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Lieven DEMEESTER
Mei QI
Luk N. VAN WASSENHOVE
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By

Lieven Demeester*

Mei Qi**

And

Luk N. Van Wassenhove***

* Assistant Professor of Operations Management at INSEAD, 1 Ayer Rajah Avenue, 138676 Singapore, lieven.demeester@insead.edu

** Adjunct Associate Professor at NUS Business School, National University of Singapore, 1 Business Link, Singapore 117592, bizqm@nus.edu.sg

*** The Henry Ford Chaired Professor of Manufacturing, Professor of Operations Management at INSEAD, Boulevard de Constance, 77305 Fontainebleau, France, luk.van-wassenhove@insead.edu

Abstract

We use a modified optimal market area model to show how supply chains are shaped by complementarities between material recycling, low-cost flexible process technologies, and plants taking advantage of local adaptation and customer proximity. Material recycling can generate substantial savings in material and disposal costs, but creates the need for reverse logistics. The latter are less costly when recycling plants serve smaller market areas and are integrated with production plants. Hence, recycling is more beneficial when combined with small-market-area strategies such as low-cost flexible process technologies, and localization. We examine these complementarities in propositions and demonstrate that, in a realistic example for an engineering plastic in Western Europe, an understanding of these complementarities can make the difference between the continuation of a supply chain without recycling and the emergence of a closed-loop supply chain with recycling, localization, and market areas less than one third their original sizes. Our analysis shows that this combination of features, labeled "organic production", qualifies as a supply-chain-level operations strategy, forms a model for emerging closed-loop supply chains, and, can have important implications for product, operations and supply chain strategies.

Key words: recycling; flexibility; localization; mini-mills; operations strategy; production systems; optimal market area

1. Introduction

In the steel industry, improvements in recycling and production technologies have led to the success of geographically distributed "mini-mills", now representing more than 50% of US steel production. In the aluminum industry, recycling of aluminum scrap represents a quickly growing percentage of total production volumes, and aluminum mini-mills have become successful operations. For plastics, mini-mills are emerging as well, recycling post-consumer plastics, and producing materials that can be used in similar applications. These growing closed-loop supply chains appear to be examples of what Demeester et al. (2004) label "organic production systems". Such systems combine recycling, small-scale plants, flexibility, and localization to take advantage of local adaptation and customer proximity. The purpose of this paper is to formally describe and investigate the complementarities between these different supply chain features, and to assess the implications for product, operations, and supply chain strategy.

The unit of analysis for this investigation is the supply chain for a specific production material, such as aluminum, steel or plastic. To model the features of organic production systems in supply chains, we modify an optimal market area model to incorporate recycling as well as the level of localization, the size-independent fixed costs, and the range flexibility of plants.

We find that investments in small-scale, flexible mini-plants complement investments in increased recycling and localization. We also find that investments in production and recycling are linked by the unique transportation cost advantage offered by their integration in one plant.

The practical implications of these ill-understood interactions can be important. Investments that are not economical when taken separately can be attractive when considered together. Using a numerical example modeled after the supply chain of an engineering plastic in Western Europe, we find that the return on joint investments in these features can easily be 50% higher than the sum of the isolated returns.

Contributions of this paper are the formulation of a formal theory behind the emergence, in several industries, of "mini-mill" networks, and an analysis of the factors that can make such networks successful. In addition, our findings clarify how recycling is linked to decentralization of production, product variety, and other non-cost-based-strategies. Because they are anchored in industrial phenomena and tested with a realistic example of a supply chain for plastics, these insights allow managers to sharpen their intuition regarding these important interactions.

This paper is organized as follows. In section 2, we clarify the features of *recycling*, *mini-scaling*, *range flexibility* and *localization* in the context of operations strategy. Section 3 describes a generic closed-loop supply chain and introduces our model. In section 4, we present our analysis and findings, including six complementarity propositions and a discussion of the integrated-plant advantage. In section 5 we present a numerical example of a supply chain for engineering plastics to illustrate the significance of our results. Section 6 discusses implications, limitations, and future research.

2. Organic Production Systems and Operations Strategy

This section introduces the different features of organic production systems and reviews literature that is relevant to the study of their interactions.

2.1 Recycling

Recycling involves the recovery and reprocessing of materials from end-of-life products. Many of its challenges for operations management have been studied extensively in the context of closed-loop supply chains (Guide and Van Wassenhove, 2003), sustainable operations (Kleindorfer et al, 2005) and environmental management (Corbett and Klassen, 2006).

Material recycling is on the rise due to governments' efforts to limit disposal in landfills and technological investments that have improved the economics of recycling. As a result, recycling has become an important component in production systems for steel, aluminum, and paper. In the United States in 1998, based on weight, 67% of steel production, 42% of aluminum production and 25% of paper production was recycled content (US EPA, 1998). The recycling of plastics is still in its early stages, but recycled content is on the rise in many applications (Plastics Europe, 2006). MBA Polymers, a US company, sources waste plastics from electronics recyclers, sorts them by type, and produces plastic pellets with 100% recycled content, used by customers to produce parts for electronic products (Minter 2006). While government incentives provide extra motivation, most increases in the recycling ratio of a material find their origin in the investments of profit-seeking private companies (Chalier and Parker, 1999; Field and Sroufe, 2004). By investing in improved collection, baling, sorting, cleaning, and processing of waste materials, private firms have a direct impact on the supply chain's recycling ratio.

2.2 Mini-scaling

Mini-scaling involves investments that lower the capital costs of production systems, making them economical at a smaller scale. Prime examples of mini-scaling are thin-slab casting in the steel industry (Schorsch, 1996), and continuous casting in the aluminum industry. Both developments eliminate the need for several casting and reheating steps, and therefore reduce space and capital requirements.

Additional examples of mini-scaling are "space-frame technology", Pirelli's Modular Integrated Robotic System (MIRS) for tire manufacturing, and recent "rapid manufacturing" technologies. In space-frame technology, used by Audi, Fiat, and the Mercedes part of DaimlerChrysler, extruded metal parts are riveted or glued together to build the skeleton of a car body. This technology "removes the need for expensive stamping machines for traditional load-bearing panels", and allows for "smaller and less expensive factories" (*Economist* 2002). With MIRS, which is protected by more than 40 patents, Pirelli has reduced the number of steps for manufacturing tires from fourteen to three, 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 (*Economist* 2000, Meyer 2006, *Tire Business* 2005). Finally, rapid manufacturing, also called additive fabrication, refers to a set of technologies that build parts layer by layer directly from a 3-D model, thus eliminating the need for costly molds or dies. While currently restricted to uniquely customized or low-volume parts, its use has been growing rapidly (Wohlers Associates 2006).

2.3 Range Flexibility

Range flexibility allows production systems to produce a wider range of products, and extends the potential markets for these systems. It is clear that innovation and investment can improve the range flexibility of a production technology. Upton (1997:1089), for example, finds that, ceteris paribus, newer paper plants have larger range flexibility and he attributes this to improved mechanical systems and advanced understanding of paper-making technology. In process industries in general, companies often seek to expand their markets by investing in process technologies that increase the range of properties or geometries possible for a given production material. For example, one of the advantages of Pirelli's MIRS manufacturing system for tires is that it can easily produce a wide range of tire sizes (*Economist* 2000). The most extreme form of flexibility in geometry comes from "rapid manufacturing" technologies (Wohlers Associates 2006). Building parts layer by layer allows for geometries that are infeasible with traditional manufacturing techniques, and opens up new applications.

2.4 Localization

Localization refers to the different mechanisms supply chains use to leverage small market areas. The first mechanism involves adapting plants to their market areas, by configuring them to suit local demand or supply factors. There are some indications that mini-mills in several industries have adopted such a localization strategy. Mittal steel executives explained to us that they allow for differences in mini-mill design, depending on local supply factors. In regions with highly-skilled labor, the plant design will contain more automated systems, whereas in other regions, simpler, manual systems are installed. MBA Polymers as well use local configurations for their "plastic mini-mills". Based on modular process design, plants are optimized for locally available waste streams (Minter 2006).

