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Plant Networks for Processing Recyclable Materials

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We use a modified optimal market area model to examine how links between material recycling and other aspects of operations strategy can shape plant networks for the processing of recyclable materials. We characterize the complementarity of the recyclate ratio, defined as the maximum recycled content, with material versatility and miniscaling of recycling plants. We also observe that it is beneficial to coordinate investments in recycling- and production-related competencies because colocated recycling and production plants (minimills) eliminate recyclate transport. We therefore consider versatile miniplants, defined as a competency that factors in both material versatility and coordinated miniscaling of recycling and production plants, and capture how it complements both the recyclate ratio and localization of production plants, a competency that takes advantage of local adaptation and customer proximity. In numerical examples for rolled aluminum and nylon resin plant networks in Europe, we find that the complementarity effects are large, as they are for nylon resins, if recycling is nascent and challenging economically and if the plant network is too centralized at first to benefit much from an increased recyclate ratio or increased localization. We find that, for the nylon resin network, considering an investment in the recyclate ratio as part of a coordinated investment plan drives the emergence of a decentralized and localized minimill network, even though an increased recyclate ratio does not link directly with either decentralization or localization. We conclude that material recycling, versatile miniplants, and localization can fit well together in a forward-looking, sustainable operations strategy.

Key words: recycling; material versatility; localization; minimills; operations strategy; plant networks; optimal market area
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1. Introduction

Material recycling is one of the important societal and economic responses to the approaching limits of the physical environment. A study published by the Waste and Resource Action Programme (2006) in the United Kingdom reviewed a large number of life-cycle assessment studies and confirmed that recycling offers more environmental benefits and lower environmental impacts than other waste management options. Material recycling reduces the amount of waste diverted to landfills, and it produces fewer emissions and uses less energy and nonrenewable resources than the production of virgin materials. So, governments and citizen groups stimulate recycling and companies invest in enabling processes and technologies to lower their environmental impact, to take advantage of favorable economics, or do both (Chalier and Parker 1999, Hart 1995).

Facilitating the rise of recycling is the emergence of recycling plants, labeled minimills when they are colocated with downstream production operations. In the U.S. steel industry, for example, more than 64 million tons of ferrous scrap were recycled in 2008, representing 65.4% of U.S. steel production (Steel Recycling Institute 2009). This high level of recycled content is strongly intertwined with the success of steel minimills, which predominantly use steel scrap as input and are typically smaller and more geographically distributed than integrated steel mills, which mostly use iron ore as input. In 2008, steel minimills were responsible for more than 57% of U.S. steel production. Similar developments are taking place in the aluminum and plastics industries. Aluminum scrap recycling (secondary smelting) accounted for approximately 34% of all aluminum produced in North America in 2008 (The Aluminum Association 2009).

Also, aluminum minimills, which remelt or refine aluminum scrap and then roll, extrude, or cast this secondary aluminum, have become successful plants. In the plastics industry, recycled content is still below 10% even for the most recycled plastics (Petcore 2011), but minimill networks are emerging as well. Examples include the bottle-to-bottle recycling of polyethylene terephthalate (PET) (Reynolds 2010) or the recycling of engineering plastics, 100% from post-consumer scrap, for use in new consumer products (Esposito 2010).

From an operations strategy perspective, the emergence of these minimill operators is interesting because they combine various competencies into coherent and competitive production systems. Successful operators of steel minimills, for example, source and process a range of scrap steel, have lower capital costs, and take advantage of proximity to customers through tight engineering relationships (Barnett and Crandall 1986, Christensen 1997, Schorsch 1996, Giarratani et al. 2006). Other studies have also described how material recycling can be usefully combined with other reinforcing competencies in more decentralized plant networks (Demeester et al. 2004, Field and Sroufe 2007).

For material processors preparing for a future with recycling, these studies imply they need to coordinate their investments in various competencies as they develop and reconfigure their plant networks. Novelis, for example, one of the largest producers of rolled aluminum, has plans to raise the recycled content in its products to 80% from its current level of 40%. This raises the question of what additional investments could complement this strategy and how this would affect their plant network. A similar question is faced by MBA Polymers, a recycler of engineering plastics that states on its website (http://www.mbapolymers.com/home/our-company) that its current plants are "the first four of our many additional plants to come."

In this paper, we shed light on these questions and examine the link between material recycling and operations strategies. Recycling can generate savings in raw material costs, but it creates the need for scrap and recyclate transportation, which are less costly when recycling plants source scrap from smaller market areas and when they are colocated with production plants. These costs and benefits drive a set of links with other competencies, which we investigate in a modified optimal market area model (Erlenkotter 1989) that jointly optimizes the recycling and production plant networks. We introduce, and capture in the model, the key competencies of material versatility, proxied by the demand density of the network, production, and recycling plant miniscaling, represented by the fixed costs of the plants, the recyclate ratio, defined as the maximum recycled content, and production plant localization, defined as the plant's capability to take advantage of local adaptation and customer proximity. The model allows us to capture the complementarities between the recyclate ratio and recycling plant miniscaling and between the recyclate ratio and material versatility. It also shows that the advantage of eliminated recyclate transport in colocated plants creates an incentive to coordinate improvements in recycling and production-related competencies. We therefore consider *versatile miniplants*, defined as a competency that factors in both material versatility and the coordinated miniscaling of recycling and production plants, and we characterize its complementarity with both material recycling and localization. Using two contrasting numerical examples, for rolled aluminum and nylon resins in Europe, we quantify the complementarity effects and examine the links between recycling, localization, and decentralization.

This paper identifies and quantifies key underlying dimensions that link operations strategy, plant networks, and material recycling, revealing that complementarities can have large effects when recycling is in its early stages. The paper also explores why centralization or decentralization of such plant networks might occur and change over time, as illustrated in the numerical examples. Finally, by connecting material recycling to localization, the paper extends the theory that links recycling with non-cost-based operations strategies.

We organize our paper as follows. In §2 we review related literature and clarify the competencies of *recycling*, *miniscaling*, *material versatility*, and *localization* in the context of operations strategy. In §3 we describe a generic plant network with closed-loop material recycling and introduce the model. In §4 we present the analytical results, and in §5 we apply the model to plant networks for rolled aluminum and nylon resins in Europe to illustrate interactions and derive insights. In §6 we conclude the paper and point to possible future research.

2. Plant Network Competencies

We review relevant operations-strategy-related literature before introducing four key competencies.

2.1. Sustainable Operations, Recycling, and Operations Strategy

By arguing for pollution prevention and product stewardship as parts of a natural-resource-based view of the firm, Hart (1995) has fueled the search for sets of competencies that offer a competitive advantage in a more constrained physical world. Empirical studies have identified several high-level, infrastructural competencies that are linked with environmental management, such as reputation-building, human capital development, process innovation, and process management (e.g., Christmann 2000, Darnall and Edwards 2006, Surrocca et al. 2010). At the same time, the field of sustainable operations has identified and developed a range of practices in the areas of product and process development, process management, and closed-loop supply chains that enable companies to reduce their impact on the environment (Kleindorfer et al. 2005, Corbett and Klassen 2006, Guide and Van Wassenhove 2009). Some studies not only describe individual practices or competencies but also identify a fit between such competencies or a fit with specific strategies, in line with the principles of operations strategy (Hayes et al. 2005, Hayes and Wheelwright 1979, Skinner 1969). Using the framework by Fisher (1997), for example, Parmigiani et al. (2011) propose that efficient supply chains are a good match with pollution-prevention practices and responsive supply chains with a product-stewardship approach.

Only a few studies have examined the fit between material recycling, an important aspect of sustainable operations, and other aspects of operations strategies. The paucity of work in this area is consistent with the observation that process industries, which include material recyclers, have received less attention than the discrete manufacturing industries in the literature on closed-loop supply chains (French and LaForge 2006). One relevant exception is a study by Field and Sroufe (2007), who provide a qualitative analysis of the U.S. paperboard industry. They argue that the use of recycled materials is most often introduced by "independent" firms that do not own assets for the production of virgin materials. Because these independent firms have traditionally competed based on flexibility, high value-added services, and customer intimacy, Field and Sroufe (2007 p. 4458) further hypothesize that "the use of recycled materials (through the addition of minimills) by independent firms will increase the use of non-cost-based operations strategies in the industry."

In another study, which is part of the literature on network design for reverse logistics (Aras et al. 2010), Fleischmann et al. (2001) offer a qualified link between material recycling and the level of decentralization of the production plant network, an important element in an operations strategy. In their examples for paper and copiers, they find that, if forward and reverse logistics networks are jointly optimized (instead of sequentially), the production plants are more decentralized. However, this decentralization appeared context-specific, with a real impact on cost only if high recycling rates warrant the relocation of production plants closer to sources of waste and away from remotely located sources of raw materials that are expensive to transport (such as wood from Scandinavian forests for paper making).

Also relevant is a study by Demeester et al. (2004), who apply analogical reasoning to the production principles of the biological cell to conceive of "organic production systems," in which competencies for material recycling, material versatility, low-cost versatile production equipment, small-scale production, and local responsiveness reinforce one another. Demeester et al. (2003) provide a more in depth description of these reinforcing links, but still qualitatively.

Finally, several studies describe the strategies of minimills in the U.S. steel industry (e.g., Barnett and Crandall 1986, Christensen 1997, Giarratani et al. 2006). These studies explain how the use of scrap materials as inputs and technologies with low capital costs allowed minimills to locate closer to customer markets than their integrated competitors and how this structural difference further motivated minimill operators to invest in other low-capital-cost technologies that allowed them to expand their product range.

To further examine the link between material recycling and other aspects of operations strategy, we perform an analytical investigation of the interaction between competencies. This approach is similar to that of other studies in operations strategy that analyze the complementarities between different parameters in a mathematical expression of firm profits (e.g., Milgrom and Roberts 1990, de Groote 1994, Chod et al. 2010), none of which, as far as we know, have modeled material recycling.

The studies reviewed above motivate us to examine the link between material recycling and miniscaling as well as material versatility and localization. We describe these various competencies next.

2.2. Material Recycling and Recycled Content

Material recycling involves the recovery and reprocessing of materials from industrial and postconsumer waste streams. We use recycled content as a measure for the extent of material recycling, defined as the percentage of production volume originating from recycled materials. In 2008, 65.4% of U.S. steel production (Steel Recycling Institute 2009) and 33.7% of North American aluminum production (The Aluminum Association 2009) was recycled content. Also in 2008, 55% of U.S. paper waste was recovered (U.S. Environmental Protection Agency 2009), generating a similar percentage of recycled content. The recycled content in plastics is still rather low (about 8.3% for PET bottles in Europe in 2010; Petcore 2011), but it is rising. MBA Polymers, for example, sources waste plastics from electronics recyclers, sorts them by type, and produces plastic pellets with 100% recycled content, which is used by their customers to produce parts for electronic or electric products (Minter 2006). Electrolux, for example, uses MBA's 100% recycled plastic in six parts of a "green" vacuum cleaner (Electrolux 2009, Esposito 2010).

Government regulations and incentives have a large and increasing role in material recycling. Ultimately, of course, it is profit-seeking companies that invest to increase the average recycled content of a material (e.g., Chalier and Parker 1999, Field and Sroufe 2007). Quite a few of these investments are market oriented to increase collection rates (e.g., Morana and Seuring 2007), whereas others are more focused on processing technologies to lower costs and improve yields and quality. MBA Polymers, for example, has developed proprietary technology that enables it to recycle plastics from automotive shredder residue and has opened several plastics-recovery plants based on this technology (Esposito 2010). In general, by investing in improved collection, baling, sorting, cleaning, and refining of waste materials, companies can strongly impact the average recycled content of materials.

