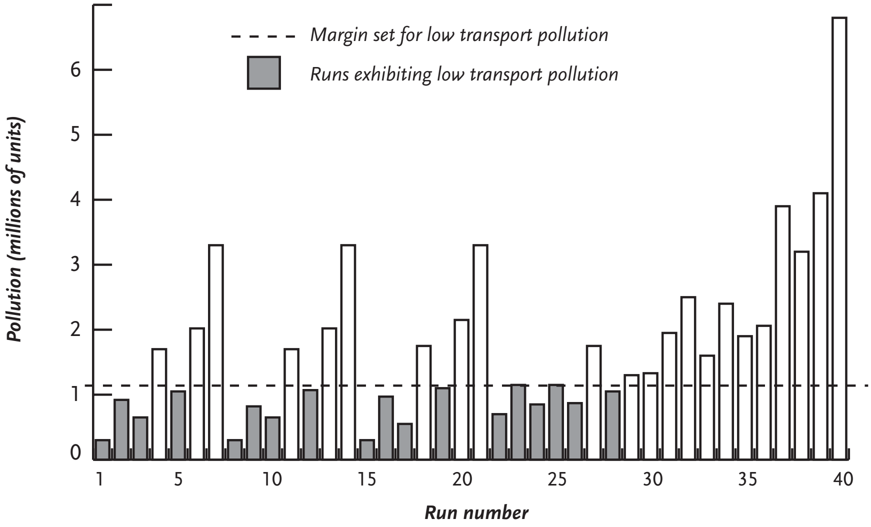

Figure 6 TOTAL SUPPLY-CHAIN TRANSPORT POLLUTION

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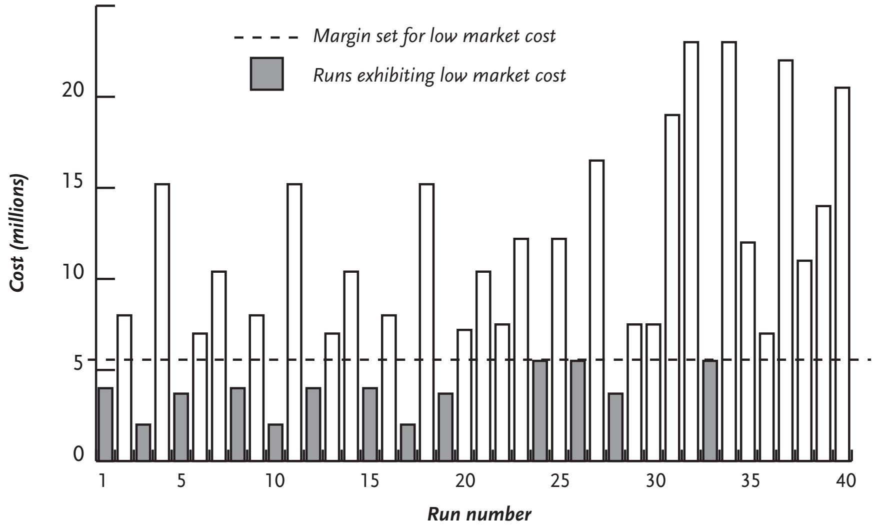

Figure 7 TOTAL SUPPLY-CHAIN MARKET COST

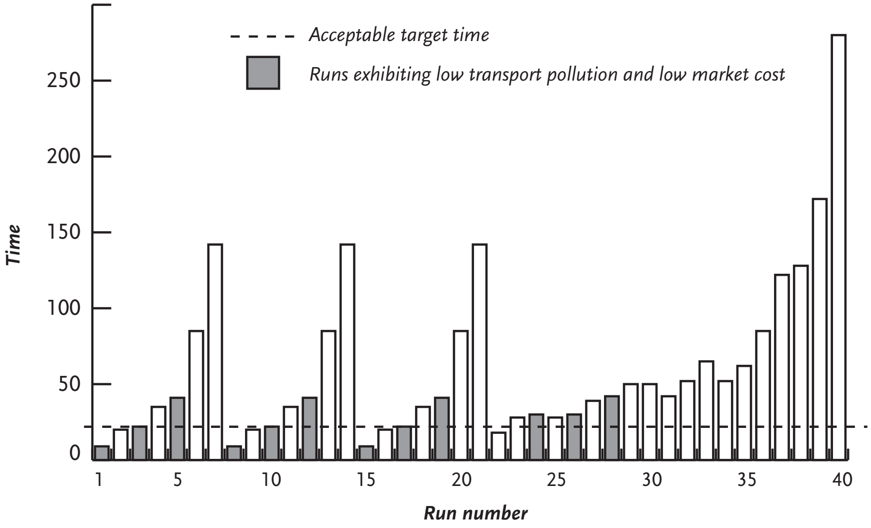

Figure 8 TOTAL SUPPLY-CHAIN 'TIME TO DELIVER'

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settings, with the distances between the casting plant and component producer set at 625 km, 1,250 km and 2,500 km, respectively.