The second mechanism employs customization capabilities to leverage the customer proximity in small market areas. For example, Nucor is well-known for co-locating steel mini-mills with customers, and for taking advantage of that proximity in developing new solutions to customer problems (Giarratani et al. 2005: p14). Proximity also yields simple lead time advantages. It is probably such lead time advantage that is leveraged by "fast fashion" providers like Zara and Bebe. Both companies choose to manufacture close to the markets they serve, despite higher labor costs (Birchall 2005).

Note that small market areas for plants do not automatically lead to localization advantage. Companies such as Mittal Steel, MBA polymers, Nucor, Zara, and Bebe have developed distinctive "localization capabilities", at considerable development costs, to leverage the smaller market areas of their plants.

2.5 Organic Production Systems as an Operations Strategy

While the importance of each of the above features is well-known, the effect of their interactions, and their potential to combine into an overall operations strategy, has not yet been studied in detail. We review a few studies that provide directions for this research.

The main tenet of operations strategy (Hayes et al. 2005, Hayes and Wheelwright 1979, Skinner 1969) is that investments in production systems should be internally coherent as well as aligned with the overall strategy of the organization. Despite the wide use of this concept, analytical investigations of operations strategies are still quite rare. Exceptions include de Groote (1994), who studied the interaction between manufacturing flexibility and product variety, and Milgrom and Roberts (1990), who show the mutually positive interactions between reductions in setup times, defects, production and development lead times, and other features of what they label "modern manufacturing". These analytical investigations show the complementarities between different parameters in a mathematical expression for firm profits. Two features are called complementary when an increase in one causes an increase in the effect on profit of another. We will adopt a similar approach to study the interaction among features of organic production systems.

Using different methods, a couple of previous studies have examined the link between material recycling and other aspects of operations strategy. Fleischmann et al. (2001) used a mixed-integer-linear-programming model to study the impact of product recovery on logistics network design. In their numerical experiments, they find that if forward and reverse logistics are jointly optimized (instead of sequentially), the optimal forward plant network is more decentralized. This effect, they point out, was observed in the European paper industry as recycling became more prominent. Another study, by Field and Sroufe (2004), contains a case analysis of the US paperboard industry, and offers hypotheses on the impact of recycling on supply chain management and operations strategy. The authors argue that the use of recycled materials will most likely be 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, the authors further hypothesize that "the use of recycled materials (through the addition of mini-mills) by independent firms will increase the use of non-cost-based operations strategies in the industry". In section 5 we discuss how our own findings expand the insights provided by these studies.

Finally, with respect to strategies of steel and other mini-mill operators, the literature to date has been mostly descriptive (e.g., Barnett and Crandall 1986, Giarratani et al. 2005). We are not aware of studies that have analytically modeled the underlying operations strategies of mini-mills.

3. Model

The unit of analysis in our model is the supply chain for a basic manufacturing material such as steel, aluminum or a type of plastic. To introduce the model, we first present a generic closed-loop supply chain, based on observations of several industrial supply chains.

3.1 A Generic Closed-Loop Supply Chain

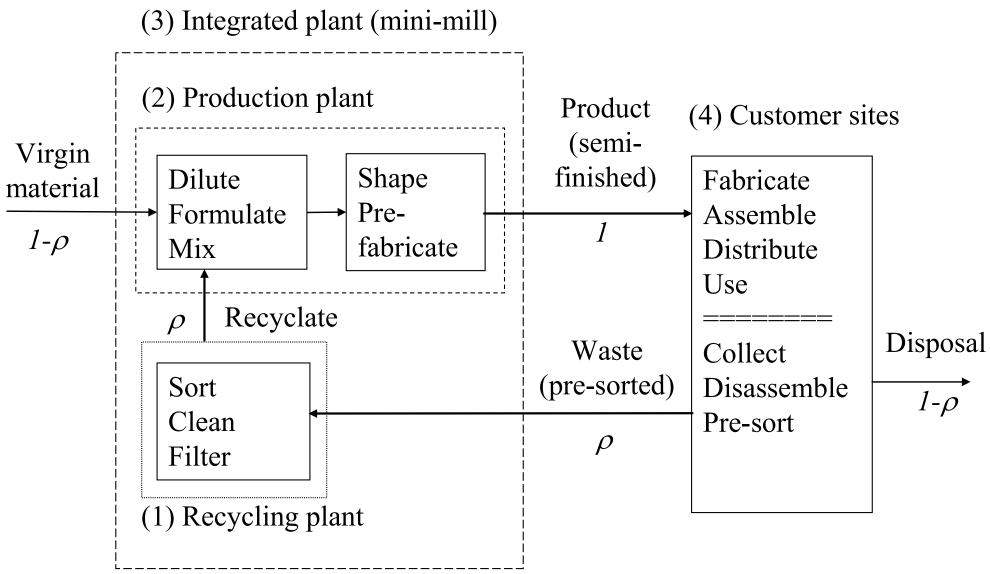

Figure 1: A generic closed-loop supply chain

Figure 1 presents a diagram of a generic closed-loop supply chain for a manufacturing material. After a product or part completes its useful life, it is either disposed of or collected, disassembled and pre-sorted in local recovery facilities (any form of repair, refurbishing or remanufacturing is assumed to be part of the useful life of the product or part). At that point, recovered materials are transported to recycling plants. There, the waste materials may undergo further size reduction and are fine-sorted, cleaned and filtered to remove contaminants. The output of a recycling plant, recyclate, is used as input for a production plant, where it may be mixed with virgin materials and other additives before it is shaped, formed or pre-fabricated into a semi-finished product. The semi-finished product is shipped to customer sites within the plant's market area for remaining fabrication and assembly into a final product. The logical separation between what we label production plants, and the final fabrication and assembly steps, is driven by the economies of scale at the production plant. We define the production plant in this material supply chain as the largest-scale operation that uses virgin material and recyclate as input to produce an output that is shipped to smaller-scale operations inside the production plant's market area.

Sometimes recycling plants and production plants are co-located to form an integrated plant. A steel mini-mill, which uses scrap steel as input, is an example of that. The scrap steel is melted and undergoes several process steps to remove contaminants before the right steel grade can be formulated. Pure iron is often added to the scrap mix in order 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. In the aluminum industry, recycling and production plants have started to integrate as well (a successful example is Aleris International's mini-mill in Uhrichsville, Ohio), but are often still separated. For plastics, recycling and production plants are mostly separated. Some integrated plants are emerging though, typically because recycling plants forward-integrate into production.

3.2 A Modified Optimal Market Model

To investigate the complementarities between *recycling*, *mini-scaling*, *range flexibility* and *localization* in closed-loop supply chains, we propose a modification of the optimal market area model (e.g. 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 jointly optimized two-stage market area model for closed-loop supply chains. 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 semi-finished product is distributed uniformly over an infinite plane, with density $d > 0$, per unit area per year. We will use d as a proxy for the *range flexibility* of the production and recycling technologies.

b) The annual cost for a plant processing an amount w per year, is $k_i + c_i w$, where k_i, $c_i \geq 0$ with the index i equalling p for production and r for recycling plants. This characterization of scale economies simplifies analysis and, according to industry experts, closely matches the economics of producing and recycling engineering plastics. In section 5 we also test one alternative characterization.