2.3. Miniscaling

We use the term miniscaling to refer to investments that lower the fixed costs of production and recycling plants, thus making such plants economical on a smaller scale. Prime examples of miniscaling are thin-slab casting and continuous casting in the steel and aluminum industry (Aleris International 2010, Schorsch 1996). Both developments eliminate the need for several casting and reheating steps, thus eliminating the fixed costs associated with these steps.

Additional examples of miniscaling are results of developments in advanced new technologies such as "space-frame technology," Pirelli's Modular Integrated Robotic System (MIRS) for tire manufacturing, and "rapid manufacturing" technologies. In space-frame technology, used by Audi, Fiat, and Daimler AG, extruded metal parts are riveted or glued together to build the skeleton of a car body. This technology "dispenses with the expensive machines needed to stamp out load-bearing panels, and so favours the use of smaller, cheaper factories" (*The Economist* 2002, p. 72). With MIRS, which is protected by more than 40 patents, Pirelli has reduced the number of steps for manufacturing tires from 14 to 3 and created a manufacturing system that occupies less space, has modest capital costs, and is economical at an annual capacity of one million instead of a typical six million tires per year (*The Economist* 2000, Meyer 2006, *Tire Business* 2005). A final technology example of miniscaling is rapid manufacturing, also called additive fabrication. These manufacturing technologies build parts layer by layer directly from 3D models, thus eliminating the need for costly molds or dies. Although currently restricted to uniquely customized or low-volume parts, its use has been growing (Wohlers Associates 2006).

Miniscaling is not restricted to technological advances. If a company develops a detailed operations manual and training program to guide its plant operations, it may be able to hire a less experienced and, therefore, less expensive workforce and management team.

2.4. Material Versatility

Material versatility is a competency that allows the plant network to support a wider range of applications, thereby increasing the total demand volume for products made from the same material. The concept of material versatility is related to that of product-range flexibility or variety flexibility (Upton 1997), but rather than focusing on increasing variety to serve smaller segments in existing markets, it emphasizes the development of different applications and different markets for the same material. In process industries, companies often seek such material versatility by investing in process technologies that increase the range of properties or geometries for a given material. An example of such an investment is when aluminum producers work with automobile manufacturers to produce aluminum sheet that can be stamped into body panels previously made from steel. An example of material versatility through new geometric shapes comes from rapid manufacturing technologies (Wohlers Associates 2006). Building parts layer by layer allows for geometries that are infeasible with traditional manufacturing techniques, and it opens up new applications for existing materials.

2.5. Localization

We use the term localization to refer to two important but different mechanisms companies can use to increase profits in small-market-area plant networks by obtaining price premiums and/or cost advantages. The first mechanism involves adaptation to local market areas by configuring plants to suit local demand or supply factors. There are already some indications that minimills in the steel industry have adopted such a localization strategy. Mittal Steel executives explained to us that they allow for differences in steel minimill design, depending on local supply factors. In regions with highly skilled labor, the plant design will contain more automated systems, whereas simpler, manual systems are installed in other regions.

The second mechanism relies on local service competencies that leverage customer proximity for small-market-area plants. For example, Nucor is well-known for locating steel minimills close to customers and for taking advantage of that proximity to develop new, additional solutions to their local customers' special problems (Giarratani et al. 2006). Customer proximity can enable such customization, made-to-order, or other service-oriented strategies in which short transportation times between the plant and customers are crucial. A second example is

NatSteel, part of the Tata Group, which uses its steel minimill in Singapore to deliver customized steel structures in just-in-time fashion to the Singapore construction industry (*Business Excellence* 2011).

It is important to note that a localization advantage is not an automatic by-product of small market areas. Companies such as Mittal Steel, Nucor, and NatSteel have developed distinctive competencies, at considerable investment costs, to take advantage of the smaller market areas of their plants.

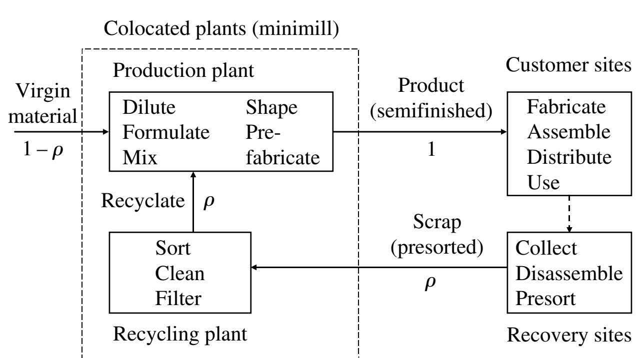
3. Model

The unit of analysis in our model is a plant network for the processing of a specific recyclable material such as steel, aluminum, or plastic. To introduce the market area model, we first present a generic plant network with closed-loop material recycling based on observations of several industrial networks.

3.1. A Generic Processing Plant Network with Closed-Loop Recycling

Figure 1 presents the material flows we consider. Recovery sites gather scrap materials by collecting and disassembling end-of-life products and by collecting fabricator scrap, if available. The recovered materials are then transported to a nearby recycling plant where they are fine sorted, cleaned, filtered, and refined to remove contaminants. The output of a recycling plant, called recyclate, is used as input for a nearby production plant, where it may be mixed with virgin materials and other additives before it is shaped, formed, or prefabricated into a semifinished product. The semifinished product will then be shipped to nearby customer sites for further fabrication, assembly into a final product, and distribution to final customers. The point of separation between what we label the production plant and the fabrication and assembly steps at customer sites is taken as a given in this study. This separation point is characterized by a smaller scale of operations at a customer site than at the production plant when measured in units of the material.

Figure 1 **A Generic Processing Plant Network with Closed-Loop Material Recycling**



Sometimes a recycling plant and a production plant are colocated, as in a steel minimill for example. In a minimill, scrap steel input is melted in an electric arc furnace and undergoes several process steps to remove contaminants before the right steel grade is formulated. Pure iron is often added to the scrap mix to dilute the level of contaminants or alloy components. At the end of the process, the steel is extruded or rolled into the desired shape and shipped to customer sites.

In the aluminum industry, recycling and production plants have started to colocate as well; Aleris International's plants in Uhrichsville, Ohio, form one such example. Mostly, however, the plants are still separated, with ingots of secondary aluminum (recyclate) from an aluminum remelter in the United Kingdom (recycling plant) being shipped to a rolling mill in Germany (production plant), for example. For plastics, recycling and production plants are mostly separated as well, with recyclate taking the form of sorted and clean plastic flakes. Some colocated plants are emerging though, either because recyclers forward-integrate (e.g., Esposito 2010) or because producers backward-integrate (e.g., Reynolds 2010).

3.2. A Modified Optimal Market Model

To investigate the links between recyclate ratio, miniscaling, material versatility, and localization in plant networks, we propose modifications to the optimal market area model (Erlenkotter 1989), which is part of a class of continuous location models (Daganzo 1999). Our analysis thus becomes grounded in a time-tested model that provides good approximations and insights about the optimal trade-off between economies of scale and distance-related costs (Geoffrion 1976; Hayes et al. 2005, p. 101). Optimal market area models have been used to gain insights in reverse logistics networks (Fleischmann 2003, Wojanowski et al. 2007), but we are not aware of any previous attempts to obtain analytical insights from a market area model with both production and recycling plants. Borrowing from Erlenkotter's (1989) notation and formulation, we specify the modified optimal market area model as follows (see Table 1 for a glossary of all the symbols used in the model):

(a) Demand for a semifinished product is distributed uniformly over an infinite plane, with density $d > 0$, per unit area per year. We use d as a proxy for the material versatility of the production and recycling technologies (see §2.4). An increase in material versatility would lead to a larger value of d.

(b) The annual cost for a plant processing amount w per year is $k_i + c_i w$, where k_i, $c_i \geq 0$ with the index i equaling p for production and r for recycling plants. This characterization of scale economies simplifies analysis and, according to industry experts,

Table 1 Symbols Used in the Model and Base Values for the Numerical Examples

Symbol	Rolled aluminum	Nylon resin	Unit	Description
Competencies				
d	1	0.12	Unit year^{-1} km^{-2}	Demand density: Units of demand per km^2 per year; proxy for material versatility
k_p	25 M	1.2 M	€ year^{-1}	Annualized size-independent fixed costs for a production plant; reducible by miniscaling
k_r	2 M	1.2 M	€ year^{-1}	Annualized size-independent fixed costs for a recycling plant; reducible by miniscaling
$\rho_{\max}$	0.4	0.1	Ratio	Recyclate ratio; maximum recycled content; $0 < \rho_{\max} < 1$
$g_{\max}$	0	0	€ unit^{-1}	Maximum localization advantage (for production plant, when R_p approaches 0)
Decision variables				
ρ	0.4	0	Ratio	Chosen recycled content; $0 \le \rho \le \rho_{\max}$
R_p	541	437	km	Production radius: Radius of the market area of a production plant
q	1/2	—	Ratio	Ratio of recycling radius R_r to production radius R_p with $q \in \{\ldots, 1/6, 1/4, 1/2, 1, 2, 4, 6, \ldots\}$
Parameters and functions				
$R_r = qR_p$	271	—	km	Recycling radius: Radius of the market area of a recycling plant
c_p			€ unit^{-1}	Variable production cost
c_r			€ unit^{-1}	Variable recycling cost (including cost of scrap)
c_m			€ unit^{-1}	Virgin material cost
P			€ unit^{-1}	Unit price prior to localization advantage
$G = P - c_m - c_p$	15	40	€ unit^{-1}	Gross margin prior to recycling, localization, and transportation
$\Delta_r = c_m - c_r$	180	100	€ unit^{-1}	Savings per recycled unit
g	0	0	€ unit^{-1}	Localization advantage per unit of demand; $g_{\max}(1 - R_p/b)$
b	500	500	km	Production market area radius at which the localization advantage becomes zero
t_p	0.06	0.06	€ unit^{-1} km^{-1}	Unit transport cost per km for semifinished product
t_r	0.03	0.03	€ unit^{-1} km^{-1}	Unit transport cost per km for recyclate
t_s	0.14	0.10	€ unit^{-1} km^{-1}	Unit transport cost per km for presorted scrap
$\pi^*(\rho, q)$			€ unit^{-1}	Unit profit for a given ρ and q, optimized for R_p
π^{**}	2.55	0.69	€ unit^{-1}	Unit profit, optimized for R_p, ρ and q

closely matches the economics of producing and recycling engineering plastics. At the end of §5.4, we also report results for a common alternative characterization of plant cost, $k_i w^\alpha + c_i w$, with $0 < \alpha < 1$.

(c) The recycled content is denoted by ρ, with $0 \le \rho \le \rho_{\max}$ and $0 < \rho_{\max} < 1$. The maximum recycled content, or recyclate ratio, is denoted by $\rho_{\max}$ and reflects constraints in availability of scrap as well as the technology, methods, infrastructure, and yields for scrap collection and recycling. The material flows, in steady state, are proportioned as indicated by the flow arrows in Figure 1. One unit of production is associated with $1-\rho$ units of virgin material and ρ units of recyclate from ρ units of scrap, assuming that the yield loss in the recycling plant is negligible. The supply of scrap from recovery sites is assumed to be distributed uniformly with a density of ρd per unit area per year, matching the need for recycled content ρ in the demand volume d.

(d) The unit cost of virgin material is denoted by c_m, and the variable cost of recycling, which includes the cost of scrap, is denoted by c_r.

(e) The market areas served by plants are square shaped, with a radius R_p for production plants and R_r for recycling plants, where "radius" refers to half the length of the square's side. For a recycling plant, the term "market area" refers to the area in which scrap is sourced, whereas for a production plant it refers to the area to which product is shipped. We assume plants to be located at the center of their market area. (We remove this restriction in one of a series of robustness tests reported on in Online Appendix B, available as supplemental material at http://dx.doi.org/10.1287/msom.2013.0437; its effect is small and does not affect the findings, so we exclude it from further analysis.) Also, without loss of generality, we restrict our analysis to a subset of solutions in which $R_r = qR_p$ with $q \in \{\ldots, 1/6, 1/4, 1/2, 1, 2, 4, 6, \ldots\}$, and market areas are arranged as in Figure 2.

