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Greening the aluminium supply chain

I. Ferretti, S. Zanoni, L. Zavanella*, A. Diana

Dipartimento di Ingegneria Meccanica, Facoltà di Ingegneria, Università degli Studi di Brescia Via Branze, 38–25123 Brescia, Italy

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Abstract

This paper originated from an industrial case study in the field of the aluminium supply chain. In particular, the most original aspects of the study are linked to the use of an alternative supply method for raw material (aluminium) in manufacturing. This method consists in the possibility of the company receiving the aluminium alloy from its supplier (refiner and remelter of secondary aluminium) in the liquid phase, as an alternative to the traditional supply of solid material.

This practice has been possible by the use of special ladles, transportable by truck and moved within factories, thanks to specially equipped overhead bridge cranes. The supply of molten metal represents a substantial benefit for the whole supply chain, because of the energy savings implicit in the method itself (i.e. both energy and time can be saved when melting the metal at the company furnaces). Moreover, the study integrates the concerns about transport pollution, addressing the topics of a green supply chain problem and incorporating the environmental aspects in its analytical description. Therefore, the study proposes a model to evaluate the economic and environmental effects of the industrial practice described. The result of the model is the determination of the supply aluminium mix, i.e. molten and solid alloy, capable of balancing the economic benefits (highest scrap values, lowest total costs, etc.) as well as environmental requirements (least pollution).

Keywords: Supply chain; Green supply chain; Aluminium supply

1. Introduction

In recent years, interest in environment preservation is increasing, and emerging as real business targets. This issue is acquiring importance for the public (Shultz and Holbrook, 1999) and for industry, but not enough effort has been produced, from the research point of view, to integrate these aims into managerial models. Until 10 years ago, the unique aim of business was to achieve the maximum economic profit or to improve the customer service (Shapiro, 2001), but now environmental topics play a very important role, becoming a central point of the strategic and operative management policies. The idea of "green business" forces the re-examination of the very purpose of a company's existence (Hick, 2000). Environmental limits can become business opportunities, which can be used as competitive advantages (Matthias, 1999). Adoption of greener management practices, as part of an enterprise's policy, is increasingly turning into a major strategy in business organisations, and it is likely to carry on well into the 21st century (Stead and Stead, 2000). In fact, the use of environmental

*Corresponding author. Tel.: +39 030 3715581; fax: +39 030 3702448.
E-mail address: zavanell@ing.unibs.it (L. Zavanella).

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management systems leads to environmental and business advantages; it is possible to achieve various benefits such as better product quality and economic benefit (US-AEP, 2001), due to the improvement in efficiency and public image of the company.

Therefore, environmental targets are to be added to economical targets (Sarkis, 2001) and, now, the company dilemma is to find the right balance between these two different dimensions, which often seem to be in contrast (Dyckhoff et al., 2004). The aim of the present study is to show how these two goals could be perceived simultaneously, driving the traditional business practice into new opportunities. In particular, the opportunity of substituting the traditional solid-ingot supply with molten aluminium will be discussed from the economic and environmental impact point of view.

Environmental issues in the supply chain have been explored using a variety of related practices, such as green supply, environmental purchasing, product stewardship, lifecycle analysis and reverse logistics (Zsidisin and Siferd, 2001). From those researches, it is possible to identify generally accepted characteristics about green supply chain practices that typify the interactions between a plant, and its suppliers and customers. These interactions are directed at achieving sustained improvements in environmental performance and can take place in either the buyer's plant and/or at the supplier's plant (Handfield et al., 1997). They also include information gathering and processing in order to evaluate or to control suppliers' behaviour regarding the natural environment (Min and Galle, 1997). Most research studies on green supply chain management tend to focus on single aspects such as green purchasing, internal environmental operations management or green logistics, as opposed to taking an integrative, whole supply chain approach as suggested by Beamon (1999), Van Hoek (1999) and Wu and Dunn (1995). Carter and Carter (1998), Carter and Ellram (1998) and Zsidisin and Siferd (2001) are among a number of authors who also suggest that green supply chain research should move from anecdotal studies towards an empirical, theoretical grounded approach (Gavaghan et al., 1998). An analysis of research needs and a critique of previous studies is examined more fully in Holt and Ghobadian (2002).