Table 1: Symbols used in model and parameters for base-case (section 5)

	Symbol	Base	Unit	Description
Features of Organic Production Systems	d	0.12	unit year^{-1} km^{-2}	demand density – units of demand per km^2; measure for *range flexibility*
	k_p	1.2M	€ year^{-1}	annualized size-independent fixed costs for a production plant; reducible by *mini-scaling*
	k_r	1.2M	€ year^{-1}	annualized size-independent fixed costs for a recycling plant; reducible by *mini-scaling*
	ρ_{max}	0.1	ratio	*recycling ratio*; maximum percentage of material that can be recycled; $0 \le \rho_{max} \le 1$
	g	0	€ unit^{-1}	maximum *localization* advantage (when R_p approaches 0)
Decision Variables	ρ	0	ratio	chosen recycling rate; $0 \le \rho \le \rho_{max}$
	R_p	437	km	production radius - radius of the market area of a production plant
	q	-	ratio	ratio of recycling radius to production radius $q \in \{..., 1/6, 1/4, 1/2, 1, 2, 4, 6, ...\}$
	$R_r = qR_p$	-	km	recycling radius – radius of the market area of a recycling plant
Parameters and Functions	c_p	-	€ unit^{-1}	variable production cost
	c_r	-	€ unit^{-1}	variable recycling cost
	c_m	-	€ unit^{-1}	virgin material cost
	P	-	€ unit^{-1}	unit price prior to *localization* advantage
	$G = P - c_m - c_p$	40	€ unit^{-1}	gross margin prior to recycling, *localization*, and transportation
	$\Delta_r = c_m - c_r$	100	€ unit^{-1}	savings per recycled unit
	$g(1-R_p/b)$	0	€ unit^{-1}	*localization* advantage per unit of demand
	b	500	km	market area radius at which the *localization* advantage becomes zero
	t_p	0.06	€ unit^{-1}km^{-1}	unit transport cost per km for semi-finished product
	t_r	0.03	€ unit^{-1}km^{-1}	unit transport cost per km for recyclate
	t_w	0.10	€ unit^{-1}km^{-1}	unit transport cost per km for pre-sorted waste
	$\pi^*(\rho, q)$		€ unit^{-1}	unit profit for a given ρ and q, optimized for R_p
	π^{**}	0.69	€ unit^{-1}	unit profit, optimized for R_p, ρ and q
	κ	-	€ unit^{-1}	investment cost per unit of annual demand to reach feature values: d, k_p, k_r, ρ, g
	$\Pi = \pi^{**} - \kappa$	-	€ unit^{-1}	net unit profit – unit profit minus investment cost per unit of annual demand

c) The chosen recycling rate is denoted by ρ, with $0 \le \rho \le \rho_{max} \le 1$. The *recycling ratio*, ρ_{max}, reflects the limitation of current recycling methods and infrastructure. The resulting material flow is assumed to be in steady-state, proportioned as indicated on the flow arrows in figure 1. The steady-state assumption allows including disposal costs (if any) in the cost of virgin material, denoted by c_m. Note that what we label as "customer sites" in figure 1 typically constitutes a substantial section of a closed-loop supply chain, stretching from the customer of a semi-finished product, typically a parts producer, to the supplier of pre-sorted waste, typically a disassembly and/or shredder operator.

d) The market areas served by plants are square-shaped, with a production radius R_p for production plants, and a recycling radius R_r for recycling plants, where "radius" refers to half the length of the square's side. Plants are located at the center of their market area. Without loss of generality, we restrict our analysis to a subset of solutions in which $R_r=qR_p$ with $q \in \{..., 1/6, 1/4, 1/2, 1, 2, 4, 6, ...\}$, and market areas arranged as in figure 2*.

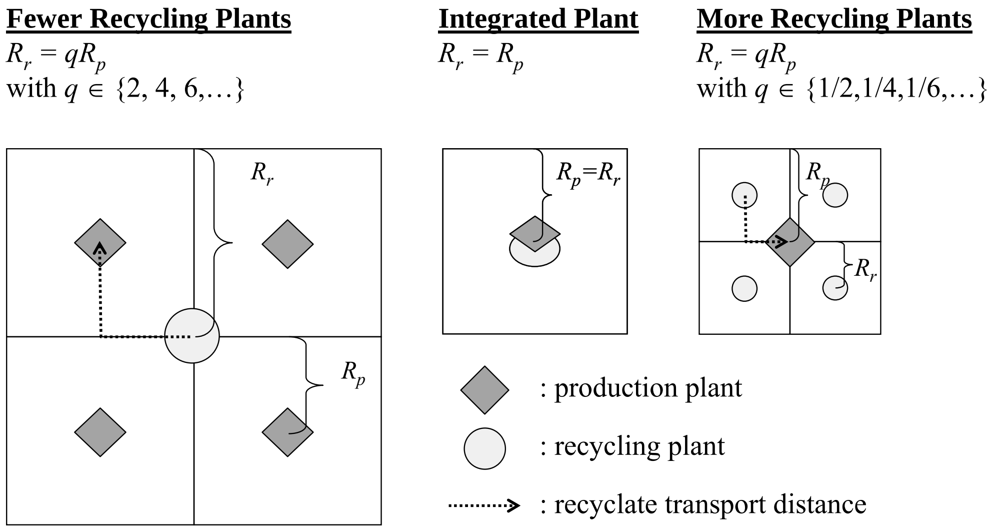

Figure 2: Geographical arrangement of production and recycling plants as a function of q

e) Transportation distances are measured with the Manhattan metric. 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, R_r, and between a recycling and a production plant, $r(q)R_p$, with $r(q) = \begin{cases} 1, \text{ if } q < 1 \\ 0, \text{ if } q = 1 \\ q, \text{ if } q > 1 \end{cases}$.

f) Unit transport costs are proportional to the distance traveled. Figure 1 shows the transport for product, waste and recyclate, with unit transport costs denoted as t_p, t_w and t_r, respectively.

g) *Localization* of production plants generates an extra gross margin, or localization advantage, of

* For $q \neq 1$, transportation costs could be reduced by locating small-area plants closer to large-area plants. In section EC.1 of the electronic companion document we show that this effect is small, so we exclude it from further analysis.

$g(1-\frac{R_p}{b})$ per unit of demand. The localization advantage increases as market areas become smaller. The maximum localization advantage g depends on local differences in demand and supply factors, and on the company's investment in localization. The constant b (with $b \geq R_p$), represents the market area radius at which the localization advantage becomes zero, and depends on the spatial rate of change in demand and supply characteristics.

The unit profit can now be expressed as follows:

$$\pi = P + g(1-\frac{R_p}{b}) - \{c_p + (1-\rho)c_m + \rho c_r\} - \frac{k_p}{4R_p{}^2 d} - \frac{\lceil \rho \rceil k_r}{4q^2 R_p{}^2 d} - t_p R_p - \rho t_w q R_p - \rho t_r r(q) R_p$$

The first term in this expression, P, is the unit price charged for the product if there is no 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. Using $G = P - (c_p + c_m)$ 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 savings per recycled unit, and rearranging the terms as a function of R_p, we can simplify the expression for the unit profit as follows:

$$\pi = G + g + \rho\Delta_r - \frac{k_p + \lceil \rho \rceil k_r / q^2}{4d} R_p{}^{-2} - \{t_p + \frac{g}{b} + \rho(q t_w + r(q) t_r)\} R_p$$

This formula reveals the modifications we have introduced to the optimal market area model. The effect of *localization* appears as a margin advantage g combined with an additional cost g/b per unit of distance from the production plant to customer sites. To add recycling ($\rho > 0$), an annual fixed cost of k_r/q^2 is added to each production plant, with $1/q^2$ corresponding to the number of recycling plants for each production plant. The extent of recycling is captured by the parameter $\rho \leq \rho_{max}$. Reduction in raw material and disposal costs leads to recycling savings of $\rho\Delta_r$ per unit of demand, but also adds an amount

$\rho(qt_w+r(q)t_r)$ to the cost per unit of distance between production plants and customer sites, reflecting the additional transportation costs for pre-sorted waste and recyclate. We now show how profits can be optimized with respect to the chosen recycling rate ρ, the production radius R_p, and the ratio q.

For any R_p and q, π is convex in ρ (linear in ρ except for a negative step at $\rho = 0^+$, to pay for the recycling facilities), so the optimal recycling rate will either equal zero, indicating no recycling, or ρ_{max}, the *recycling ratio*.