(f) Transportation distances are measured with the Manhattan metric, so the average distance between a production plant and a customer site is R_p (e.g., Erlenkotter 1989), between a customer site and a recycling plant is R_r, and between a recycling and a production plant is $r(q)R_p$, where

$$r(q) = \begin{cases} 1 & \text{if } q < 1, \\ 0 & \text{if } q = 1, \\ q & \text{if } q > 1. \end{cases}$$

This can be verified as follows: If the market areas for production and recycling plants are the same size ($q = 1$), the plants are colocated (distance $= 0$). If they are different in size ($q \neq 1$), the average distance between the two plants is driven by the larger market area (see Figure 2).

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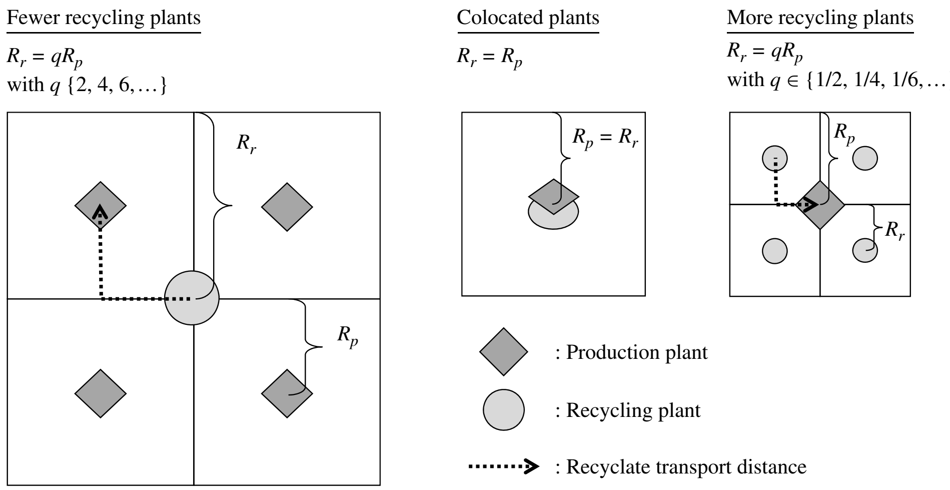
Figure 2 **Geographical Arrangement of Production and Recycling Plants as a Function of q**



(g) Unit transport costs are proportional to the distance traveled. The unit transport costs per kilometer (km) for product, scrap, and recyclate are denoted as t_p, t_s, and t_r, respectively.

(h) Localization of the production plants generates an extra unit advantage g, with $0 \le g \le g_{\max}$, where the maximum localization advantage, $g_{\max}$, depends on local differences in demand and supply factors as well as on the company's investments in localization capabilities. Typically, the localization advantage decreases as the market area increases. So if we use b (with $b \ge R_p$) to represent the market area radius at which the localization advantage becomes zero, then the localization advantage g can be characterized as $g_{\max}(1 - R_p/b)$. Note that we do not model the localization of recycling plants. This allows us to keep the model relatively simple and study the more remote link between the localization of production plants and the recyclate ratio.

The market shape and distance metric assumptions in (e) and (f) allow for a simple calculation of recyclate transport distance but may seem restrictive or unrepresentative. However, Erlenkotter (1989) shows that using other assumptions is equivalent to changing the transportation costs by a constant factor. Assuming that an equivalent recyclate transportation cost can be achieved in approximately the same way, we can test for different assumptions by varying the transportation costs t_p, t_s and t_r. (We describe the results of such a robustness test in §5.2.)

Given the above assumptions, the unitized profit, or unit profit, of the plant network can be expressed as

$$\pi = P + g_{\max}\left(1 - \frac{R_p}{b}\right) - \{c_p + (1-\rho)c_m + \rho c_r\} - \frac{k_p}{4R_p^2 d} - \frac{\lceil\rho\rceil k_r}{4q^2 R_p^2 d} - t_p R_p - \rho t_s q R_p - \rho t_r r(q) R_p.$$

The first term in this mathematical expression, P, is the unit price of an end product prior to localization. The second term reflects the localization advantage, and the third contains the variable costs. The fourth and fifth contain the fixed costs per unit of demand for the two plant types ($\lceil\rho\rceil = 0$ if $\rho = 0$ and $\lceil\rho\rceil = 1$ if $\rho > 0$) and the sixth, seventh, and eighth terms reflect the transportation costs per unit of demand. With $G = P - (c_p + c_m)$ as a measure of the gross margin prior to recycling, localization, and transportation and $\Delta_r = c_m - c_r$ as a measure of the variable savings per recycled unit prior to transportation, we rearrange the terms as a function of R_p and simplify the expression as follows:

$$\pi = G + g_{\max} + \rho\Delta_r - \frac{k_p + \lceil\rho\rceil k_r/q^2}{4d} R_p^{-2} - \left\{t_p + \frac{g_{\max}}{b} + \rho(q t_s + r(q) t_r)\right\} R_p.$$

This expression clearly reveals the modifications we have introduced to the optimal market area model (Erlenkotter 1989). The effect of localization appears as a margin advantage $g_{\max}$ combined with an additional cost $g_{\max}/b$ per unit of distance from the production plant to customer sites. To recycle ($\rho > 0$), an annual fixed cost of k_r/q^2 is added to the annual fixed cost of a production plant, with $1/q^2$, the number of recycling plants per production plant, to be decided. The extent of recycling is captured by ρ ($\le \rho_{\max} < 1$), the number of units recycled per unit of demand. Reduction in virgin material costs leads to recycling savings of $\rho\Delta_r$ per unit of demand, but it adds $\rho(q t_s + r(q) t_r)$ to the cost per unit of demand per unit of distance between production plants and customer sites, reflecting the additional transportation costs for presorted scrap and recyclate.

We use the results from Erlenkotter (1989) to find the optimal $R_p^*(\rho, q)$ and $\pi^*(\rho, q)$ for any ρ and q:

$$\pi^*(\rho, q) = G + g_{\max} + \Delta_r\rho - 3\left(\frac{1}{2}\right)^{4/3}\left(\frac{k_p + \lceil\rho\rceil k_r/q^2}{d}\right)^{1/3} \cdot\left(t_p + \frac{g_{\max}}{b} + \rho(qt_s + r(q)t_r)\right)^{2/3}, \quad (1)$$

$$R_p^*(\rho, q) = \left(\frac{1}{2}\right)^{1/3}\left(\frac{k_p + \lceil\rho\rceil k_r/q^2}{d(t_p + g_{\max}/b + \rho(qt_s + r(q)t_r))}\right)^{1/3}. \quad (2)$$

We observe that, for all values of q, π^* is convex in ρ except for a negative step at $\rho = 0^+$, so the optimal recycled content will either equal zero, indicating no recycling, or $\rho_{\max}$, the recyclate ratio. These assumptions and observations lead to an expression of the optimal unit profit as

$$\pi^{**} = \max_{\rho\in\{0,\, \rho_{\max}\},\, q\in\{\ldots,1/6,1/4,1/2,1,2,4,6,\ldots\}} \pi^*(\rho, q) \quad (3)$$

with corresponding optimal values ρ^{**}, q^{**}, and $R_p^{**} = R_p^*(\rho^{**}, q^{**})$. To find ρ^{**} and q^{**}, we perform a simple exhaustive search. If $\rho = 0$, $\pi^*(0, q)$ does not depend on q. If $\rho = \rho_{\max}$, the optimal q can be found with a simple search heuristic because, both for $q < 1$ and $q > 1$, $\pi^*(\rho_{\max}, q)$ has only one local maximum.

4. Interactions and Complementarities

In this section, we analyze the interactions and complementarities between the recyclate ratio, production and recycling miniscaling, material versatility, and localization.

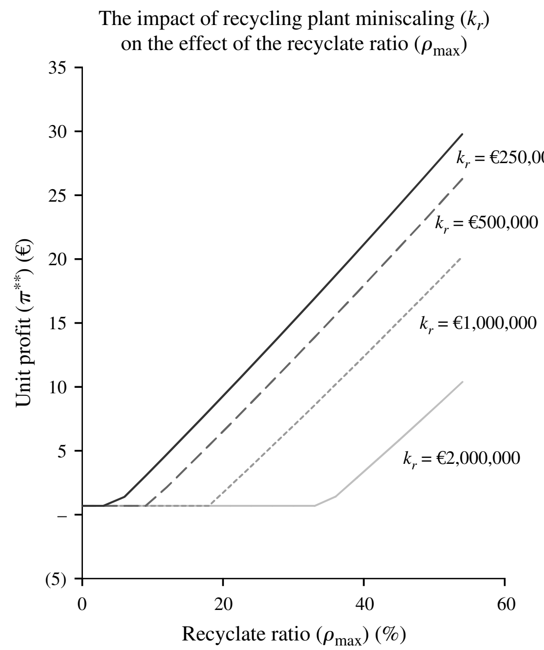
4.1. Recyclate Ratio, Recycling Miniscaling, and Material Versatility

In the presented model, the recyclate ratio complements recycling miniscaling and material versatility. We describe these complementarities in Propositions 1 and 2 (proofs available in Appendix A).

Proposition 1. *The recyclate ratio and recycling miniscaling are complementary. Or mathematically, if* $k_{r2} < k_{r1}$ *and* $\rho_{\max 2} > \rho_{\max 1}$, *then* $\pi^{**}(k_{r2}, \rho_{\max 2}) - \pi^{**}(k_{r2}, \rho_{\max 1}) \geq \pi^{**}(k_{r1}, \rho_{\max 2}) - \pi^{**}(k_{r1}, \rho_{\max 1})$.

We illustrate this complementarity in Figure 3, which charts the optimal unit profit (π^{**}) as a function of $\rho_{\max}$ for different values of k_r. (The charts in Figures 3 and 4 are all anchored around the parameter values of the nylon resin example described in §5; see Table 1 for the parameter values.) The figure shows that recycling miniscaling improves the benefits derived from an increased recyclate ratio. One reason for this is that when the recycling technology is miniscaled the recyclate ratio at which recycling becomes optimal decreases (this can be observed in Figure 3). In addition, recycling miniscaling leads to more decentralized recycling plants, reduced scrap transportation costs, and thus increased benefits from higher recyclate ratios. This is reflected in the steeper slopes of the curves for a smaller k_r. This complementarity between recycling miniscaling and recyclate ratio can explain the lack of success of feedstock recycling, a capital-intensive process (large k_r) in which scrap plastics are chemically broken down into precursor components for reuse. In 2003, feedstock recycling was an outlet for only 1.7% of all plastic waste in Western Europe, compared with 14.8% for other recycling processes (Plastics Europe 2004). In Germany, according to executives at a large plastics manufacturer, the discontinuation of certain types of feedstock recycling was because of a lack of government guarantees for the supply of plastic scrap (low recyclate ratio). Appropriate sharing of costs aside, it is perhaps no surprise that, given the substantial scrap transportation costs associated with the large market areas of these expensive recycling plants (large k_r), no investments were made to increase the recyclate ratio. Feedstock recycling technology appears to be positioned on the nonincreasing part of one of the lower curves in Figure 3.