Runs 15, 17 and 19 are for Case C location settings. The 'far distances' selected for run 15 is 625 km, for run 17 is 1,250 km and for run 19 is 2,500 km. For run 15, the mode of transportation selected between the metal supplier and casting plant is of type 1 (by trucks only). As for runs 17 and 19, the mode of transportation selected between the first two plants is type 2 (by trucks and rail).

Runs 24 and 26 refer to a Case D location setting, where the trade-off of least costs, least pollution and distance between the plants can be found in the combined distances of 625 km and 1,250 km, as well as the use of trucks and rail.

Finally, run 28 is also for a Case D setting. This time, the 'far distances' are selected as 625 km for the first two plants in the chain, and 2,500 km for the last two plants. The transport modes selected are type 1 from the supplier to the casting plant, and type 2 from the component producer to the market.

The total 'time to deliver' displayed in Figure 8 depicts the minimum total travelling time between plants, for the distances and transport type selected. A 'target time' is selected to meet the requirements of 'just-in-time' demands. Based on the 'target time' margin, runs 5, 12, 19, 24, 26 and 28 are omitted from the selection described above, leaving runs 1, 3, 8, 10, 15 and 17 for further consideration.

Conservation of energy

Within the selected runs, the next issue addressed is the conservation of energy. At the metal supplier, melting of metal is performed to transform the aluminium into slabs or ingots of the right shapes and sizes. The metal-melting activity consumes a high amount of energy. At the casting plant, these slabs or ingots of aluminium metal are melted again for the billet production process.

In order to conserve energy, it was suggested that *molten metal* be transferred by truck from the metal supplier to the casting plant. This suggestion is reasonable for travel distances within 50 km. Therefore the Case A and Case B settings (runs 1, 3, 8 and 10) are the final selections.

This suggestion saves energy and costs for the casting plant. In the drive towards establishing sustainable development, this type of energy calculation is treated as an essential part of the model. An ideal condition requires 294 kWh (kilowatt-hours) for processing 1 tonne of aluminium. This is the energy equation used for the casting plant plus an additional estimate of 1% to compensate for metal losses. The energy requirement of the component producer is estimated to be 25% of that consumed by the casting plant.

The energy savings for the casting plant are shown in Figure 9 (in megawatt-hours, MWh). The results show that the location of the component producer results in no significant differences in the amount of energy spent.

The energy savings have also been evaluated for the metal supplier. On average, the energy consumption is quite high for melting metal—usually an average value of about 15 kWh for every kilogram of metal. However, some very efficient plants may get down to 13.5 kWh per kilogram. This type of energy difference is definitely a significant value for metal production when taken on an annual basis. By adopting this type of energy saving for the metal supplier, the energy savings for the supply chain can be up to about 90%. These types of energy-conservation methods are important factors for enterprises that want to demonstrate good corporate citizenship. Such consideration involves caring for future generations who may face shortages in energy supply (Denton 1998). An additional environmental bonus arising from better energy efficiency is less burning of coal and fewer greenhouse gas emissions.

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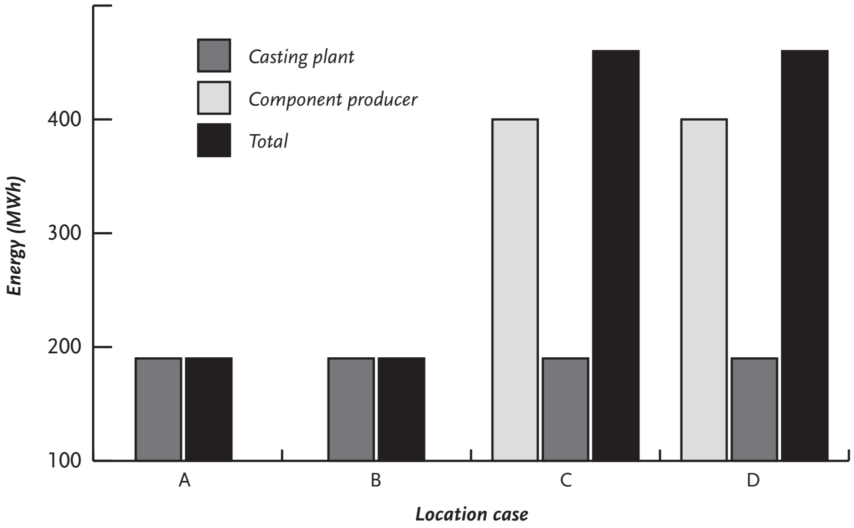

Figure 9 ENERGY DIFFERENCES FOR THE CASTING PLANT AND COMPONENT PRODUCER

Final results and discussion

Further analyses of the selected locations were performed based on the marketing needs and demands of aluminium components. The end-user or market will demand a guaranteed 'just-in-time' supply or will impose a price reduction because of the need to maintain stocks. It is therefore necessary for the model to reflect this demand in terms of the final transportation time or an offsetting price reduction for the maintenance of stocks at or adjacent to the market. Although the model is capable of taking these factors into account in terms of real, or input, details, it cannot take into account 'perceived' or attitudinal resistance to the model logic.