The optimal unit profit $\pi^*(\rho, q)$, and the optimal production radius $R_p^*(\rho, q)$, take on their typical form (e.g., Erlenkotter, 1989):

$$\pi^*(\rho,q) = G + g + \Delta_r\rho - 3(\tfrac{1}{2})^{\frac{4}{3}}(\frac{k_p + \lceil\rho\rceil k_r/q^2}{d})^{\frac{1}{3}}(t_p + \frac{g}{b} + \rho(qt_w + r(q)t_r))^{\frac{2}{3}} \tag{1}$$

$$R_p^*(\rho,q) = (\tfrac{1}{2})^{1/3}(\frac{k_p + \lceil\rho\rceil k_r/q^2}{d(t_p + \frac{g}{b} + \rho(qt_w + r(q)t_r))})^{1/3} \tag{2}$$

In the no-recycling case, when $\rho = 0$, q is irrelevant. For the recycling case, when $\rho = \rho_{max}$, it is easily seen that 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, as is clear from the fourth term in $\pi^*(\rho_{max}, q)$. It is the negative of the cubic root of a function of the form $a+bq+cq^2+dq^{-1}+eq^{-2}$, in which a, b, c, d and e are all positive scalars. Such a function, and thus its cubic root, has only one local minimum for $q > 0$. So we can write:

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

with corresponding optimal values ρ^{**}, R_p^{**}, and q^{**}. We define

$$q^{**} = \operatorname*{arg\,max}_{q\in\{\ldots,\frac{1}{6},\frac{1}{4},\frac{1}{2},1,2,4,6,\ldots\}} \pi^*(\rho_{max},q) \tag{4}$$

even if ρ^{**} is 0 and the value of q irrelevant for the optimal solution.

4. Analysis and Findings

4.1 Complementarities

To investigate the pairwise complementarities of the features of organic production systems, we consider a net unit profit function of the following form:

$$\Pi(d,k_p,k_r,g,\rho_{max}) = \pi^{**}(d,k_p,k_r,g,\rho_{max}) - \kappa(d,k_p,k_r,g,\rho_{max}) \quad (5)$$

with $\kappa(d,k_p,k_r,g,\rho_{max})$ representing the annualized cost, per unit of demand, of the investments needed to reach the indicated levels of the parameter values. In the remainder of this subsection we describe four pairwise complementarities in the form of propositions.

***Production mini-scaling* (reduction in k_p) and *localization* (g)** – We assume that investments to improve *localization* do not increase when *production* technology is *mini-scaled* (i.e. if $k_{p2} < k_{p1}$ and $g_2 > g_1$, then $\kappa(k_{p2},g_2) - \kappa(k_{p2},g_1) \leq \kappa(k_{p1},g_2) - \kappa(k_{p1},g_1)$). Given that *mini-scaling* is typically the result of a reduction of the number of production steps (as in Pirelli's MIRS process, described in section 2.2), the *localization* of such a process should indeed not become more difficult as a result. Also, the *localization* of plants and their *mini-scaling* both benefit from better process knowledge, so this assumption seems very reasonable. It leads to the following proposition.

PROPOSITION 1: *Production mini-scaling and localization are complementary with respect to net unit profit. Or, mathematically, if* $k_{p2} < k_{p1}$ *and* $g_2 > g_1$, *then* $\Pi(k_{p2},g_2) - \Pi(k_{p2},g_1) \geq \Pi(k_{p1},g_2) - \Pi(k_{p1},g_1)$. (proof in appendix)

We illustrate this complementarity in figure 3, which charts the optimal unit profit (π^{**}) as a function of g for different values of k_p. The chart in this figure, like the charts in figures 4-7 as well, is anchored around the parameter values of the engineering plastic supply chain we describe in section 5 and thus displays realistic effects. It shows that *production mini-scaling* (reduction in k_p) improves the benefits derived from *localization* (increase in g). This complementarity can help explain Pirelli's production of extra large (30-inch) tires in its MIRS plant in Georgia, USA (Pirelli USA 2006). The MIRS technology has a low capital cost, hence more plants can be built with smaller market areas. For those small-market-area plants it makes sense to invest in localization, leading Pirelli to produce this specialized tire for a customer type that is found almost exclusively in the US market.

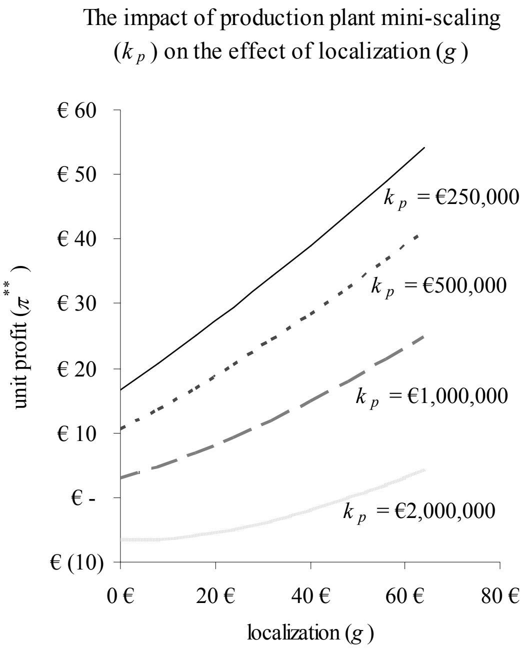

Figure 3

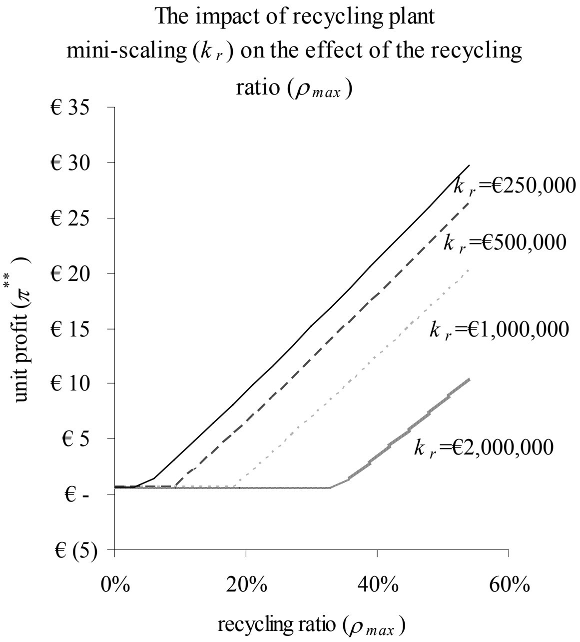

Figure 4

Recycling mini-scaling **(reduction in k_r) and** ***recycling ratio*** **(ρ_{max})** – For this interaction, we assume that investments to improve the *recycling ratio* are not more costly when *recycling* technology has been *mini-scaled* (i.e., if $k_{r2} < k_{r1}$ and $\rho_{max2} > \rho_{max1},$ then $\kappa(k_{r2},\rho_{max2}) - \kappa(k_{r2},\rho_{max1}) \leq \kappa(k_{r1},\rho_{max2}) - \kappa(k_{r1},\rho_{max1})$). This is a reasonable assumption, since *mini-scaling* is typically the result of a reduction of the number of recycling steps, each one of which may need to be adjusted when the *recycling ratio* is increased. It leads to the following proposition.

PROPOSITION 2: *Recycling mini-scaling and recycling ratio increases are complementary with respect to net unit profit. Or, mathematically, if* $k_{r2} < k_{r1}$ *and* $\rho_{max2} > \rho_{max1},$ *then* $\Pi(k_{r2},\rho_{max2}) - \Pi(k_{r2},\rho_{max1}) \geq \Pi(k_{r1},\rho_{max2}) - \Pi(k_{r1},\rho_{max1})$. (Proof in appendix)

Figure 4 provides an illustration. As the *recycling* technology is *mini-scaled,* the value of the *recycling ratio* at which recycling becomes economical is reduced and the benefit of an increased *recycling ratio* rises. This effect can explain the current lack of success of feedstock recycling, a capital-intensive process in which waste 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 to 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 due to a lack of government guarantees for the supply of plastic waste (low *recycling ratio*). Appropriate sharing of costs aside, it is perhaps no surprise that, given the substantial reverse logistics costs associated with the large market areas of these expensive recycling plants (k_r high), no investments were made to increase the *recycling ratio*. Feedstock recycling technology appears to be positioned on the non-increasing part of one of the lower curves in figure 4.

***Range flexibility* (*d*) and *localization* (*g*) -** We assume that improved *range flexibility* (*d*) does not increase the unit investment costs (κ) for increases in *localization* (g). While the overall investment costs can be expected to rise when a wider range of products are being produced, it is reasonable to assume that they will not rise more than proportionally. This leads to proposition 3.