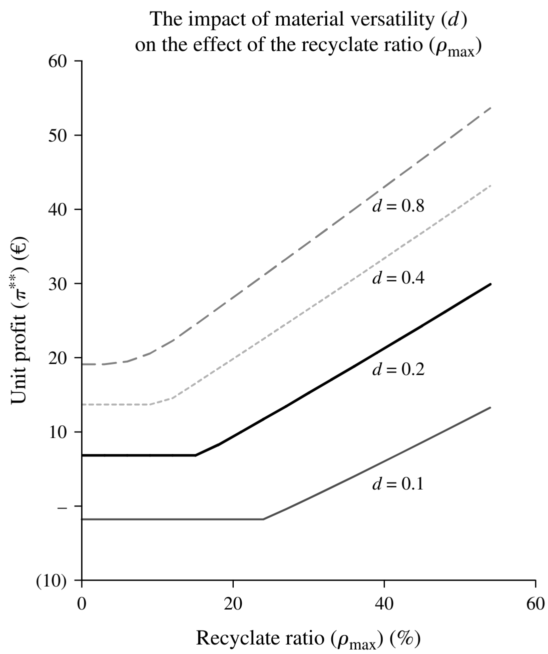
Figure 3 **Recyclate Ratio and Recycling Plant Miniscaling**



Proposition 2. *The recyclate ratio and material versatility are complementary. Or mathematically, if* $d_2 > d_1$ *and* $\rho_{\max 2} > \rho_{\max 1}$, *then* $\pi^{**}(d_2, \rho_{\max 2}) - \pi^{**}(d_2, \rho_{\max 1}) \geq \pi^{**}(d_1, \rho_{\max 2}) - \pi^{**}(d_1, \rho_{\max 1})$.

This second complementarity is illustrated in Figure 4. As material versatility increases, the recyclate ratio at which recycling becomes optimal decreases.

Figure 4 **Recyclate Ratio and Material Versatility**



Also, once in recycling mode, the benefits of an increased recyclate ratio are higher because the smaller-sized market areas associated with more versatile materials involve lower scrap and recyclate transportation costs. This complementarity may have been an important factor in the success of the minimills in the steel and aluminum industries. In its September 2005 reports to investors, Aleris International (2005) mentions how its "expanded plant network provides favorable freight dynamics" (i.e., smaller market areas) and how its strategy includes "extending [its production capability] to higher-margin products" (i.e., increasing material versatility) as well as "acquiring [a] wider basket of scrap types" (i.e., increasing the recyclate ratio).

To present additional results, we first discuss the presence of a colocation bonus to motivate a more restricted model with coordinated miniscaling of recycling and production plants.

4.2. Colocation Bonus

When the production and recycling market areas are equal in size, with production and recycling plants colocated ($q = 1$), a special benefit arises because the transport between plants is eliminated. Eliminating recyclate transport provides a bonus to improvements that lead to such solutions, and a penalty for improvements that force a separation of plants. This is illustrated in Figure 5, also based on the nylon resin example, with $\rho_{max} = 40\%$ and $\Delta_r = €200$ to assure that recycling is economical for the chosen range of k_r.

The figure examines the unit profit increase from the same recycling miniscaling effort (a reduction of k_r from €1,200,000 to €120,000) for different production technologies with a fixed cost k_p ranging from €10,000,000 to €1,000. The four bars on the chart show the average unit profit increase for four different scenarios, illustrated at the bottom of the

Figure 5 **Colocation Bonus**

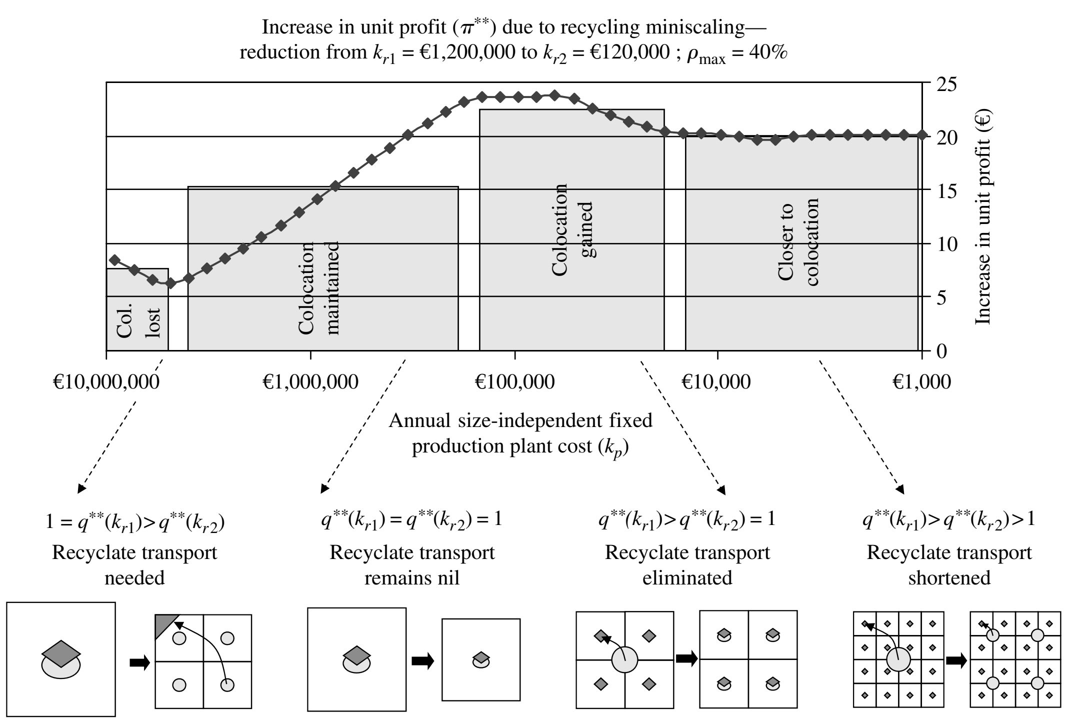


figure and labeled "colocation lost," "colocation maintained," "colocation gained," and "closer to colocation." The chart shows that the largest benefit accrues when recycling miniscaling eliminates recyclate transport by facilitating the colocation of recycling plants with previously more decentralized production plants ("colocation gained"). The least benefit accrues when recycling miniscaling forces the separation of production and recycling plants ("colocation lost").

The effect of this *colocation bonus* also applies to improvements in localization capabilities. An increase in localization can generate an additional colocation bonus when the resulting incentive to reduce the production radius justifies the colocation of production plants with previously more numerous recycling plants. However, a similar increase in localization can incur a penalty when it causes production plants to separate from a large-scale recycling technology to reduce the production radius.

Colocated plants have additional advantages that are not captured by our model. In aluminum plant networks, for example, the colocation of plants can eliminate several capital-intensive cooling and reheating steps. (This was confirmed to us by an executive at Novelis, a large aluminum processor.)

In summary, the colocation bonus provides an incentive for operations managers to coordinate their improvement efforts such that a colocated-plant solution becomes or remains optimal ($q^{**}=1$). We consider this effect to formulate additional results by introducing the concept of *versatile miniplants*.

4.3. Versatile Miniplants, Recyclate Ratio, and Localization

By postulating that $k_r = \theta k_p$ ($\theta > 0$), we define the competency of versatile miniplants (d/k_p), encompassing both material versatility (increase in d) and the coordinated miniscaling of recycling and production plants (reduction of k_p, with $k_r = \theta k_p$). The motivation for defining this competency is as follows. Because both material versatility and miniscaling are directly related to manufacturing technology (§2), it is common for innovations to combine changes in both dimensions. We have discussed several examples of such innovations: Pirelli's development of the MIRS process to manufacture tires, the use of space-frame technology in the automobile industry, and the development of rapid manufacturing technologies. Typically, such innovations leverage economies of scope or a form of process or product modularity to obtain a wider variety of outputs (material versatility) with relatively low-cost, small-scale equipment (miniscaling). The miniscaling in versatile miniplants is assumed to be coordinated for production and recycling technologies ($k_r = \theta k_p$). Such coordination could naturally take place if the same process knowledge underlies production and recycling miniscaling. It could also take place intentionally. The colocation bonus, discussed in the previous subsection, can provide a strong incentive to develop production and recycling technology jointly.

The competency of versatile miniplants allows the formulation of additional results. Using $k_r = \theta k_p$ in Equation (1), we can see that the competency of versatile miniplants (d/k_p) behaves like d in Proposition 2, which leads to Proposition 3. (The proof is similar to that of Proposition 2 and an illustration would be similar to Figure 4.)

Proposition 3. *The recyclate ratio and versatile miniplants (increase in d/k_p, with $k_r = \theta k_p$) are complementary. Or mathematically, if $(d/k_p)_2 > (d/k_p)_1$ and $\rho_{\max 2} > \rho_{\max 1}$, then $\pi^{**}((d/k_p)_2, \rho_{\max 2}) - \pi^{**}((d/k_p)_2, \rho_{\max 1}) \geq \pi^{**}((d/k_p)_1, \rho_{\max 2}) - \pi^{**}((d/k_p)_1, \rho_{\max 1})$.*

This proposition further connects the recyclate ratio with competencies that are related to the production technology. If the miniscaling of production technology is linked to the miniscaling of recycling technology, for reasons we discussed above, it will lead to smaller market areas for recycling plants, smaller transportation distances for scrap, and thus more incentive to increase the recyclate ratio.

Given our interest in recycling and given the complementarity between the recyclate ratio and versatile miniplants, it is also useful to study which other competencies complement versatile miniplants because these would then be indirectly linked to recycling. We do this for the localization competency in the following proposition.

Proposition 4. *Localization and versatile miniplants are complementary (if the versatile miniplant improvements are sufficiently large). Or mathematically, if $g_{\max 2} > g_{\max 1}$ and $(d/k_p)_2 > (d/k_p)_1$, together with*

$$\frac{(d/k_p)_2}{(d/k_p)_1} > \left(1 + \frac{\theta}{q^{**}(g_{\max 1})^2}\right) \cdot \left(\frac{t_p + g_{\max 2}/b}{t_p + g_{\max 2}/b + \rho_{\max}(q^{**}(g_{\max 1})t_s + r(q^{**}(g_{\max 1}))t_r)}\right),$$

then

$$\pi^{**}((d/k_p)_2, g_{\max 2}) - \pi^{**}((d/k_p)_2, g_{\max 1}) \geq \pi^{**}((d/k_p)_1, g_{\max 2}) - \pi^{**}((d/k_p)_1, g_{\max 1}).$$

Proposition 4 is driven by the fact that versatile miniplants allow plant networks to achieve economies of scale in smaller market areas. As a result, such plant networks can take better advantage of localization. The extra condition in the proposition ensures that the production market radius R_p^{**} decreases when d/k_p increases from $(d/k_p)_1$ to

$(d/k_p)_2$. The condition is required because when an increase in d/k_p causes ρ^{**} to switch from 0 to $\rho_{\max}$ there are two types of interactions that may cause the production radius R_p^{**} to increase instead of decrease. A first interaction arises from the restriction that the recycling radius R_r equals qR_p, with $q \in \{\ldots, 1/6, 1/4, 1/2, 1, 2, 4, 6, \ldots\}$. A second type of interaction takes place because of the colocation bonus. If an increase in d/k_p warrants the start of recycling, colocated plants ($q = 1$) with a radius larger than the existing production radius may be optimal because it reduces the number of recycling plants to be built while also avoiding the transport of recyclate. The effects of these interactions are both countered when the increase in d/k_p is large enough, as specified in the condition. In the nylon resin example from §5, where $g_{\max 1} = €0$ and $g_{\max 2} = €50$, the condition in Proposition 4 specifies that $(d/k_p)_2/(d/k_p)_1 > 1.064$ (i.e., a 6.4% increase).

Figure 6 shows how higher values of d/k_p lead to an increase in benefits derived from localization ($g_{\max}$). This effect can provide some explanation for the development of local service capabilities at Nucor's steel minimills. As Nucor benefited from the lower capital costs and improved product range associated with advanced minimill technologies (an increase in d/k_p), they located plants closer to customers (a decrease in R_p). They also learned to take advantage of that proximity (increase in $g_{\max}$) by developing new additional solutions to their local customers' special problems (Giarratani et al. 2006).