An additionally interesting reference for the present study is the paper by Khoo et al. (2001). The authors focus on the aluminium supply chain, using a simulation-based approach to find the optimal value of the decision variables taken into account, i.e. plant locations and type of transport considering both cost and pollution. However, the authors consider different transportation means, but they do not consider the alternative between solid and liquid state transportation. Moreover, the study marginally investigates the environmental aspect, and it does not link this aspect to the economical one.

The present study offers a mathematical model of the aluminium supply chain (in this case, the chain consists of one refiner for several companies, called component producers). The decision variables of this model are the percentages of aluminium supplied in solid ingots and in the molten state for each refiner-component producer pair.

As a first step, the importance of the aluminium industry is shown and the parties in the chain are introduced and commented on. Successively, the alternative supply strategy is discussed, considering the differences with the usual ingot supply. Afterwards, a single-refiner single-producer model is presented to describe the economic and pollution parameters adopted and the optimisation variables considered. Finally, the extension of the model to an environmentally complex supply chain is introduced and its cost optimisation is carried out. The conclusion refers to a real case of two different supply chains observed in Lombardy. Achievable benefits are discussed according to the approach suggested.

2. The aluminium supply chain

The light metal industry belongs to the second half of the 20th century, but despite its relative youth, this sector shows a constant improvement and development of new technologies. In particular, aluminium fulfils an important role in our ordinary life, regardless of its rarity just 80 years ago. Three main properties characterise this metal: low-density, high mechanical properties and good corrosion resistance. The aluminium industry receives raw material from two different provisions, called "primary" and "secondary". The primary industry is principally fed by bauxite, which involves the use of a large amount of electrical energy, with negative consequences on the final cost of finished products. The secondary aluminium is a metallic alloy obtained by recycling the scraps of manufacturing processes and exhausted product recovery, thus allowing a saving in raw materials and energy. In other terms, the latter process involves the use of less electricity.

From an ecological point of view, aluminium recycling contributes to sustainable development, because the metal is not consumed, but simply reused during the product lifetime. These motivations fully justify the aluminium nickname "green metal". Its environmental benefits are both direct (recycling) and indirect (e.g. lighter vehicles). Moreover, aluminium recycling technologies have proved to be successful in recent years, with excellent results and increasing advantages (Roskill, 2003). In Italy, the chronic lack of raw material (i.e. bauxite) has boosted the secondary production, which covers more than 65% of total aluminium production.

In the secondary industry, two industrial parties are to be distinguished. According to their production, they are conventionally defined as refiners and remelters, adopting the Organisation of European Aluminium refiners and remelters (OEA)(terms. Mainly using scraps as raw material, refiners produce alloys suitable for casting and die casting. Remelters produce metal for extrusion and rolling companies. Fig. 1 shows the aluminium supply chain scheme. The present paper focuses on the framed part, mainly considering refiners and their respective customers, i.e. casting and die-casting companies. Such a model excludes primary aluminium producers (six large leader companies) who generally act independent of other factors and the customers they supply.

An alternative supply option to the traditional ingot supply, i.e. molten aluminium, was introduced first in Germany, as an industrial solution to regulation concerns, and it is now being considered for application in Italy and other European countries.

There are more benefits deriving from the use of secondary aluminium than the few considered in the previous paragraph: A further economical and environmental advantage comes from the possibility of component producers receiving, from the refiner, a melted alloy in place of solid ingots. This is possible thanks to particularly coated and insulated ladles, transported by trucks equipped with a special tightening system. The use of this transport technique allows the refiner to optimise the run of his furnaces, to reduce the energy consumption and to obtain a considerable saving in storage costs. Moreover, the component producer will obtain a significant energy saving (the theoretical amount of electricity required to melt one ton of aluminium scrap is 294 kWh) and a reduction in storage costs.