PROPOSITION 3: *Range flexibility and localization are complementary with respect to net unit profit if the increase in range flexibility is large enough. Or, mathematically, if* $d_2 > d_1$,

$$\frac{d_2}{d_1} > \left(\frac{k_p + k_r / q^{**}(g_1)^2}{k_p}\right)\left(\frac{t_p + \frac{g_2}{b}}{t_p + \frac{g_2}{b} + \rho_{max}(q^{**}(g_1)t_w + r(q^{**}(g_1))t_r)}\right), \text{ and } g_2 > g_1, \text{ then}$$

$\Pi(d_2,g_2) - \Pi(d_2,g_1) \geq \Pi(d_1,g_2) - \Pi(d_1,g_1)$. (Proof in appendix)

The underlying dynamic for this complementarity is clear. Increased *range flexibility* of production and recycling technology allows supply chains to achieve economies of scale in market areas with smaller radiuses. As a result such supply chains can take better advantage of *localization*.

The condition in the proposition ensures that the production market radius R_p^{**} decreases when the range flexibility d increases from d_1 to d_2. The condition is required because, when an increase in range flexibility d causes ρ^{**} to switch from 0 to ρ_{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 $q \in \{..., 1/6, 1/4, 1/2, 1, 2, 4, 6, ...\}$. A second type of interaction takes place because of the discontinuity in $r(q)$ at $q=1$. This effect is more interesting, and we discuss it in detail in section 4.2. The result is that, if an increase in the range flexibility d warrants the start of recycling, an integrated plant ($q=1$), with a radius larger than the existing production radius, may be optimal as it reduces the number of recycling plants to be built, while also avoiding the transport of recyclate ($r(1)=0$). The effects due to these interactions are both countered when the increase in range flexibility is large enough, as specified in the condition. In the numerical example of section 5, if we use g_1 = €0 and g_2= €50, the condition in proposition 3 specifies that $d_2/d_1 > 1.064$.

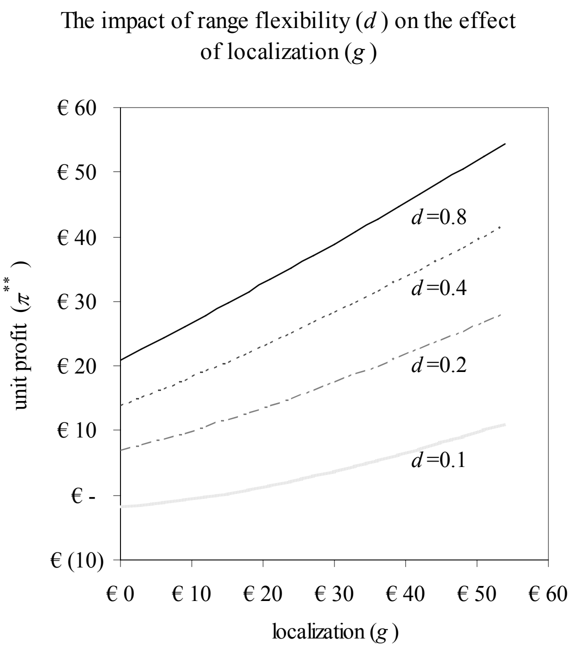

Figure 5

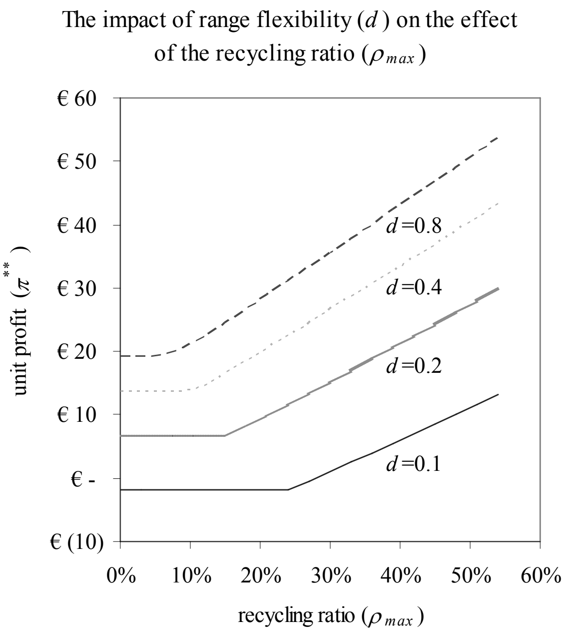

Figure 6

Proposition 3 is illustrated in figure 5, which shows how higher values of *range flexibility* (d) lead to an increase in benefits derived from *localization* (g). This effect can provide some explanation for the development of process modularity at MBA Polymers, an operator of plastic mini-mills. As this company succeeded in gaining a wider acceptance for their recyclate-based plastics (an increase in range flexibility d), they started to build a worldwide network of regional plants (a decrease in R_p). This led them to pay more attention to differences in local supply and demand conditions, so they developed a highly modular process (Minter 2006) that can more effectively be localized and adapted (increase in *g*).

***Range flexibility* (*d*) and *recycling ratio* (ρ_{max})** – For this interaction as well we assume that increases in *range flexibility* (*d*) do not raise the investment cost for increasing the *recycling ratio* (ρ_{max}) more than proportionally. This leads to the next proposition.

PROPOSITION 4: *Range flexibility and recycling ratio increases are complementary with respect to net unit profit. Or, mathematically, if* $d_2 > d_1$ *and* $\rho_{max2} > \rho_{max1}$, *then* $\Pi(d_2,\rho_2) - \Pi(d_2,\rho_{max1}) \geq \Pi(d_1,\rho_{max2}) - \Pi(d_1,\rho_{max1})$. (Proof in appendix)

This proposition is illustrated in figure 6. As *range flexibility* increases, the *recycling ratio* at which recycling becomes economical decreases, and the benefits of an increased *recycling ratio* are higher because the smaller-size market areas associated with higher *range flexibility* involve lower reverse logistics costs. It seems quite conceivable that this complementarity has contributed to the success of the mini-mill model in the steel and aluminum industry. In its September 2005 reports to investors, Aleris International, a large US aluminum recycler, mentions how its “expanded plant network provides favorable freight dynamics” (i.e., smaller market areas), and how its strategy includes “extending [its mini-mill model] to higher-margin products” (i.e., increasing *range flexibility*), as well as “acquiring [a] wider basket of scrap types” (i.e., increasing the *recycling ratio*) (Aleris International 2005).

4.2 Integrated-Plant Bonus

The interactions, with respect to net unit profit, of the remaining six pairs of features are more mixed[*]. They do include, however, an important link between production and recycling, which we describe here.

When the production and recycling market areas are equal in size ($q=1$), and the plants co-located, a special benefit arises because the transportation between those plants is eliminated. Eliminating recyclate transport provides a bonus to investments that lead to an integrated-plant solution, and a penalty for investments that force a separation of plants. This is illustrated in figure 7, which also uses the engineering

[*] A discussion of these mixed interactions is available in section EC.2 of the electronic companion document.

plastics base case as an anchoring point (to assure that recycling is economical for the chosen range for k_r, ρ_{max} is set to 40%, and Δ_r to €200).