Propositions 3 and 4 provide a simple synthesis of the complementarities among recycling, miniscaling,

Figure 6 **Versatile Miniplants and Localization**

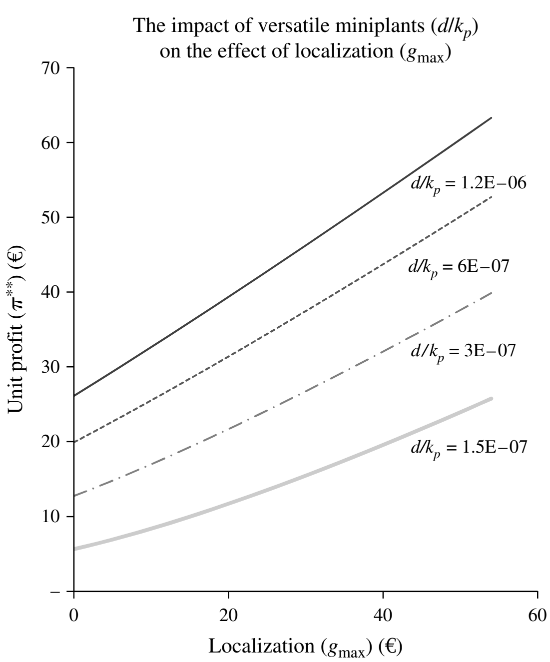
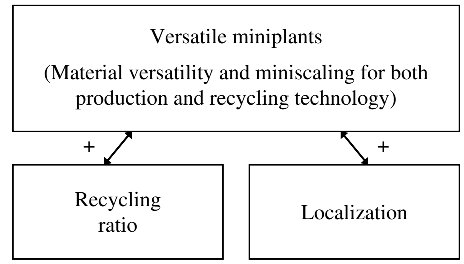


Figure 7 **Synthesis of Complementarities**



material versatility, and localization, as shown in Figure 7.

5. Insights from Numerical Examples

In this section, we apply the model to European plant networks for two different recyclable materials to obtain extra insights.

5.1. Plant Networks for Rolled Aluminum and Nylon Resins

The parameter values for the base case of the two examples are listed in Table 1, and the corresponding plant network solutions are described in the second column of Table 2. We describe them here.

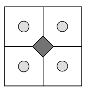
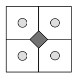
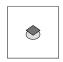
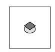
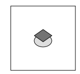
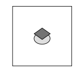
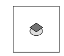
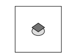
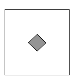
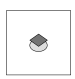
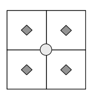
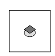
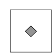
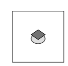
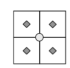
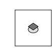
5.1.1. Rolled Aluminum. Aluminum production comes in two types: cast aluminum, used by foundries to cast aluminum parts, and wrought aluminum, used by rolling mills to produce rolled aluminum (plate, sheet, or foil) and by extruders to produce a wide range of profiles. Because of differences in alloying elements, the recycling plants for cast and wrought aluminum are different and are called refiners and remelters, respectively. In our first example, we focus on rolled aluminum with remelters as recycling plants and rolling mills as production plants. We estimated the model parameters using industry reports (e.g., EAA/OEA 2006) and press releases.

d: In 2004, 27 countries in the European Union (EU-27; 4.325 million (M) km^2) produced 4.4 M tons of rolled aluminum, corresponding to a demand density d of approximately 1 ton per square km per year.

k_p and k_r: A typical rolling mill costs €240 M for a plant capacity of 200,000 (or 200 k) tons. We estimate that a 20% rate applies for annual interest, depreciation, and maintenance costs and that 50% of those annual costs are independent of the size of the plant, reflecting relatively high economies of scale. To that amount we add the size-independent annual labor costs (estimated at €1 M) to arrive at a value for k_p of €25 M. A typical remelter investment is less than €30 M for a plant capacity of 60–90 k tons and, with slightly lower economies of scale, a similarly derived estimate for k_r is €2 M.

$\rho_{\max}$: In 2004, in the EU-27 the overall recycled content in aluminum production was 45%, higher for

Table 2 Impact of Competency Improvements in Different Plant Networks

	Base case	(1) Recyclate ratio	(2) Versatile miniplants	(1) Recyclate ratio (2) Versatile miniplants	(3) Localization	(1) Recyclate ratio (3) Localization	(2) Versatile miniplants (3) Localization	(1) Recyclate ratio (2) Versatile miniplants (3) Localization
Rolled aluminum								
Parameter changes	—	$\rho_{\max}$: 40% → 80%	d: 1 → 1.2 ton/km^2 k_p: €25 M → 12.5 M	(1) and (2)	$g_{\max}$: €0 → €50/ton	(1) and (3)	(2) and (3)	(1), (2), and (3)
Plant network	$R_p^{**} = 541$ km $\rho^{**} = 40\%$ $q^{**} = 1/2$	$R_p^{**} = 481$ km $\rho^{**} = 80\%$ $q^{**} = 1/2$	$R_p^{**} = 373$ km $\rho^{**} = 40\%$ $q^{**} = 1$	$R_p^{**} = 327$ km $\rho^{**} = 80\%$ $q^{**} = 1$	$R_p^{**} = 397$ km $\rho^{**} = 40\%$ $q^{**} = 1$	$R_p^{**} = 367$ km $\rho^{**} = 80\%$ $q^{**} = 1$	$R_p^{**} = 304$ km $\rho^{**} = 40\%$ $q^{**} = 1$	$R_p^{**} = 281$ km $\rho^{**} = 80\%$ $q^{**} = 1$
Configuration ◆: Prod. plant ○: Recyc. plant								
Plants in EU-27 (kt, k tons)	p: 4 × 1,172 kt r: 16 × 117 kt	p: 5 × 927 kt r: 20 × 185 kt	p: 8 × 669 kt r: 8 × 268 kt	p: 10 × 515 kt r: 10 × 412 kt	p: 7 × 630 kt r: 7 × 252 kt	p: 8 × 540 kt r: 8 × 432 kt	p: 12 × 443 kt r: 12 × 177 kt	p: 14 × 379 kt r: 14 × 303 kt
Unit profit increase (change in π^{**})	—	€49.61/ton	€19.47/ton	€71.96/ton = €49.61 + €19.47 + €2.88 (+4.2%)	€5.87/ton	€56.51/ton = €49.61 + €5.87 + €1.04 (+1.9%)	€36.10/ton = €19.47 + €5.87 + €10.76 (+42%)	€91.76/ton = €49.61 + 19.47 + 5.87 + €16.81 (+22.43%)
Nylon resins								
Parameter changes	—	$\rho_{\max}$: 10% → 40%	d: 0.12 → 0.24 ton/km^2 k_p, k_r: €1.2 M → 0.6 M	(1) and (2)	$g_{\max}$: €0 → €50/ton	(1) and (3)	(2) and (3)	(1), (2), and (3)
Plant network	$R_p^{**} = 437$ km $\rho^{**} = 0$	$R_p^{**} = 464$ km $\rho^{**} = 40\%$ $q^{**} = 1$	$R_p^{**} = 261$ km $\rho^{**} = 10\%$ $q^{**} = 2$	$R_p^{**} = 292$ km $\rho^{**} = 40\%$ $q^{**} = 1$	$R_p^{**} = 315$ km $\rho^{**} = 0\%$	$R_p^{**} = 368$ km $\rho^{**} = 40\%$ $q^{**} = 1$	$R_p^{**} = 203$ km $\rho^{**} = 10\%$ $q^{**} = 2$	$R_p^{**} = 232$ km $\rho^{**} = 40\%$ $q^{**} = 1$
Configuration ◆: Prod. plant ○: Recyc. plant								
Plants in EU-27	p: 6 × 92 kt r: none	p: 5 × 103 kt r: 5 × 41 kt	p: 16 × 65 kt r: 4 × 26 kt	p: 13 × 82 kt r: 13 × 32 kt	p: 11 × 48 kt r: none	p: 8 × 65 kt r: 8 × 26 kt	p: 28 × 39 kt r: 7 × 16 kt	p: 20 × 51 kt r: 20 × 21 kt
Unit profit increase (change in π^{**})	—	€9.69/ton	€14.87/ton	€35.45/ton = €9.69 + €14.87 + €10.89 (+44%)	€13.72/ton	€18.79/ton = €9.69 + €13.72 − €4.61 (−20%)	€42.19/ton = €14.87 + €13.72 + €13.60 (+48%)	€59.69/ton = €9.69 + 14.87 + €13.72 + €21.41 (+55.93%)
Investment cost Invest—YES or NO	— —	€10/ton NO	€30/ton NO	€40/ton (10 + 30) NO	€15/ton NO	€25/ton (10 + 15) NO	€45/ton (30 + 15) NO	€55/ton (10 + 30 + 15) YES

cast aluminum and lower for wrought aluminum. We assume the recyclate ratio, $\rho_{\max}$, to be 40%. This matches the recycled content reported by Novelis, a larger rolled aluminum producer, in 2012 and reflects the economical attractiveness of aluminum recycling.

$g_{\max}$, b: Because we did not identify any descriptions of localization of rolling mills, we assume a base value of €0 for $g_{\max}$. The base value for b assumes that any localization advantage will disappear when the production market radius is larger than 500 km (a production market area about twice the size of Spain).

Other parameters: The values of €0.06, €0.14, and €0.03 for t_p, t_s, and t_r, respectively, lie within the range of available per-ton-per-km transport costs in Europe (Herry 2002, Table 42) and reflect the differences in transport efficiencies. Scrap transport is the least efficient because scrap is difficult to pack efficiently and may include other waste. Recyclate transport is most efficient because it is similar to a standardized bulk product (e.g., ingots) and semifinished product transport can be expected to fall somehere in between. The €180 value for $\Delta_r (= c_m - c_r)$, the savings per recycled ton of aluminum, is high enough to reflect the economic value of recycling aluminum but not so high we can ignore the competition for scrap (the scrap price is part of c_r). The €15 value for G results in a near-zero unit profit of €2.55.

In this example we adjusted the value of t_s from an original estimate of €0.1 (Herry 2002, Table 42) to €0.14/ton/km, slightly weakening the complementarity effects but better matching the volume of recycling plants in the solution (117 k tons) to volumes of existing remelters. This higher, calibrated value of t_s can reflect potential benefits for recycling plants located close to sources of scrap. As mentioned, we don't explicitly model such localization of recycling plants, but it can be a factor as well (e.g., Field and Sroufe 2007).

The plant network in the base-case solution has four production plants in the EU-27, each producing about 1,172 k tons per year with recycled content of 40%. Although many existing rolling mills in Europe have less capacity, capacities of 1,000 k tons and more are efficient. For example, Novelis' rolling mill in Neuss, Germany, has a capacity of 1,500 k tons. The solution also has four recycling plants with a capacity of 117 k tons each, for each production plant ($\rho^{**} =$ 40%, $q^{**} = 1/2$). This capacity is close to reported capacities; Hydro Norsk reports remelters with capacities between 60 k and 90 k tons.

5.1.2. Nylon Resins.

Nylon resins are a type of engineering plastics used in automotive, electrical, and electronic applications. The virgin material is used by compounders, the production plants in the model, to produce pellets with various characteristics that are used by fabricators (molders, extruders, etc.) to produce parts. Proposed recycling technologies clean, separate, and filter scrap materials to be compounded anew.

d: We use a demand density of 0.12 ton per km^2, for a total demand of 519,000 tons in EU-27 (4.325 M km^2). This represents 1.15% of all thermoplastics consumption in Europe in 2003, close to the 2% share of polyamides, the plastics that nylon resins form the bulk of (Plastics Europe 2004).

k_p and k_r: In 2004, MBA Polymers built a €17 M minimill in Austria (20 k tons). Assuming 20% of the cost is paid annually, 60% of it independent of size, and an annual size-independent labor cost of €360,000, the fixed costs, $k_p + k_r$ add up to €2.4 M. We assume that $k_r = k_p =$ €1.2 M and report, in §5.2, on varying these values in a robustness test.