Additionally, the supply technique implies a strong partnership between the two supply chain parties: This reinforced link is not based on the price (as in the pure ingot supply), but on technical and managerial factors. Two main constraints may slow down the implementation of the technique: On the one hand, the impossibility of the refiner to reach customers farther away than 200–250 km, and on the other, the component producer needs to be equipped with a special overhead bridge crane, which differs from the traditional one (two hooks must be moved separately: One for the raising and one for the overturning of the ladle containing the molten aluminium). A special overhead bridge crane

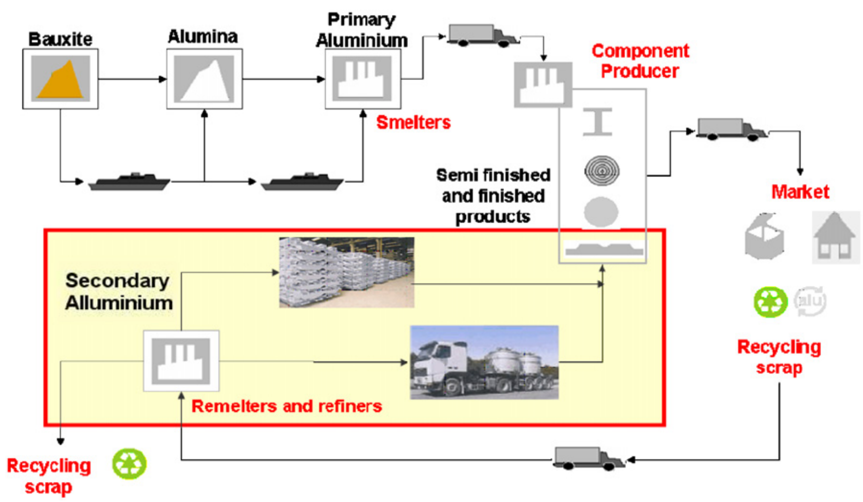

Fig. 1. The aluminium supply chain.

is necessary to facilitate the work and for safety. In fact, accidents occurred when ladles with *draw off* from the bottom, were eliminated, thanks to the adoption of the so-called "teapot technique". Nowadays, the molten aluminium handling operation may be considered fully safe.

Following the industrial analyses carried out in Lombardy, it can be stated that the refiner technological levels are more advanced than those of the component producers: Some of them claim that the investment in special bridge crane has been postponed until a future layout redefinition. Nowadays, thanks to the present study too, refiners are aware of the environmental and economic efficiency of the molten-metal supply method, while component producers are still resistant. However, this situation may vary in the short term, as Italian laws on the environmental impact of metal fusion plants are evolving. In fact, this work was prompted by this development.

3. Single-buyer single-vendor case

The present section deals with the case of one refiner (single-vendor) and one component producer (single-buyer). This basic model is used as a reference so as to introduce the complete model of the economic and environmental evaluation of the aluminium supply chain. Therefore, a successive section will extend the basic model to a supply chain consisting of multiple refiners and multiple component producers.

At first, only the economic evaluation and the consequent comparison will be carried out. This preliminary analysis considers the traditional solid metal supply and, successively, the molten metal supply is modelled.

3.1. Traditional ingot (solid metal) supply

The costs that will be taken into account have been attributed to the two different parties, i.e. the refiner (R) and the component producer (P). Moreover, different cost components have been considered separated, i.e. costs for the aluminium alloy production (PR), aluminium ingots solidification (IS), aluminium transport (TR), aluminium ingots holding (IH), aluminium ingots melting (IM), molten aluminium warm-up (WU), molten aluminium keeping (KP), additional equipments depreciation (D).

The notation used in the model, for the cost components faced by the refiner, are reported as follows:

- cPR (€/ton): the production cost to obtain the molten aluminium alloy;
- cIS (€/ton): aluminium ingot solidification cost;
- cTR (€/(ton km)): transport cost;
- cDR (€/year): yearly depreciation of the specific equipment (portable ladles to carry out transports).

The notation used in the model, for the cost components faced by the component producer, are reported as follows:

- cIH (€/(ton year)): Ingot holding cost, including physical space allocation and related components, as due to the ingot inventory equipment and management and financial costs related to the capital tied-up.
- cIM (€/ton): Cost of ingot melting.
- cWU (€/ton): Warm-up costs of the liquid aluminium from the transported ladle temperature to the furnace temperature.
- cDP (€/year): Yearly depreciation of the specific equipment (overhead bridge crane).
- cKP (€/(ton day)): Cost due to maintaining the melting aluminium in the furnace, i.e. holding costs of melting aluminium in furnace.