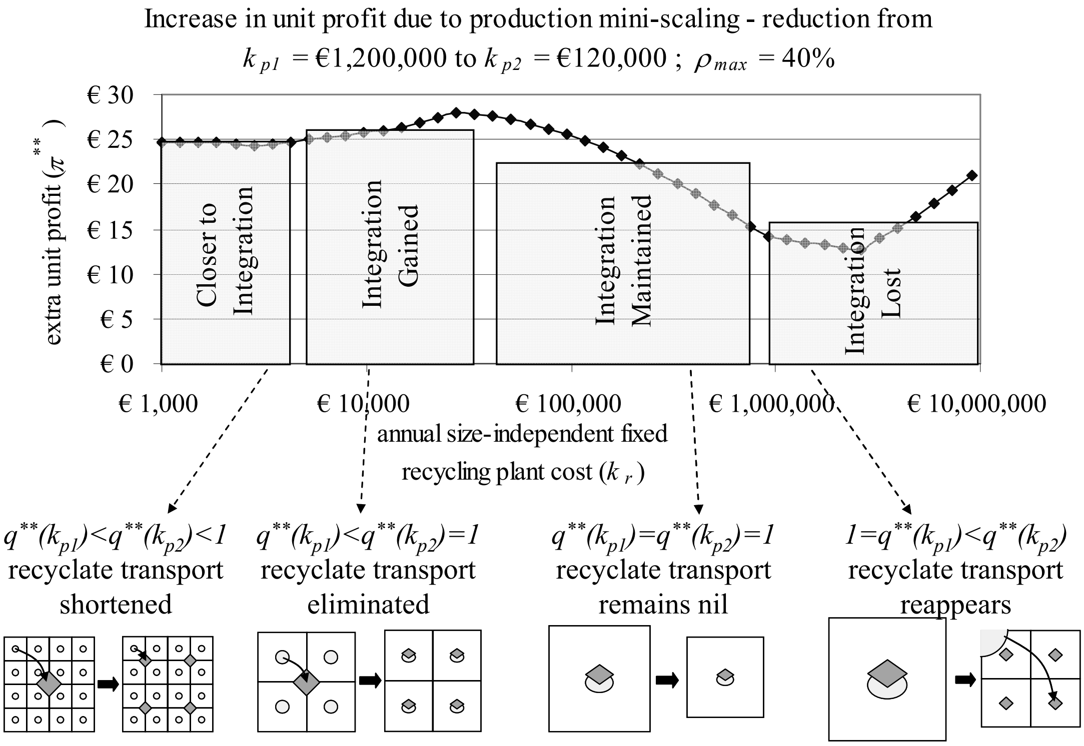

Figure 7: Integrated-Plant Bonus

The figure examines the extra profit per unit that can be gained from the same *production mini-scaling* effort (a reduction of k_p from €1,200,000 to €120,000), when faced with different recycling technologies, for which the annual size-independent fixed costs range from €1,000 to €10,000,000. Part of the effect of *production mini-scaling* involves either shortening, eliminating, maintaining at nil, or re-establishing the transport of recyclate depending on the cost, and therefore the preferred market area radius, of the recycling technology. The four bars on the chart show the average unit profit increase for those four different scenarios, which are labeled "closer to integration", "integration gained", "integration maintained" and "integration lost", respectively. The chart shows that the largest benefit accrues when *production mini-scaling* eliminates recyclate transport by moving the supply chain towards an integrated-plant solution ("integration gained"), and that the least benefit accrues when it forces the separation of production and recycling plants ("integration lost").

The effect of the *integrated-plant bonus* also applies to investments that increase *localization*. An increase in *localization* can generate an additional *integrated-plant bonus* when the resulting pressure to reduce the production radius justifies the integration 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 in order to reduce the production radius.

Integrated production and recycling plants have additional advantages that are not captured by our model. In the aluminum supply chain, for example, the co-location and integration of recycling and production plants can eliminate several capital-intensive cooling and re-heating steps (this was confirmed to us by an executive at Novelis, a large aluminum recycler and producer).

In summary, the *integrated-plant bonus* provides an incentive for supply chain managers to coordinate their investments, such that the integrated-plant solution remains the preferable one ($q^{**}=1$). We consider this effect when we synthesize our findings by using the concept of *flexible mini-plants* next.

4.3 Flexible mini-plants

To synthesize our findings we introduce the concept of *flexible mini-plants*, by considering joint investments in *range flexibility* (d) and *mini-scaling* (k_p and k_r). Since both features are directly related to a manufacturing technology, it is quite common for innovations to combine improvements in both. We have discussed several examples of such investments: 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 investments leverage a form of process or product modularity to obtain a wide variety of outputs with relatively low-cost, small-scale equipment. In addition, we assume that the development of such *flexible mini-plants* also includes the *mini-scaling* of recycling technology. Such coordination could naturally take place if the same process knowledge underlies *production* and *recycling mini-scaling*. It could also take place intentionally. The *integrated-plant bonus*, discussed in the previous section, can provide a strong incentive to develop production and recycling technology jointly. We formalize these assumptions by postulating, from here onwards, that $k_r=\theta k_p$, and investments in *flexible mini-plants* have the effect of reducing the factor d/k_p. Using $k_r = \theta k_p$ in (1), we see that d/k_p behaves as d in propositions 3 and 4, leading to equivalent propositions 5 and 6 below.

PROPOSITION 5: *Flexible mini-plants (d/k_p, with $k_r=\theta k_p$) and localization are complementary with respect to net unit profit (if the flexible mini-plant investments have a large enough effect).* (Condition and proof similar to proposition 3)

PROPOSITION 6: *Flexible mini-plants (d/k_p, with $k_r=\theta k_p$) and recycling ratio increases are complementary with respect to net unit profit.* (Proof similar to proposition 4)

Propositions 5 and 6 provide a simple synthesis of the complementarities among features of organic production systems, also shown in figure 8.

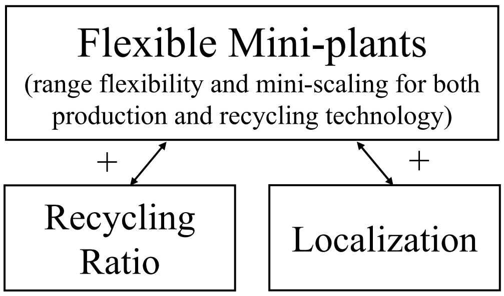

Figure 8: Operations Strategy of Organic Production Systems – Synthesis

5. The Supply Chain for an Engineering Plastic in Western Europe

We use a numerical example, modeled after a recyclable engineering plastic in Western Europe (15 countries, 3.2M km^2), to demonstrate the practical relevance of the complementarities we study. Table 1 above contains the base-case parameters discussed below.

Market size and range flexibility - In 2003, 33.25 Million tons of thermoplastics were consumed in Western Europe, of which 2% were polyamides (Plastics Europe 2004). We consider a plastic with a demand density d of 0.12 ton per square kilometer per year and a total demand of 384,000 tons, or a market share of, approximately, 1.15%. This makes the market size and range flexibility of the product in our example comparable to that of nylon resins, which form the bulk of the polyamide group.

Production and recycling plants - The values for k_p and k_r are estimates for the annualized fixed costs that are independent of facility size. For example, MBA Polymers built a 20,000 ton per year combined recycling and production plant in Austria, at a cost of €17 million. Assuming 60% of this capital cost is independent of the size of that facility, the annual interest, depreciation, and maintenance costs are 20% of that capital cost, and an additional €360,000 per year is needed to administer the facility, a value of €2.4M for $k_p + k_r$ would follow, consistent with the chosen values of €1.2M each. Given that extruders, which are part of the "production" component of plastic mini-mills, are the more capital intensive part of an integrated plant, the value we use for k_r certainly does not underestimate the cost of recycling (we also test for values of k_r that are lower by 50% later on).

Recycling ratio and localization - A base-value for the *recycling ratio*, $\rho_{\max}$, of 10% reflects existing limitations in collection infrastructure and recycling technology. The base value of €0 for g reflects a supply chain with very limited *localization*. The base value for b assumes that any localization advantage will disappear when the production market radius is larger than 500 km.

Other parameters - The values of €0.06, €0.10 and €0.03 for t_p, t_w, and t_r respectively, lie within the range of officially available per-ton-per-km transport costs in Western Europe (Herry 2002: tabelle 42) and also reflect the differences in transport efficiencies. The transportation of waste is typically least efficient, since waste is difficult to pack efficiently, and not always perfectly sorted. The transport of recyclate is most efficient because it is like a bulk product, and that of the semi-finished product can be expected to lie somewhere in-between. With the price of oil (~ €170 per ton if oil costs \$30 per barrel) as a lower bound for c_m (oil is the basic raw material for virgin plastic), the €100 value for Δ_r (= c_m - c_r) is low enough to account for a significant variable recycling cost, c_r. The value of €40 for G, finally, results in a profit for the base case that is close to zero.