$\rho_{\max}$: Ten percent reflects limitations in collection infrastructure and recycling technology for nylon resins.

$g_{\max}$, b: Values estimated at €0 and 500 km are the same as for rolled aluminum.

Other parameters: The parameters t_p, t_s, and t_r have the same values as in the first example, without the adjustment for t_s. The €100 value for $\Delta_r (= c_m - c_r)$, the savings per ton of recyclate, is lower than the value for rolled aluminum, reflecting the challenges in recycling nylon resins. With $G =$ €40, unit profit is near zero (€0.69).

The base-case solution has six production plants in EU-27, each producing about 90 k tons per year. This plant capacity is consistent with those of existing nylon resin compounders. (According to an industry expert, the capacities in 2006 ranged from 5 k to 120 k tons, and 90 k tons is about optimal.) The solution has no recycling plants ($\rho^{**} = 0$), consistent with negligible levels of nylon resin recycling to date.

5.2. Size of Complementarity Effects

To illustrate the size of complementarity effects, we show the impact of three separate and four combined competency improvements on the plant network structure and profits for each network (Table 2).

5.2.1. Improvement Options and Complementarity Effects.

For rolled aluminum, the first improvement option (1) increases the recyclate ratio from 40% to 80%. This is in line with Novelis' stated goal of increasing recycled content to 80% by 2020. The second option (2) increases the competencies of material versatility and miniscaling simultaneously under the label of versatile miniplants. By growing the number of applications, as in the automotive industry for example, rolled aluminum can achieve a 20% increase in demand density d. Also, by investing in continuous casting technologies, production plants can be miniscaled (k_p can be reduced by 50%). There is no miniscaling of the recycling plant, consistent with the notion that improvements are coordinated to achieve a colocated plant solution. The third option (3) increases localization to reach a maximum localization advantage of €50 per ton (about 2% of the price of rolled aluminum).

For each set of combined improvements, the *unit profit increase* in Table 2 is also written as the sum of the effects of separate improvements plus the extra effect of complementarity. Consistent with Propositions 3 and 4, this extra effect is positive for the (1) + (2) and the (2) + (3) combinations, and for rolled aluminum, it is also positive for the (1) + (3) combination. For the triple combination (1) + (2) + (3), the extra effect (€16.81) is higher than the sum of the three paired complementarity effects, driven by a further reduction in market area, which is a fit for all three improvement strategies.

For nylon resins, the first improvement option (1) increases the recyclate ratio from 10% to 40% and is considered feasible by a representative of a plastic minimill operator by 2020, assuming that legislation and technology investments keep moving in the right direction. Improvement option (2) for versatile miniplants assumes a two-fold increase in material versatility (d) and a coordinated 50% reduction in k_p and k_r through miniscaling. The third improvement option (3) increases the maximum localization advantage, $g_{\max}$, to €50 per ton, equivalent to approximately 2% of the price of nylon resin. Table 2 shows that the complementarities of Propositions 3 and 4 have a large effect for nylon resins. The relative effect of the complementarities is highest in the triple improvement, with a combined profit increase (€59.69) that is 55.93% higher than the sum of the separate profit increases for the three improvement options (€9.69 + €14.87 + €13.72).

We tested for the sensitivity of the complementarity effects using simulations in which the parameter values were varied independently with a coefficient of variation of 0.2. The resulting distributions of the complementarity effects (€) for triple improvements had coefficients of variations of approximately 0.19 with means that were within 5% of the original values. Given this moderate sensitivity of the complementarity effects to parameter values, it is worth examining what drives the size of the effects.

5.2.2. Settings with Large Complementarity Effects. For nylon resins, the complementarity between (1) recyclate ratio and (2) versatile miniplants has a larger effect (44% compared with 4.2% for rolled aluminum; see Table 2). What-if analysis reveals that this difference is driven by the smaller demand density, the smaller recycling savings ($\Delta_r = c_m - c_r$), and the smaller initial recyclate ratio for nylon resins. Because of these parameter values for nylon resins, the market area for a hypothetical recycling plant in the base case is too large to benefit much from improvements in the recyclate ratio. In Figure 4 this is true for the lower curve, representative of the nylon resin base case, with a zero or low gradient with respect to the recyclate ratio. The potential for complementarity effects, by moving to curves with higher gradients, also seen in Figure 4, are quite high. This is not true for rolled aluminum, where the base case already holds immediate and large benefits from improving the recyclate ratio. As for the complementarity between localization and versatile miniplants, both examples display a large effect of complementarity (42% and 48%) because both base cases are situated on an improvement curve comparable to the lowest curve in Figure 6. In both base cases, improvements in localization do not increase unit profit much because the production radius, R_p^{**}, approaches the value for b, the radius at which the localization advantage disappears. Thus, the potential for complementarity, by moving to higher curves in Figure 6, is high. In summary, the complementarity effects can be large when recycling is nascent and challenging economically and the networks are too centralized at first for recycling or localization to have much benefit.

5.3. Competency Coordination and Plant Network Transformation

The examples can also illustrate how complementarities between competencies can impact the transformation of plant networks.

5.3.1. Evaluating Alternative Networks. For a rolled aluminum producer like Novelis, the analysis in Table 2 suggests the following. If Novelis plans to improve the recyclate ratio, as they have announced, but do not invest in other competencies, there is not much reason to alter the configuration of their plant network, which is not much different for the base case and for improvement option (1) in Table 2. However, the table shows that if they would also develop versatile miniplants and improve localization, they could benefit from a reconfigured plant network that eliminates the transport of a growing amount of recyclate and takes advantage of customer proximity. Instead of planning to supply more recyclate to their existing network of rolling mills, they could consider transitioning to a different plant network by building colocated remelter-plus-rolling mills in areas close to old or new customers and sources of scrap. Thus, to evaluate the full benefits of an alternative plant network, Novelis can consider combinations of improvements in a model that jointly optimizes the recycling and production plant network.

5.3.2. Investing in Competencies. To fully investigate the impact of complementarities on the transformation of plant networks, it is also useful to consider the investment costs for competency improvements. We present such analysis for one of the two plant network examples, choosing the nylon resin example because it illustrates how the coordination of multiple competency investments can significantly impact a plant network in which recycling is nascent and economically challenging (with no recycling plants in the base case).

We assume that the unitized investment costs are €10, €30, and €15 per ton of demand for the improvements in (1) recyclate ratio, (2) versatile miniplants, and (3) localization, respectively. The bottom three rows in Table 2 show how these unitized investment costs can be subtracted from the unit profit increases for an improvement scenario to conclude whether there has been an increase in overall, or economic, profit to make the investment worthwhile. The assumed unitized investment costs correspond to the following *total* investment costs for a plant network in the EU-27: (1) €36.3 M, (2) €218 M, and (3) €54.5 M for the three improvement options, assuming that the investment is spread equally over seven years and over the total demand for each year (e.g., for the recyclate ratio investment, €10 per ton $*$ 519,000 tons of demand per year $*$ 7 years equals €36.3 M; and for the versatile miniplant investment, which is also associated with a doubling of demand density, €30 per ton $*$ 1,038,000 tons of demand per year $*$ 7 years equals €218 M).

The assumed investment costs can illustrate the impact of complementarities but are also representative of strategic investments in practice. Shaw Industries, for example, a carpet manufacturer, invested "over $30 million" to improve a process technology for recycling nylon (Shaw Industries 2011). The investment cost for versatile miniplants is assumed to be significantly larger than the other two investment costs because it is associated with the most challenging technical task. Correspondence with an industry expert has indicated that a 50% reduction in capital costs, for example, would indeed be unlikely without breakthroughs that require significant investments. These investments are large for even mid-sized companies, but the assumption is that the resulting technologies and investment costs are shared across an entire EU-27 plant network. Also, some producers are large; BASF, for example, produces nylon resins and spent €1.6 billion on R&D and €3.4 billion on capital projects in 2011.

The unitized investment costs for the combined investments are assumed to be simple sums of their separate unitized investment costs, implying that the improvements in recyclate ratio, versatile miniplants, and localization do not complicate nor simplify each other, *per unit of demand*. So, for the (1) + (2) improvement combination, we assume that the total investment costs will be €218 M for the versatile miniplants plus €72.6 M (=2 $*$ 36.3) for the recyclate ratio, with the doubling of the investment costs for the recyclate ratio driven by the doubling of the demand density d as part of the versatile miniplants improvement. These assumptions for investment costs satisfy the conditions, described and discussed in §A.2 of Appendix A, that are sufficient to extend the complementarity propositions from §4 to a measure of unit *economic* profit, defined as unit profit minus unitized investment cost. We also assume here, reasonably, that investments in recyclate ratio and localization of production do not complicate nor simplify each other.

5.3.3. Coordinated Investments and Emergence of a Minimill Network. Because of the complementarities, only the triple investment option increases economic profit (last row in Table 2). Separate investments that are not economical become attractive when considered together, thereby illustrating how the complementarities in Figure 7 can create a need to coordinate investments. The attractive triple investment shows how, even though they are not linked through complementarity, the recyclate ratio investment and the localization investment are connected nevertheless because they can "join forces" to "help pay" for versatile miniplants, a competency from which both benefit because of the associated smaller market areas.

The nylon resin example shows that an understanding of the complementarities can make the difference between the continuation of a plant network without recycling and the emergence of one that features recycling, localization, and versatile miniplants with market areas one third their original sizes. It is also worth noting that the sum of all transportation costs per ton of demand, and assumably, associated emissions, are lower in the new network, post triple investment, even though the more expensive transportation for scrap is added. (This can be verified in the transportation cost terms in the unit profit π.)

5.4. Recyclate Ratio, Decentralization, and Localization

The two examples also offer insight into how the recyclate ratio impacts decentralization and localization of plants.

5.4.1. Recyclate Ratio and Decentralization. An increase in the recyclate ratio always leads to more decentralized recycling plants because of the increase in scrap transport. (This can be proven for the general model.) This decentralization of recycling plants will often lead to more decentralized production plants because the recyclate transport "pulls" the plants together. This effect can be observed in the rolled aluminum example by comparing R_p^{**} in Table 2 between the base case and (1), (2) and (1) + (2), (3) and (1) + (3), and (2) + (3) and (1) + (2) + (3). The recycling plants in the base case are more decentralized than the more expensive production plants ($q^{**} = 1/2$) and an increased recyclate ratio exerts a stronger "pull" on the production plants toward more decentralized recycling plants, here leading to a decentralization of production. In the nylon resin example though, increasing the recyclate ratio in isolation consistently leads to an increase in R_p^{**}, i.e., a centralization of production (compare R_p^{**} in Table 2 as in the rolled aluminum example above). In this example, the increase in recyclate ratio and the corresponding recyclate transport pulls the production plants toward recycling plants that, even after this increase, "prefer" to be more centralized than the production plants.

5.4.2. Recyclate Ratio and Localization. The interaction between the recyclate ratio and localization is closely related. For rolled aluminum the localization of production decentralizes production plants and causes colocation with more decentralized recycling plants to become optimal ($q^{**} = 1$). This colocation is beneficial when the recyclate ratio is increased because recyclate transport is avoided. So localization and recyclate ratio are complementary (see (1) + (3) in Table 2). This happens because k_p is much larger than k_r and the recycling plants are more decentralized in the base case ($q^{**} = 1/2$). For nylon resins, the interaction is negative. If the recyclate ratio is increased (going from (3) to (1) + (3) in Table 2) after introducing localization, recycling becomes optimal and introduces recyclate transport. This recyclate transport pulls the production plants toward more centralized recycling plants, thereby reducing the benefits from localization.