3.2. Traditional ingot (solid metal) supply

Total costs of the refiner (R) may be written as the sum of relative cost:

$$\mathrm{CR}(q) = \mathrm{CPR} + \mathrm{CIS} + \mathrm{CTR} = (\mathrm{cPR} + \mathrm{cIS})D + \mathrm{cTR}\frac{D}{q}d, \quad (1)$$

while the total costs of the component producer (P) are:

$$\mathrm{CP}(k, q) = \mathrm{CIH} + \mathrm{CIM} = \mathrm{cIH}\frac{kq}{2} + \mathrm{cIM}D, \quad (2)$$

where d is the distance between the refiner and the component producer (km) (round trip), k is the number of vehicles used per delivery, q is the aluminium solid quantity which is transportable per travel by each vehicle (ton), and D is the yearly quantity supplied by the refiner to the component producer (ton/year).

The total costs of the whole supply chain (SC) are

$$\mathrm{CSC} = \mathrm{CR} + \mathrm{CP}.$$

3.3. Molten metal supply

Summarising, the yearly total costs of the refiner, with the supply of molten aluminium, are

$$\mathrm{CR}'(q') = \mathrm{CPR} + \mathrm{CTR} + \mathrm{CDR} = \mathrm{cPR}D + \mathrm{cTR}\frac{D}{q'}d + \mathrm{CDR}, \quad (3)$$

while the component producer costs are

$$\mathrm{CP}'(k, q') = \mathrm{CWU} + \mathrm{CIH} + \mathrm{CDP} = \mathrm{cWU}D + \mathrm{cKP}\sum_t \mathrm{IM}_t + \mathrm{CDP}, \quad (4)$$

where IM_t is the molten metal inventory in the furnace at period t (day), that can be recursively calculated as $\mathrm{IM}_t = \mathrm{IM}_{t-1} + q'k - D_t$, q' is the quantity of liquid aluminium transportable per travel by each vehicle (ton); D_t is the demand faced by the component producer at period t, $D = \Sigma_t D_t$; T is the time horizon considered.

In the basic single-buyer single-vendor case, the total cost of aluminium supply (SC) is

$$\mathrm{CSC}' = \mathrm{CR}' + \mathrm{CP}'.$$

So as to evaluate the economic advantage achievable thanks to molten aluminium supply, it is possible to calculate the difference between the two total costs, as evaluated in the single-buyer single-vendor case, i.e.

$$\Delta C = \mathrm{CSC} - \mathrm{CSC}' = \left(\mathrm{cIS}D + \mathrm{cTR}\frac{D}{q}d + \mathrm{cIH}\frac{kq}{2} + \mathrm{cIM}D\right) - \left(\mathrm{cTR}\frac{D}{q'}d + \mathrm{cWU}D + \mathrm{cKP}\sum_t \mathrm{IM}_t + \mathrm{CDR} + \mathrm{CDP}\right). \quad (5)$$

The numerical experiments carried out on this basic case show the considerable economic advantages achievable by molten aluminium supply, even when applying distances close to its technical limit (maximum delivery distance of 200 km). In numerical terms, a distance of 100 km determines a cost saving between 4% and 5% on the aluminium selling price (one ladle per day, i.e. 1500 ton/year) and 3–4% on the aluminium selling price (four ladles per day, i.e. 6000 ton/year). But, beyond the costs, the environmental impact needs to be taken into account, as below.

3.4. Environmental impact

The environmental impact of the two alternative chains has been computed considering the following main pollutants:

- carbon monoxide (CO);
- oxides of nitrogen (NO_x);
- particulate matter (PM);
- volatile organic compounds (VOCs).

In the case examined, two main causes contribute to pollution: transport (T) and the re-melting (M) process in the component producer furnace. As far as the former is concerned, both levels and type of transport pollution depend on the combination of two additional factors: The type of transportation, i.e. the truck and its load, and the distance travelled. Therefore, diesel engine vehicles, with loads between 16 and 35 ton, were considered. Table 1 shows the atmosphere emissions due to transport, for each of the pollutants considered. As far as re-melting is concerned, emissions into the atmosphere have been considered for the natural gas consumption (N m^3) of the furnace and considering the related best available technologies (BAT). Table 2 shows the pollutant production due to the secondary aluminium re-melt process.