Base case solution - Using (1) and (2), we find that without recycling ($\rho = 0$), the profit per ton, π^*, is €0.69, and the optimal production market radius, R_p^*, is 437 km, resulting in approximately four production plants in Western Europe, each producing about 90,000 tons of plastic per year. This plant capacity is consistent with the capacities of existing nylon resin compounding plants in Europe (according to an industry expert, the capacities in 2006 ranged from 5,000 to 120,000 tons per year and a plant size of 90,000 tons is about optimal). We also find that with recycling ($\rho = \rho_{\max}$=10%), the highest profit is achieved when the market radius for the recycling plant is 828 km, twice the size of the optimal production radius of 414 km. So q^{**} equals *2,* and there is one recycling plant for every four production plants (as on the left side of figure 2). However, recycling results in a loss of €(4.66), because the €10 of recycling savings per ton of demand is not sufficient to pay for the extra fixed costs of the recycling facility and the additional transportation costs to and from that facility. So, under our base-case assumptions, recycling is not economical, consistent with negligible levels of nylon recycling up to date.

5.1 Separate Investments

We assume this supply chain is faced with three separate investment options, as listed in table 2. For each option, table 2 shows the induced parameter changes, the unit investment cost (κ), the structure of the resulting supply chain and the increase in unit profit (π^{**}).

The first option involves investing in *flexible mini-plants* and would result in a two-fold increase in *range flexibility* (d) and the *mini-scaling* of the production and recycling technology by fifty percent (50% reduction of k_p and k_r). The postulated investment cost of €30 per ton would represent a total investment cost of €230.4M, if we consider the Western European market and assume a 10% cost of capital (€30 per ton x 3,200,000 km^2 x 0.24 ton per km^2/10%). This is a large investment to accomplish what is assumed to be a challenging technical task (correspondence with an industry expert indicated that a 50% reduction in capital costs would indeed be unlikely without major R&D investments). The post-investment supply chain would include one recycling plant for every four production plants (q^{**}=2), and would generate €14.87 of extra profit per ton. Note that, since we analyze the profit *per unit of demand*, we do not consider the benefits of increased sales (in units). The described benefits would be captured by the supply chain even if it were cannibalizing the sales of one of its own comparable plastics. The investment remains unlikely however, since the cost (€30 per ton) far outweighs the benefit (€14.87 per ton).

The second investment would result in an increase of the *recycling ratio* from 10% to 40%. This would involve the development of supply chain coordination mechanisms to increase collection rates, as well as sorting and cleaning technologies to improve material yields in the recycling process (a representative of a plastic mini-mill operator considers a recycling ratio of 40% feasible by 2020, if legislation and technology investments keep moving in the right direction). The postulated investment cost of €10 per ton would represent a total investment of €38.4M under the same cost-of-capital assumptions. Such an investment would result in a supply chain with integrated production and recycling plants (q^{**}=1) but its benefits (€9.69 ton) would not exceed its costs (€10 per ton).

A final investment opportunity is to increase *localization* to reach a value of €50 per ton for *g*, at an investment cost of €15 per ton, or a total investment of €57.6M, under the same assumptions as before. This might involve the development of process modularity to take advantage of localized plant configurations, or the development of customization capabilities that rely on customer proximity. Such an investment would result in smaller market areas as expected but its benefits (€13.72 per ton) would also not exceed its costs (€15 per ton).

Table 2: Separate Investments

Investment Option	*Parameter Changes*	*Investment Cost (κ)*	*Resulting Supply Chain*	*Extra Unit Profit*	*Invest?*
(1) Flexible mini-plants	d: 0.12 → 0.24 ton/km^2 k_p, k_r: €1,2M → €0.6M	€30 / ton	R_p^{**}=261 km ρ^{**}=10%, q^{**}=2	€14.87 / ton	no
(2) Recycling ratio	ρ_{max}: 10% → 40%	€10 / ton	R_p^{**}=464 km ρ^{**}=40%, q^{**}=1	€9.69 / ton	no
(3) Localization	g: €0 → €50 / ton	€15 / ton	R_p^{**}=315 km ρ^{**}=0%	€13.72 / ton	no

5.2 Combined Investments

Table 3 shows the impact of *combined* investments. The stated investment costs for the two paired investments, which are simple sums of their component investment costs, are consistent with our assumptions for propositions 1 through 4. Use of the overall sum of the per unit investment costs, i.e. €55 per ton, for the cost of the combination of all three options further implies that the improvements in *localization* and *recycling ratio* do not complicate each other, which is a reasonable assumption since the efforts appear independent. The last column in the table shows the impact of the complementarities as the difference between the extra profit generated by the combined investment and the sum of the extra profits generated by the separate investments. Due to the complementarities described earlier, the two pairwise investments both generate larger per unit profit increases than the sum of their separate investments. However, neither complementarity is large enough by itself to make the pairwise investments profitable.

Table 3: Impact of Complementarities for Combined Investments

Combined Investments[*]	*Investment Cost (κ)*	*Resulting Supply Chain*	*Extra Unit Profit*	*Invest?*	*Impact of Complementarities*[**]
(1) Flexible mini-plants + (2) Recycling ratio	€40 / ton	R_p^{**}=292km ρ^{**}=40%, q^{**}=1	€35.45 / ton	no	€35.45 – (€9.69 + €14.87) = €10.89 / ton
(1) Flexible mini-plants + (3) Localization	€45 / ton	R_p^{**}=203km ρ^{**}=10%, q^{**}=2	€42.19 / ton	no	€42.19 – (€14.87 + €13.72) = €13.60 / ton
Organic Production System Strategy: (1) Flexible mini-plants + (2) Recycling ratio + (3) Localization	**€55 / ton**	$\boldsymbol{R_p^{**}}$**=232km** $\boldsymbol{\rho^{**}}$**=40%,** $\boldsymbol{q^{**}}$**=1**	**€59.69 / ton**	**YES**	**€59.69 – (€14.87 + €9.69 + €13.72) = €21.41 / ton** **+ 55.93%**

[*]Resulting parameter changes are the union of the parameter changes described for the different options in table 2
[**] Comparison with the extra unit profits generated by separate investments (see table 2)

5.3 Organic Production System Strategy

Only when all three investment options, and both complementarities, are combined, do the investments make sense from a net unit profit perspective. With the triple investment (bottom row in table 3), the supply chain transforms into an "organic production system" with 15 integrated production and recycling plants in Western Europe, instead of the 4 production plants prior to investment. The resulting supply chain has a localization advantage of €26.79, recycling savings of €40, fixed costs of €23.21, and transportation costs of €23.21 per ton, compared to no localization advantage, no recycling, fixed costs of €13.10, and transportation costs of €26.21 per ton prior to investments. Interestingly, because market areas have become more than three times smaller, the transportation costs for the emerging closed-loop supply chain, with its expensive reverse logistics, are still lower than before.

In summary, the strategy of combined investments in *flexible mini-plants*, *localization*, and *recycling ratio* qualifies as an operations strategy for organic production systems and it is clear that an understanding of the underlying complementarities is necessary to evaluate the value of this operations strategy.

5.4 Robustness of results

To understand the robustness of the above results, we evaluated the impact of the complementarities in a wide range of circumstances*. In the numerical example, the extra profit generated by the triple investment exceeds the extra profit generated by the three separate investment options by 55.93% (from bottom-right cell in table 3). Table 4 shows the impact of the complementarities for a range of different parameter sets, in which we either doubled or halved the parameter values of the base case. The impact of the complementarities ranged from 20% to 112%.

Table 4: Impact of Complementarities (%) under Different Parameter Values

	d	k_r	ρ_{max}	g	b	Δ_r	t_p, t_w, t_r
Parameter values* x 2	d_1= 0.24 d_2= 0.48	k_{r1}= €2.4M k_{r2}= €1.2M	ρ_{max1} = 20% ρ_{max2} = 80%	g_1= €0 g_2= €100	b=1000 km	Δ_r = €200	t_p= €0.12 t_w= €0.20 t_r = €0.08
Impact of complementarities in triple investment	29%	83%	30%	50%	31%	20%	46%
Parameter values* x 50%	d_1= 0.06 d_2= 0.12	k_{r1}= €0.6M k_{r2}= €0.3M	ρ_{max1} = 5% ρ_{max2} = 20%	g_1= €0 g_2= €25	b=250 km	Δ_r = €50	t_p= €0.03 t_w= €0.05 t_r = €0.02
Impact of complementarities in triple investment	112%	39%	61%	56%	60%**	48%	38%

* an index of 1 refers to pre-investment values and an index of 2 refers to post-investment values
** when b = 250 km investing in *localization* alone will not generate extra unit profit because R_p^* remains larger than b

In addition, we tested a different characterization of scale economies by formalizing the annual costs of a facility as $k_i w^{\alpha} + c_i w$, with w the annual volume of the facility (we used a typical value of 0.66 for α and, to obtain an equivalent base-case with 4 plants producing approximately 90,000 tons per year, we set $k_p = k_r =$ €1900). In this base-case, the extra profit generated by the triple investment exceeded the extra profit generated by the three separate investment options by 52.88%. In experiments similar to those in table 3, the impact of the complementarities in the triple investment ranged from 29% to 96%.