5.4.3. Recyclate Ratio and Decentralization of Production Plants. So, we find that, in the nylon resin example, because of the colocation bonus, an increase in the recyclate ratio can lead to centralization of production. However, once recycling is established in a colocated plant, given the benefit of reducing scrap transport distance and maintaining colocation, an increase in the recyclate ratio will decentralize both recycling and production, as seen in the rolled aluminum example. In combination with earlier observations, this analysis further shows how various investments and their coordination can shape plant networks over time. In the nylon resin example, increasing the recycling ratio in isolation might induce a centralization of production plants. However, as seen in the example, the complementarities can create incentives to invest in all three competencies combined and so the *ultimate* effect of considering a recyclate ratio investment would still be a significant decentralization of production.

A final note regarding decentralization relates to a robustness test we performed by using an alternative characterization of *economies of scale* by formalizing the annual costs of a plant as $k_i w^\alpha + c_i w$, with w the annual volume of the plant and $0 < \alpha < 1$. (We tested with $\alpha = 0.66$.) The complementarity effects (%) for the triple improvement scenarios were within 2% of those reported in Table 2. Interestingly, because $k_i w^\alpha$ reduces for smaller-volume plants, the number of plants in the triple-improvement solution increased by more than 50% in both examples compared with the figures in Table 2, thereby amplifying the potential decentralization of the plant network in coordinated investment plans.

6. Conclusion

The analysis we have presented enhances the insights from existing qualitative and descriptive work regarding the link between material recycling and operations strategy in process industries (Christensen 1997; Demeester et al. 2003, 2004; Field and Sroufe 2007). With a modified optimal market area model, we are able to quantify the effect of complementarities between material recycling, versatile miniplants, and localization for specific plant networks. The numerical examples also illustrate that these complementarities have a large effect when recycling is nascent and challenging economically and the networks are too centralized for recycling or localization to have much benefit. Finally, because we separated competencies for recycling and production plants, such as miniscaling and localization, we uncovered a link between these competencies, driven by a colocation bonus: Companies benefit from coordinating investments such that colocation of recycling and production plants either becomes or remains optimal.

A related insight involves the link between material recycling and the decentralization of the production plant network, which was found to be significantly positive only under certain context-specific conditions by Fleischmann et al. (2001). We find that, because of the colocation bonus, if the economics favor a centralized recycling network, the introduction of recycling may actually cause a centralization of production. This is also why we find that the recyclate ratio is not always complementary to the localization of production. However, in both numerical examples, even though recycling did not always lead to decentralization of production directly, an increased recyclate ratio provided extra incentive to develop the complementary competencies of versatile miniplants and, indirectly, localization. And these improvements could ultimately lead to a significant decentralization of production. Thus, the more significant impact of recycling on decentralization may only appear when complementary improvements are considered simultaneously in a coordinated investment plan.

Our findings also offer qualified support for the hypothesis that recycling-based plant networks will be associated with noncost-based (i.e., differentiation-based) operations strategies such as localization (Demeester et al. 2004, Field and Sroufe 2007). Even though the recyclate ratio and localization of production are not always complementary, they are clearly connected because both are complementary with versatile miniplants, which can be "paid for jointly" by adding up the two effects. In addition, in terms of the framework presented by Parmigiani et al. (2011), we have found a qualified fit between material recycling, a product stewardship capability, and decentralized, localized, and thus potentially more responsive supply chains. These wider implications can also be seen as follows. If there are increasing incentives to introduce material recycling, the resulting decentralization of material processing plants may also influence the operations strategies of fabricators and assemblers. A manufacturer of desktop printers, for example, could, in the presence of decentralized production networks for recyclable plastics, decide to perform the final assembly of plastic housing components in distributed regional centers instead of in a central manufacturing plant. The manufacturer could leverage the regional versatile miniplants for the supply of plastic housing parts and could offer a wider and more localized variety of options (e.g., exterior colors) by leveraging this decentralized and thus potentially postponed part of their manufacturing process. The regional center could become part of the recycling loop by taking back and disassembling end-of-life printers to return plastic parts to the nearby versatile miniplant. So, the emergence of versatile miniplants for recyclable materials could engender more local, postponed forms of manufacturing and more locality-driven product variety.

In conclusion, the analysis presented here indicates that material recycling, versatile miniplants, and localization of production can go hand in hand as important competencies in sustainable, more decentralized, and more localized plant networks.

Supplemental Material

Supplemental material to this paper is available at http://dx.doi.org/10.1287/msom.2013.0437.

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Appendix A

A.1. Proofs of Propositions

Proof of Proposition 1. It suffices to show that $\partial\pi^{**}(k_{r2}, \rho_{\max})/\partial\rho_{\max} \geq \partial\pi^{**}(k_{r1}, \rho_{\max})/\partial\rho_{\max}$ for all $0 < \rho_{\max} < 1$. If the optimal values of ρ and q are the same for k_{r2} and k_{r1}, this can easily be verified. Inspection of (1) shows that a decrease in k_r can also cause a shift in the optimality of ρ and q from $(\rho = 0, q)$ to $(\rho = \rho_{\max}, q)$ or from $(\rho = \rho_{\max}, q = q_1)$ to $(\rho = \rho_{\max}, q = q_2 < q_1)$. For the first type of shift, $\partial\pi^{**}/\partial\rho_{\max}$ shifts from zero to a positive value, so this will not break the inequality. If the second type of shift occurs, say at value k'_r, then $\pi^*(q_2) = \pi^*(q_1)$ at k'_r, which means that $q_2 t_s + r(q_2)t_r < q_1 t_s + r(q_1)t_r$ (from (1)). Because we can write

$$\frac{\partial\pi^*}{\partial\rho_{\max}} = \Delta_r - \frac{2}{3}(G + g_{\max} + \rho\Delta_r - \pi^*(q)) \cdot \frac{q t_s + r(q)t_r}{t_p + g_{\max}/b + \rho_{\max}(q t_s + r(q)t_r)}$$

with a simple substitution in the derivative, we can verify that $\partial\pi^*(q_2)/\partial\rho_{\max} > \partial\pi^*(q_1)/\partial\rho_{\max}$ at value k'_r. □

Proof of Proposition 2. It suffices to show that $\partial\pi^{**}(d_2, \rho_{\max})/\partial\rho_{\max} \geq \partial\pi^{**}(d_1, \rho_{\max})/\partial\rho_{\max}$ for all $0 < \rho_{\max} < 1$. If the optimal values of ρ and q are the same for d_2 and d_1, then it can be easily verified that this inequality will hold. Inspection of (1) shows that an increase in d can cause a shift in the optimality of ρ from $(\rho = 0)$ to $(\rho = \rho_{\max})$ but no shift in the optimal q. If said shift occurs, $\partial\pi^{**}/\partial\rho_{\max}$ shifts from zero to a positive value so the inequality will hold. □

As mentioned in §4.3, the proof of Proposition 3 is similar.

The next proof relies on the nondecreasing property of q^{**} with respect to $g_{\max}$, shown as a lemma first.

Lemma 1. *If $g_{\max 1} \leq g_{\max 2}$, then $q^{**}(g_{\max 1}) \leq q^{**}(g_{\max 2})$.*

Proof of Lemma 1. If $g_{\max 1} = g_{\max 2}$, $q^{**}(g_{\max 1}) = q^{**}(g_{\max 2})$. For $g_{\max 1} < g_{\max 2}$, we prove by contradiction. Suppose $q^{**}(g_{\max 1}) > q^{**}(g_{\max 2})$. Because π^* is continuous and differentiable in $g_{\max}$, there exists $g'_{\max} \in [g_{\max 1}, g_{\max 2}]$, $q_1, q_2 \in \{\ldots, 1/4, 1/2, 1, 2, 4, \ldots\}$ such that $q_1 = q^{**}(g'{}_{\max}{}^{-}) > q^{**}(g'{}_{\max}{}^{+}) = q_2$ with

$$\left.\frac{\partial\pi^*(\rho_{\max}, q_1)}{\partial g_{\max}}\right|_{g'_{\max}} < \left.\frac{\partial\pi^*(\rho_{\max}, q_2)}{\partial g_{\max}}\right|_{g'_{\max}};$$

i.e., $g'_{\max}$ is the turning point of $q^{**}(g_{\max})$ switching from q_1 to q_2. From (1) and (2), we derive $\partial\pi^*/\partial g_{\max} = 1 - R^*_p/b$, so, $R^*_p(q_1) > R^*_p(q_2)$ at $g'_{\max}$. With $q_1 > q_2$, we can see from (2) that this implies $q_1 t_s + r(q_1)t_r < q_2 t_s + r(q_2)t_r$, with $r(q)$ from part (f) of §3.2. This inequality can only hold if $q_1 = 1$ and $q_2 < 1$. This implies that $\pi^*(\rho_{\max}, q = q_1 = 1) > \pi^*(\rho_{\max}, q = q_2)$ at $g_{\max} = g'_{\max^+}$ and so $q^{**}(g'_{\max^+}) > q_2$. We arrive at a contradiction. □

Proof of Proposition 4. Let $v = d/k_p$. It suffices to show that for all $g_{\max} \in [g_{\max 1}, g_{\max 2}]$, $\partial\pi^{**}(v_2, g_{\max})/\partial g_{\max} \geq \partial\pi^{**}(v_1, g_{\max})/\partial g_{\max}$, or because $\partial\pi^*/\partial g_{\max} = 1 - R^*_p/b$, that $R^{**}_p(v_2) \leq R^{**}_p(v_1)$. It is clear from (2) that if an increase in v does not cause a change in ρ^{**} or q^{**}, then the condition will be met. It is also clear from (1) and (3) that an increase in v can cause a change in ρ^{**}, from 0 to $\rho_{\max}$, but no change in q^{**}. Thus, for all $g_{\max} \in [g_{\max 1}, g_{\max 2}]$ for which $\rho^{**}(v_1) = 0$ and $\rho^{**}(v_2) = \rho_{\max}$, we need to show that

$R_p^{**}(v_2) \le R_p^{**}(v_1)(*)$. Recall that $k_r = \theta k_p$, $(\theta > 0)$. From (2) we see that (*) holds if and only if

$$\frac{v_2}{v_1} \ge (1+\theta/q^{**}(g_{\max})^2) \cdot \left(\frac{t_p + g_{\max}/b}{t_p + g_{\max}/b + \rho_{\max}(q^{**}(g_{\max})t_s + r(q^{**}(g_{\max}))t_r)}\right).$$

We show this holds for all $g_{\max} \in [g_{\max 1}, g_{\max 2}]$ if

$$\frac{v_2}{v_1} \ge (1+\theta/q^{**}(g_{\max 1})^2) \cdot \left(\frac{t_p + g_{\max 2}/b}{t_p + g_{\max 2}/b + \rho_{\max}(q^{**}(g_{\max 1})t_s + r(q^{**}(g_{\max 1}))t_r)}\right).$$

First note that replacing $g_{\max}$ with $g_{\max 2}$ does not make the second factor smaller. Also, because $g_{\max 1} \le g_{\max}$, by Lemma 1, $q^{**}(g_{\max 1}) \le q^{**}(g_{\max})$. So replacing $q^{**}(g_{\max})$ with $q^{**}(g_{\max 1})$ does not make the first factor smaller. Neither does this replacement make the second factor smaller as long as $q^{**}(g_{\max 1})t_s + r(q^{**}(g_{\max 1}))t_r \le q^{**}(g_{\max})t_s + r(q^{**}(g_{\max}))t_r(^{**})$. Otherwise, suppose (**) does not hold. Observing the behavior of $r(q)$ at $q=1$, we can see (**) does not hold only when $q^{**}(g_{\max 1}) < 1$ and $q^{**}(g_{\max}) = 1$. However, it is also easy to see from (1) that if (**) does not hold, $\pi^*(g_{\max 1}, q=1) > \pi^*(g_{\max 1}, q<1)$, which contradicts $q^{**}(g_{\max 1}) < 1$. □

A.2. Investment Costs and Economic Profits

To fully investigate the complementarity of competencies in plant networks, it is also useful to consider interactions between the investment costs for competency improvements (e.g., Milgrom and Roberts 1990). To do so, we can consider a unit economic profit function (inclusive of investment costs) of the following form:

$$\Pi(d, k_p, k_r, g_{\max}, \rho_{\max}) = \pi^{**}(d, k_p, k_r, g_{\max}, \rho_{\max}) - \kappa(d, k_p, k_r, g_{\max}, \rho_{\max}), \quad (4)$$

with $\kappa(d, k_p, k_r, g_{\max}, \rho_{\max})$ representing the annualized cost, per unit of demand, of the investments needed to reach the indicated levels of the parameter values. Each of the propositions in §4 can be modified to reflect the unit economic profit Π, with additional conditions on unitized investment costs κ.