Considering that 1 ton of aluminium 120 N m^3 of natural gas to melt, it is possible to arrange an emissions balance and to find the emissions (E) produced in 1 year for each pollutant k. So as to

Table 1
Transport emission (eT)

Emission type in atmosphere (k)	NO_x	VOCs	CO	PM
(g/km)	8.47375	0.93685	2.0208	0.6267

Source: APAT (2000).

Table 2
Aluminium melting emission from furnace (eF)

Emission type in atmosphere (k)	No_x	VOCs	CO	PM
BAT approximate values (mg/N m^3)	100–300	5–50	20–100	1–5
Assumed value (mg/N m^3)	200	20	60	2.5

Source: European IPPC Bureau (2001).

compare the two techniques, it is necessary to consider transport and re-melting emissions: In fact, they are the only two polluting factors that change in the two alternative chains. In the case of ingot re-melting, the results are:

$$E_k = eT_k \frac{D}{q} d + eF_k\, D\,(120 \times 10^{-3}), \tag{6}$$

while in the case of liquid aluminium supply, considering that only 10 N m^3 of natural gas are necessary to raise the temperature of 1 ton to the right melting point, it is possible to write

$$E'_k = eT_k \frac{D}{q'} d + eF_k D\,(10 \times 10^{-3}). \tag{7}$$

It has to be underlined that ladle-based transport allows the delivery of less material per travel, even if smaller process emissions are determined (in the molten metal supply, it is not necessary to re-melt ingots, thus saving energy and emissions).

Once the emissions related to the two different transport types for each type of polluting substance have been evaluated, they may be matched up. The numerical experiments carried out on this basic case show considerable environmental advantages up to 40–50 km distances, and the balance may be considered as positive up to 90–100 km.

4. The model of the aluminium green supply chain

This section expands the single-buyer single-vendor model to a more general case, i.e. a supply chain with one refiner that supplies several component producers. A fundamental assumption of the basic model is that the supply agreement between the refiner and the component producer refers uniquely to one type, i.e. entirely molten or entirely solid metal. A more general model of the supply chain considers a different configuration, as both solid and molten metal may be supplied in different percentages (mixed supply). In particular, the refiner has to deliver a constant quantity to the component producer, according to the customer demand forecast: this is due to the stochastic nature of the demand and, therefore, its real value may differ from the estimated one. The difference between the real demand value and the quantity of molten metal agreed is to be covered by the stock of aluminium ingots, which is held by the component producer.

An important decision variable of the model is the quantity of metal regularly supplied, i.e. daily, by the refiner to the component producer: This value determines the quantity of ingots used by the component producer to face the eventual shortage of aluminium. Initially, the objective function focuses on the minimisation of the whole supply chain cost, according to the parameters discussed in the basic case, and considering the level of pollution generated as a constraint that could be adjusted to obtain different solutions. In other terms, the economic evaluation is considered first and its unconstrained optimal solution is found, regardless of the pollution level. Subsequently, a decreasing level of pollution is imposed as a constraint. The responsiveness of the supply chain will be measured by the penalty cost induced by this additional constraint, which forces the solution to a suboptimum value, from the mere point of view of the cost. In this case, it is important to highlight that the economic analysis of the supply chain considers only the differential costs, which allows the model to obtain the percentage of molten and solid ingot to be supplied, as detailed hereafter.

Let us introduce the following notation:

- $i = 1,\ldots,N$ is the refiner index (i.e. the supply chain consists of N refiners);
- $j = 1,\ldots,M$ is the index of the component producer (i.e. the supply chain consists of M component producers);
- $t = 1,\ldots,T$ is the period index (e.g. days) of the time horizon considered (the total length of the time horizon is T).

It is possible to define the following costs faced by the refiners pertaining to the supply chain:

- Production costs (the differential component considers only the ingot solidification process):

$$\text{CIS} = \sum_{i=1}^{N}\sum_{j=1}^{M}\sum_{t=1}^{T}\left[\text{Ingot}_{ijt}\,\text{cIS}\right]. \tag{8}$$

- Total transportation cost (both for molten and solid metal supply):

$$\text{CTR} = \sum_{i=1}^{N}\sum_{j=1}^{M}\left(\frac{\text{Molten}_{ij}}{q'} Td_{ij}\,\text{cTR} + \sum_{t=1}^{T}\left[\frac{\text{Ingot}_{ijt}}{q} d_{ij}\text{cTR}\right]\right), \tag{9}$$

where

- Molten_{ij} (ton) is the amount of molten aluminium supplied by the ith refiner to the jth component producer (the amount of molten aluminium supplied is assumed to be constant over the planning horizon. Its value is fixed at the beginning of the horizon itself, on the basis of the stochastic data concerning the expected demand);