The final range of locations were confirmed to be runs 1, 3, 8 and 10. These locations guarantee that, in the supply chain, recycling is promoted, marketing costs are low, delivery time is shortened and transport pollution is minimised. The rest of the discussion is concerned with the following three areas: (i) green supply chain, (2) the use of simulation and (3) reliability and limitations of the simulation model.

Green supply chain

It was mentioned earlier that enterprises are facing increasing pressure to balance marketing performance with environmental issues. These issues are creating new challenges for businesses, such as energy preservation and pollution abatement, not only as a precondition for long-term survival but also as an ingredient for long-term profitability (Gifford 1997; Miller 1998). Therefore, companies have created networks of suppliers to build common understanding and learning about waste reduction and operational efficiencies in the delivery of existing products and services (Cox 1999).

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In alignment with sustainable business requirements, in this model energy conservation is adopted for the supply chain by selecting near distances to allow the transfer of molten metal between plants. The design of the plant location settings also promotes the return of scrap metal for recycling and allows optimal marketing performance (in terms of cost and time) as well giving rise to low transport pollution. In this manner, environmental, marketing and customer needs are all satisfied, given the strict logic of the model.

The use of simulation

The case study has demonstrated the advantages of simulation as a powerful tool for making decisions. The various decision scenarios enabled outcomes (in terms of pollution and cost levels) that do not incur any losses in time or expense. This tool has been tested for its application in other parts of industry for creating 'greener' plants and for environmental management purposes (Khoo *et al.* 2001; Spedding *et al.* 1999; Taplin *et al.* 2001).

In testing the outcomes of a series of decisions, quantitative results are required in order to make comparisons of costs and benefits easier. This approach has demonstrated the potential of advanced technology in playing a significant role in sustainable development and creating more socially responsible business enterprises—not because of potential breakthroughs to replace natural resources or to clean up the air but because technological advances can facilitate dissemination of information, enhancement of communication and visual verification that the right decisions are being made (Christensen 1999; Saemann 1992).

Reliability and limitations of the simulation model

The model was created to reflect true-to-life outcomes of a series of decisions. The robustness of the simulation model depends on several factors:

Availability of data

The outcome of the simulation results relied heavily on the accuracy of the data collected, which was treated as the model **variables**. In the case study, we worked closely with the owner of the plants to ensure that the data (e.g. costs, distances, etc.) used for the simulation reasonably reflected the actual case.

Design of the model

The methodology used for designing the model has a direct effect on its ability to represent the true-to-life events. The simulation model incorporated simple mathematical formulae to form the model's logical actions (also known as the system's **behaviour**). Again, we worked closely with the plant owner to inspect the model's logical actions (this is known as a 'walk-through approach') to ensure that the model was fit for its intended purpose.

Limitations

The simulation model and its results were based on **ideal** conditions. In order to make the system more realistic, unexpected events could be programmed within its logic, such as cases of machine or vehicle breakdowns, human intervention (in handling material), changes in customer orders or the fluctuation of market demands. These cases would interrupt the schedule for the delivery of goods to the end-user. In order to include these factors within the simulation study, more intensive research on transportation, marketing demands and the production line of each plant would have to be carried out. This

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type of work also requires a higher level of programming and, perhaps, a more sophisticated simulation package. Other areas, such as the option for selecting more fuel-efficient transport types and their associated costs could also be incorporated.

Conclusions

In this paper we have demonstrated the potential of simulation tools to create a green supply chain that balances the concerns of transport pollution, marketing costs, time to market, recycling of scrap metal and energy conservation. The simulation tool allowed the testing of a series of decisions and their outcomes, while saving costs and time for the plants. The final selected plant locations demonstrate how a supply chain consisting of four plants could tackle transport pollution and energy issues while meeting customer demands. Part of the rationale for this supply-chain design is the recognition that the Earth is a legitimate stakeholder and that the reduction of pollution (carbon monoxide, VOCs, nitrogen oxides and particulate matter) serves to help maintain its natural climate.

The results of the simulation study were derived from an ideal situation. It is suggested that further developments be made such as the study of material ordering, production time and inventory control—from supplier, to distributor, to end-users—in the pursuit of establishing a green supply chain. The same approach and methodology could be applied to other supply-chain cases, provided that the relevant data was available and that the operations of the real system could be modelled.

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