P1′: *Recyclate ratio* and *recycling miniscaling*. For this complementarity to hold for economic profit (i.e., if $k_{r2} < k_{r1}$ and $\rho_{\max 2} > \rho_{\max 1}$, then $\Pi(k_{r2}, \rho_{\max 2}) - \Pi(k_{r2}, \rho_{\max 1}) \ge \Pi(k_{r1}, \rho_{\max 2}) - \Pi(k_{r1}, \rho_{\max 1})$), it is sufficient that investments to improve the recyclate ratio are not more costly when recycling technology has been miniscaled (i.e., if $k_{r2} < k_{r1}$ and $\rho_{\max 2} > \rho_{\max 1}$, then $\kappa(k_{r2}, \rho_{\max 2}) - \kappa(k_{r2}, \rho_{\max 1}) \le \kappa(k_{r1}, \rho_{\max 2}) - \kappa(k_{r1}, \rho_{\max 1})$). This condition would hold if miniscaling is the result of a reduction of the number of processing steps, each of which would need a similar adjustment when the recyclate ratio is increased. The modifications for the other propositions are similar, and we comment on the conditions for investment costs

P2′: Propositions 2–4 may involve increases in d, and one might expect investment costs for other improvements to increase when combined. However, because the original propositions hold for unit profit and κ in (4) is also per unit, it is sufficient that the total investment costs increase no more than proportionally. For example, this requires that, if material versatility (d) doubles, the total investment costs for increasing the recyclate ratio are less than doubled. It would appear that this condition could hold for materials and technologies where waste availability is not a major constraint.

P3′ and P4′: For Proposition 3 and 4, the conditions are a combination of those for P1′ and P2′ except that for P4′ the recyclate ratio is replaced with localization. We can also comment here that, although the overall investment costs for localization are expected to rise when plants become more versatile, one can envisage situations in which these investment costs would not rise more than proportionally.

References

Aleris International (2005) Investor meeting/September 2005. Retrieved September 28, 2005, http://media.corporate-ir.net/media_files/irol/18/186390/0905InvestorPres.ppt.

Aleris International (2010) Uhrichsville, Ohio (Rolling Mill). Retrieved June 1, 2010, http://www.aleris.com/locations/united-states/urichsville-rolling.

Aras N, Boyaci T, Verter V (2010) Designing the reverse logistics network. Ferguson M, Souza GC, eds. *Closed Loop Supply Chains: New Developments to Improve the Sustainability of Business* (CRC Press, New York), 67–97.

Barnett DF, Crandall RW (1986) *Up from the Ashes: The Rise of the Steel Minimill in the United States* (The Brookings Institution, Washington, DC).

Business Excellence (2011) Natsteel: Building from scrap. (December 22), http://www.bus-ex.com/article/natsteel.

Chalier A, Parker J (1999) The economics of technological innovation in recycling. Working paper, Department of Economics, Reed College, Portland, OR.

Chod J, Rudi N, Van Mieghem JA (2010) Operational flexibility and financial hedging: Complements or substitutes? *Management Sci.* 56(6):1030–1045.

Christensen C (1997) *The Innovator's Dilemma* (Harvard Business School Press, Boston).

Christmann P (2000) Effects of "best practices" of environmental management on cost advantage: The role of complementary assets. *Acad. Management J.* 43(4):663–680.

Corbett CJ, Klassen RD (2006) Extending the horizons: Environmental excellence as key to improving operations. *Manufacturing Service Oper. Management* 8(1):5–22.

Daganzo C (1999) *Logistics Systems Analysis*, 3rd ed. (Springer, Berlin).

Darnall N, Edwards D Jr (2006) Predicting the cost of environmental management system adoption: The role of capabilities, resources and ownership structure. *Strategic Management J.* 27(4):301–320.

de Groote X (1994) Flexibility and marketing/manufacturing coordination. *Internat. J. Production Econom.* 36(2):153–167.

Demeester L, Eichler K, Loch CH (2004) Organic production systems: What the biological cell can teach us about manufacturing. *Manufacturing Service Oper. Management* 6(2):115–132.

Demeester L, Loch CH, Van Wassenhove LN (2003) Organic production systems. Working Paper 2003/24/TM, INSEAD, Fontainebleau, France.

EAA/OEA (European Aluminium Association and Organisation of European Aluminium Refiners and Remelters) (2006) Aluminium recycling in Europe: The road to high quality products. Retrieved February 2, 2012, http://recycling.world-aluminium.org/uploads/media/fl0000217.pdf.

Economist, The (2000) Re-inventing the wheel. *The Economist* 355(8167):57–58.

Economist, The (2002) Incredible shrinking plants. *The Economist* 362(8261):71–73.

Electrolux (2009) My other vacuum cleaner is (still) a Porsche. Press release (June 3, 2009), http://newsroom.electrolux.com/uk/2009/06/03/shredded-cars-are-the-raw-material-for-the-newest-ultra-silencer-vacuum-cleaner-from-electrolux/.

Erlenkotter D (1989) The general optimal market area model. *Ann. Oper. Res.* 18(1–4):45–70.

Esposito F (2010) MBA moving toward being a global recycler. *Plastic News* (March 15), http://www.plasticsnews.com/article/20100315/NEWS/303159959/mba-moves-toward-being-global-recycler.

Field JM, Sroufe RP (2007) The use of recycled materials in manufacturing: Implications for supply chain management and operations strategy. *Internat. J. Production Res.* 45(18):4439–4463.

Fisher ML (1997) What is the right supply chain for your product? *Harvard Bus. Rev.* 75(2):105–116.

Fleischmann M (2003) Reverse logistics network structures and design. Guide VDR Jr, Van Wassenhove LN, eds. *Business Aspects of Closed-Loop Supply Chains* (Carnegie Mellon University Press, Pittsburgh), 117–148.

Fleischmann M, Beullens P, Bloemhof-Ruwaard JM, Van Wassenhove LN (2001) The impact of product recovery on logistics network design. *Production Oper. Management* 10(2):156–173.

French ML, LaForge RL (2006) Closed-loop supply chains in process industries: An empirical study of producer re-use issues. *J. Oper. Management* 24(3):271–286.

Geoffrion AM (1976) The purpose of mathematical programming is insight, not numbers. *Interfaces* 7(1):81–92.

Giarratani F, Gruver G, Jackson R (2006) Agglomeration and market entry in the U.S. steel industry. Working paper, Industry Studies Association, University of Pittsburgh, Pittsburgh.

Guide VDR Jr, Van Wassenhove LN (2009) The evolution of closed-loop supply chain research. *Oper. Res.* 57(1):10–18.

Hart SL (1995) A natural-resource-based view of the firm. *Acad. Management Rev.* 20(4):986–1014.

Hayes R, Pisano G, Upton D, Wheelwright S (2005) *Operations, Strategy, and Technology: Pursuing the Competitive Edge* (John Wiley & Sons, Hoboken, NJ).

Hayes RH, Wheelwright SC (1979) Link manufacturing process and product life cycles. *Harvard Bus. Rev.* 57(1):133–140.

Herry M (2002) Transportpreise und Transportkosten der verschiedenen Verkehrsträger im Güterverkehr. Verkehr und Infrastruktur Nr. 14, Kammer für Arbeiter und Angestellte für Wien, Vienna, Austria.

Kleindorfer PR, Singhal K, Van Wassenhove LN (2005) Sustainable operations management. *Production Oper. Management* 14(4):482–492.

Meyer B (2006) Pirelli VP says speedy R&D turnover is key. *Rubber and Plastics News* (October 30), http://www.globaltirenews.com/headlines2.html?id=1163435827.

Milgrom P, Roberts J (1990) The economics of modern manufacturing: Technology. *Amer. Econom. Rev.* 80(3):511–528.

Minter A (2006) Blazing the plastic recycling trail. *Scrap Magazine* (July/August):61–66.

Morana R, Seuring S (2007) End-of-life returns of long-lived products from end customer—Insights from an ideally set up closed-loop supply chain. *Internat. J. Production Res.* 45(18–19):4423–4437.

Parmigiani A, Klassen RD, Russo MV (2011) Efficiency meets accountability: Performance implications of supply chain configuration, control, and capabilities. *J. Oper. Management* 29(3):212–223.

Petcore (2011) Petcore and EuPR publish PET collection figures for 2010—European PET bottle collection increases by more than 6%. Press release (July 8), http://www.petcore.org/content/petcore-and-eupr-publish-pet-collection-figures-2010-european-pet-bottle-collection-increase.

Plastics Europe (2004) *An Analysis of Plastics Consumption and Recovery in Europe (2002–2003)* (Association of Plastic Manufacturers in Europe, Brussels).

Reynolds P (2010) Solid gains in bottle-to-bottle recycling. *Packaging World Magazine* (April 1), http://www.packworld.com/article-29495.

Schorsch LL (1996) Why minimills give the US huge advantages in steel. *McKinsey Quart.* (2):44–55.

Shaw Industries (2011) The case for product stewardship—A Shaw perspective. Retrieved December 18, 2012, http://www.epa.gov/smm/web-academy/2011/pdfs/deLozier_smm_311.pdf.

Skinner W (1969) Manufacturing—Missing link in corporate strategy. *Harvard Bus. Rev.* 47(3):136–145.

Steel Recycling Institute (2009) 2008 The inherent recycled content of today's steel. Retrieved October 12, 2011, http://www.recycle-steel.org/en/~/media/Files/SRI/Media%20Center/Inherent2008.ashx.

Surrocca J, Tribó JS, Waddock S (2010) Corporate social responsibility and financial performance: The role of intangible resources. *Strategic Management J.* 31(5):463–490.

The Aluminum Association (2009) Facts at a glance—2008. Retrieved June 1, 2010, http://www.aluminum.org/Content/NavigationMenu/NewsStatistics/StatisticsReports/FactsAtAGlance/factsataglance.pdf.

Tire Business (2005) Pirelli adds MIRS module. *Tire Business* 23(8):12.

Upton DM (1997) Process range in manufacturing: An empirical study of flexibility. *Management Sci.* 43(8):1079–1092.

U.S. Environmental Protection Agency (2009) Municipal solid waste generation, recycling, and disposal in the United States: Facts and figures for 2008. Retrieved June 1, 2010, http://www.epa.gov/epawaste/nonhaz/municipal/pubs/msw2008rpt.pdf.

Waste and Resources Action Programme (2006) *Environmental Benefits of Recycling, an International Review of Life Cycle Comparisons for Key Materials in the UK Recycling Sector* (Waste and Resources Action Programme, Banbury, Oxfordshire, UK).

Wohlers Associates (2006) *Wohlers Report 2006: Rapid Prototyping and Manufacturing State of the Industry—Annual Worldwide Progress Report* (Wohlers Associates, Fort Collins, CO).

Wojanowski R, Verter V, Boyaci T (2007) Retail-collection network design under deposit-refund. *Comput. Oper. Res.* 34(2):324–345.