- Ingot_{ijt} (ton) is the total amount of solid aluminium (ingots) produced and delivered by the ith refiner to the jth component producer, at the period t, i.e.
  - $$\text{Ingot}_{ijt} = \begin{cases} D_{jt} - \text{Molten}_{ij} - \text{moltenStock}_{jt-1} & \text{if } D_{jt} \geqslant \text{Molten}_{ij}, \\ 0 & \text{otherwise,} \end{cases}$$
    $$i = 1, \ldots, N; \quad j = 1, \ldots, M; \quad t = 1, \ldots, T,$$

  where
  - D_{jt} (ton) is the real demand faced by the jth component producer at period t;
  - moltenStock_{jt} (ton) is the quantity of molten aluminium held in period t in the furnace of the jth component producer waiting to be filled;
    - q' (ton) is the capacity of the ladle transported, i.e. the quantity of molten aluminium deliverable per truck travel;
    - q (ton) is the quantity of aluminium ingots deliverable per truck trip;
    - d_{ij} (km) is the travel distance between ith refiner and jth component producer (round trip).

The component producers pertaining to the aluminium supply chain considered will face the following costs:

- Total holding costs of the aluminium ingots:

$$\text{CIH} = \text{cIH} \sum_{j=1}^{M} \sum_{t=1}^{T} \text{ingotStock}_{jt}, \tag{10}$$

  where
  - ingotStock_{jt} (ton) is the quantity of ingots stocked in the warehouse of the jth component producer at period t. Average stock of ingots to be held is computed at the level that guarantees the 99.5% service level (due to the stricter restriction of the automotive sector, in which great part of the aluminium companies operate), considering that demand is given by the difference between the stochastic final demand and the amount of molten aluminium received).
- total holding costs of the molten aluminium:

$$\text{CKP} = \text{cKP} \sum_{j=1}^{M} \sum_{t=1}^{T} \text{moltenStock}_{jt}, \tag{11}$$

  where
  - moltenStock_{jt} (ton) is the quantity of molten aluminium in the holding furnace of the jth component producer during the tth period:

$$\text{moltenStock}_{jt} = \begin{cases} \text{Molten}_{ij} - D_{jt} + \text{moltenStock}_{jt-1} & \text{if } D_{jt} < \text{Molten}_{ij}, \\ 0 & \text{otherwise,} \end{cases}$$
$$j = 1, \ldots, M; \quad t = 1, \ldots, T$$

- warm-up costs of the liquid aluminium from the transported ladle temperature to the furnace temperature:

$$\text{CWU} = \text{cWU}T \sum_{i=1}^{N} \sum_{j=1}^{M} \text{Molten}_{ij}. \tag{12}$$

In conclusion, the whole supply chain costs are:

$$\text{CSC} = \text{CIS} + \text{CTR} + \text{CIH} + \text{CWU} + \text{CKP}.$$

The decision variables, i.e. the amount of molten aluminium to transport from each refiner to each component producer, may be found by the minimisation of total costs:

$$\min\,(\text{CSC}(\text{Molten}_{ij})).$$

Once the total costs are minimised, the total pollution generated in the cost-optimal configuration identified is to be evaluated. The calculation is to be carried out for each polluting substance k (where $k = 1,\ldots,4$), as due to transport and solid metal re-melting:

- transport pollution (including both solid and molten metal transport)

$$ET_k = \sum_{i=1}^{N} \sum_{j=1}^{M} \left(\frac{\text{Molten}_{ij}}{q'} T d_{ij} eT_k + \sum_{t=1}^{T} \left[\frac{\text{Ingot}_{ijt}}{q} d_{ij} eT_k \right], \quad k = 1, \ldots, 4 \right) \tag{13}$$

- pollution of solid aluminium re-melting:

$$\text{EF}_k = 0.12\, \text{e}F_k \sum_{i=1}^{N} \sum_{j=1}^{M} \sum_{t=1}^{T} \text{Ingot}_{ijt}, \quad k = 1, \ldots, 4; \tag{14}$$

- pollution of molten metal worming:

$$\text{EW}_k = 0.01 eF_k \sum_{i=1}^{N} \sum_{j=1}^{M} \text{Molten}_{ij} P = 1, \ldots, 4. \tag{15}$$

Table 3
Pollutant monthly concentration limits $e\lim_k$

Pollutant (k)	NO_x	VOCs	CO	PM
Limit ($g/N\,m^3$)	1	4	0.2	0.2

Source: UE Directive 1999/30/EC.

The total pollution of each kth pollutant is equal to

$$\mathrm{ETot}_k = \mathrm{ET}_k + \mathrm{EF}_k + \mathrm{EW}_k, \quad k = 1, \ldots, 4.$$

So as to resume the different pollutant productions into a unique index, a graduation of their relative importance is introduced. It is determined on the basis of the concentration ($g/N\,m^3$), and its limit, is given by the current regulation (see Table 3). This approach allows the pollutant comparison in terms of environmental impact of the alternative supply chains, i.e. the value of the pollution level index may be evaluated as

$$\mathrm{PL} = \sum_{k=1}^{4} \frac{\mathrm{ETot}_k}{e\mathrm{Lim}_k}, \quad k = 1, \ldots, 4, \tag{16}$$

where $e\mathrm{Lim}_k$ is the concentration limit given by the regulations, for the kth pollutant.

5. A real case application

The real case below shows that the introduction of the mixed supply strategy may give significant green benefits rather than the traditional supply of ingots.

In this section, the model proposed for the economic and environmental impact assessment is applied to a real supply chain, assuming as reference two chains in the area of Lombardy (Italy). The main aim is to show how the approach proposed could be successfully applied to improve the current configuration of the chain and the related agreements, both in terms of cost and pollution. It should be noted that the present research is configured as a compulsory study that fits into a program of a green supply chain, promoted me for an ISO 14000 certification of the refiner plant involved.

In particular, both chains consist of a refiner and three component producers. Fig. 2 shows the geographic context of the two chains, highlighting the refiner and component producer distances, together with the relative importance of the final customers (circle dimension).

In particular, Fig. 2 shows that the supply chain of the refiner on the left is less extended, in terms of total distance, and that 60% of the total amount of metal supplied is utilised. The total amount of aluminium in these supply chains is more than 200,000 ton/year. For confidential reasons it is not possible to detail the cost structure of the supply chain parties, and the results shown are normalised according to the optimal value.

In order to implement the model developed in the previous sections, we have used the programming language Visual Basic 6, building both the user friendly interfaces for the company manager and the optimisation model that, due to the relatively small number of parameters, could be exhaustively computed.

The most interesting result of the model application refers to the curves that express the change in the optimal cost value due to changes in the maximum level of pollution allowed (Fig. 3a).

An important finding is that the two different chains exhibit a different sensibility in their total cost with respect to the pollution level allowed, i.e. imposing a reduced level of pollution implies a different cost penalisation in the two chains. For example, imposing a 10% decrease in pollution production implies less than 4% penalty costs to one chain and about 15% to the other. Fig. 3a curves may be interpreted as an efficiency boundary. Other solutions exist for the chain configuration (they could be represented in the upper right of the curve), but no point may exist in the bottom left of the curve. Therefore, the curve may be interpreted as the optimal trade-off between costs and maximum allowed pollution levels. Some important benchmarks may be considered, i.e. the two limiting configurations (all molten metal supply or all ingot supply). As Fig. 3b shows, the limiting conditions, compared to the minimum cost configurations found from the model application, offer consistently larger values for the total cost and pollution levels.

The results clearly show how the optimal mixed strategy, as found by the application of the model, significantly outperforms both the entirely solid metal supply and the entirely molten supply.

6. Conclusion

The present study demonstrated the potential of the introduction of a “green practice” in supply chain management. To this end, a model is

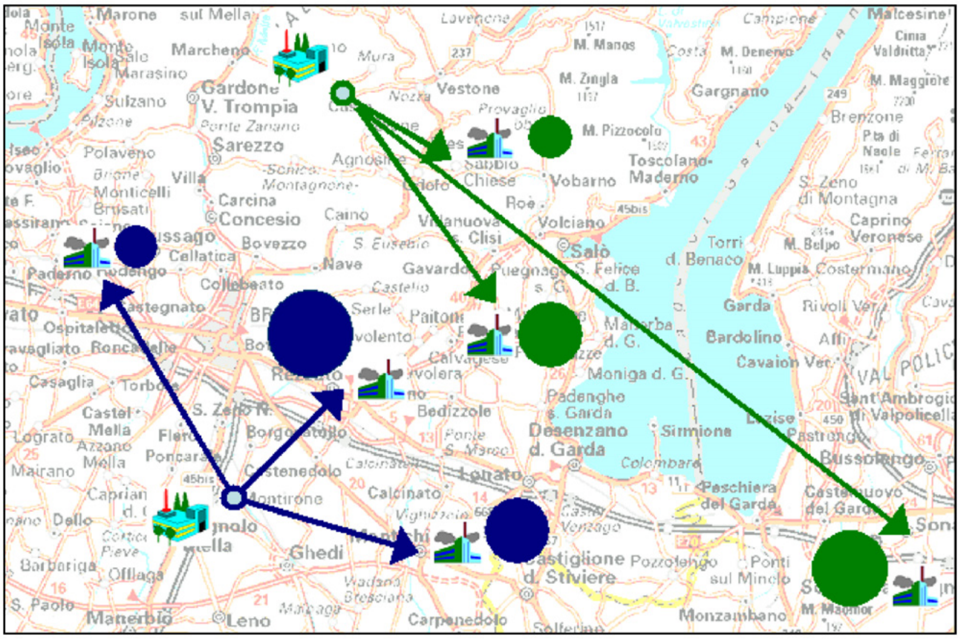

Fig. 2. Lombardy area with the two supply chains considered.

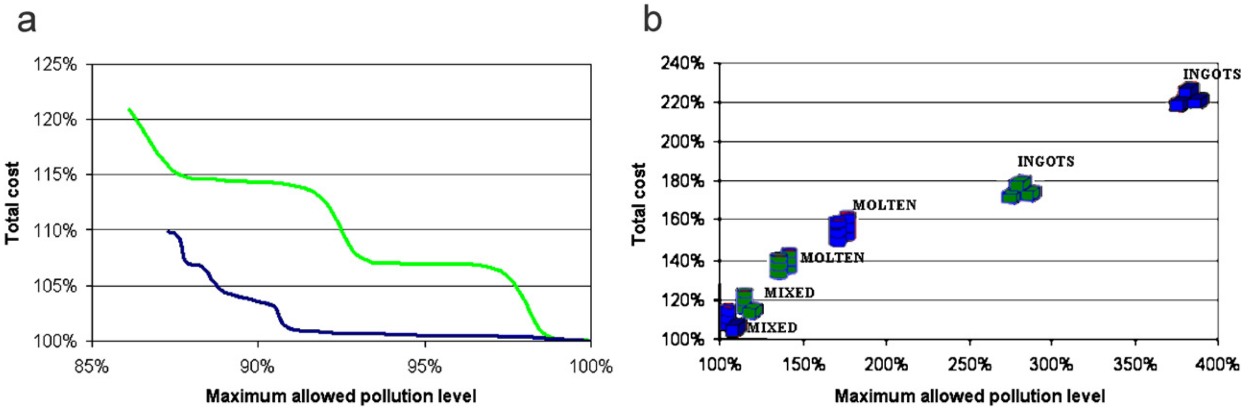

Fig. 3. (a) Results of optimal cost while varying the maximum allowed pollution level. (b) Total costs and pollution level for the different solutions.

introduced and described. It may help managers to appreciate "green" chains, going beyond the traditional cost minimisation and profit maximisation approach. In fact, they may quantify the best level of pollution impact for the own chain. The application of the model shows how different supply chains may balance total pollution and total costs in a more effective way.

The economic efficiency is measured in terms of a trade-off analysis between the environmental impact (i.e. total pollution emissions) and consequent supply chain costs. While pursuing this goal of combined economic-environmental efficiency, the existence of a trade-off curve was identified. It represents the efficiency boundary. The same approach and methodology may be applied to other supply chain cases and the evaluation of their current positioning, in terms of total cost and pollution levels, may be assessed and compared thanks to the efficiency boundary, thus offering the proper information to undertake the best course of action.

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