As seen in table 4, the only scenario in which the impact of the complementarities becomes relatively

* In section EC.3 of the electronic companion we also report that the impact increases in the case of price-setting .

small (20%), is when Δ_r is large, in other words, when the economical incentives for recycling are very strong to begin with. This indicates that the effects studied here are most relevant when the economic rationale for recycling is not trivial, as is true perhaps for a large number of material supply chains.

6. Discussion

In this paper we show analytically that supply chain investments in *flexible mini-plants* (low-cost, flexible production and recycling technologies) complement investments in *localization* and *recycling ratio* increases. Supply chains exploiting these complementarities may constitute an emerging operations strategy, which we call organic production systems. We show that, in a realistic example for an engineering plastic in Western Europe, a clear understanding of these complementarities can make the difference between the continuation of a supply chain without recycling and the emergence of a closed-loop supply chain that features recycling, localization, and market areas less than one third their original sizes. Our findings help to explain the success of mini-mill operators in the steel industry and can inform the study of emerging mini-mill networks in other industries.

Our results also clarify the role of recycling in operations strategy. Our numerical example confirms Fleischmann et al's (2001) finding that the introduction of recycling has a decentralization effect. Our model makes clear that this effect will hold as long as the fixed cost for a recycling plant is not too large, the recycling ratio not too small, and the reverse transportation cost not too low, conditions that are probably quite common (this can be confirmed by checking that $R_p^*(\rho_{max}, q^{**}) < R_p^*(\rho = 0)$ in our model). Importantly, our results also show that complementary investments in *flexible mini-plants*, which in turn invite investments in *localization*, will reinforce this decentralization effect. We thus find clear analytical support for the interesting hypothesis that the introduction of recycling in a supply chain will lead to more non-cost-based operations strategies (Field and Sroufe 2004).

As material recycling becomes more common, the resulting decentralization of production may also have interesting effects on the product and supply chain strategies of other companies. A manufacturer of desktop printers, for example, could, in the presence of decentralized production networks for plastics, decide to perform the final assembly of plastic housing components in distributed regional centers instead of a central manufacturing plant. The manufacturer could rely on regional flexible mini-plants for the supply of plastic housing parts, and could even offer a wider variety of options (e.g., exterior colors) by taking full advantage of this decentralized and thus potentially postponed part of the supply chain. The regional center could become part of the recycling loop by taking back end-of-life printers and performing simple disassembly to return plastic parts to the region's flexible mini-plant. So, the emergence of flexible mini-plants for materials could engender more local, postponed forms of manufacturing and more locality-driven product variety.

The model presented here contained several simplifications and limiting assumptions that warrant some discussion. We mentioned that the "customer sites" in our generic supply chain model represent large sections of closed-loop supply chains. Our model is a good approximation if those sites are dispersed geographically and if the flow of materials across sites, which could be significant, results in a net flow of materials that is close to zero for small enough areas. For supply chains where these conditions do not hold our results need to be considered with care. A second simplification of the model is the assumption that the demand density d is the same for the recycling and production technology. This may not always be the case and so more complex models that allow for one-to-many, or many-to-many, links between recycling and production technologies could form interesting extensions. We would hypothesize that our main findings would hold though. The integrated-plant bonus would remain important and, as before, flexible mini-plants would facilitate small market areas, and thus stimulate both recycling and localization. Finally, our model assumes that the material supply chain is integrated and monopolistic. The prices and quantities of pre-sorted waste, recyclate, and virgin materials, are treated as constants or decision variables, not the result of market mechanisms. Investment decisions and their impacts on profits are considered at the supply chain level, not at the level of potentially separated, or competing, entities within closed-loop supply chains. Removing those limitations could provide answers to a set of important questions. Under what type of contractual agreements can the different partners in a closed-loop supply chain coordinate their investments in order to take advantage of the described complementarities? And, if coordination failures would hamper the emergence of organic production systems, how can governments interested in their associated effects, such as local manufacturing activity, disposal reduction, or reduced dependence on natural resources undo those failures? These questions represent interesting avenues for future research.

Appendix 1: Proofs of Propositions

In the proof of proposition 3 we make use of **Lemma 1:** If $g_1 < g_2$ then $q^{**}(g_1) \le q^{**}(g_2)$

Proof: Suppose $q^{**}(g_1) > q^{**}(g_2)$. Then there is a $g' \in [g_1, g_2]$, and a q_1 and q_2 such that $q_1 = q^{**}(g^{'-}) > q^{**}(g^{'+}) = q_2$. We also know that $\left.\frac{d\pi^*(\rho_{max}, q_1)}{dg}\right|_{g'} < \left.\frac{d\pi^*(\rho_{max}, q_2)}{dg}\right|_{g'}$ because $q^{**}(g)$ switches from q_1 to q_2 at g' and π^* is continuous and differentiable in g. We also know that $\frac{d\pi^*}{dg} = 1 - \frac{R_p^*}{b}$, so, $R_p^*(q_1) > R_p^*(q_2)$ at g'. With $q_1 > q_2$ we can see from (2) that this implies that $q_1 t_w + r(q_1) t_r < q_2 t_w + r(q_2) t_r$. Inspection of $r(q)$ shows that this can only hold if $q_1 = 1$ and $q_2 < 1$, from which it follows, given (1), that $\pi^*(\rho_{max}, q=1) > \pi^*(\rho_{max}, q=q_2)$ at $g = g^{'+}$ and so $q^{**}(g^{'+}) \neq q_2$.

Proof of proposition 1: Because of the assumption regarding κ it suffices to show that $\pi^{**}(k_{p2},g_2) - \pi^{**}(k_{p2},g_1) \ge \pi^{**}(k_{p1},g_2) - \pi^{**}(k_{p1},g_1)$. Since π^{**} is continuous and differentiable w.r.t. g except perhaps at a finite number of switch values $g_{m1},.., g_{mn}$, this inequality can be rewritten as $\int_{g_1}^{g_{m1}} \left(\frac{d\pi^{**}(k_{p2},g)}{dg} - \frac{d\pi^{**}(k_{p1},g)}{dg}\right)dg + \ldots + \int_{g_{mn}}^{g_2} \left(\frac{d\pi^{**}(k_{p2},g)}{dg} - \frac{d\pi^{**}(k_{p1},g)}{dg}\right)dg \ge 0$, with $g_{m1},.., g_{mn}$ a finite number of values for which the left and right derivatives of either $\pi^{**}(k_{p2},g)$ or $\pi^{**}(k_{p1},g)$ are not the same. Because $\frac{d\pi^*}{dg} = 1 - \frac{R_p^*}{b}$ for all values of ρ and q, we can rewrite the inequality as $\int_{g_1}^{g_{m1}} (R_p^{**}(k_{p1},g) - R_p^{**}(k_{p2},g))dg + \ldots + \int_{g_{mn}}^{g_2} (R_p^{**}(k_{p1},g) - R_p^{**}(k_{p2},g))dg \ge 0$. This will hold if

$R_p^{**}(k_{p2}) \le R_p^{**}(k_{p1})$ for all g. It is clear from (2) that $R_p^*(k_{p2}) \le R_p^*(k_{p1})$, so if the optimal values of ρ and q are the same for k_{p2} and k_{p1} then $R_p^{**}(k_{p2}) \le R_p^{**}(k_{p1})$. If the optimal values change from ρ_1 and q_1 to ρ_2 and q_2 as k_p decreases from k_{p1} to k_{p2}, say at value k_p', then $\left.\frac{d\pi^*(\rho_2,q_2)}{dk_p}\right|_{k_p'} < \left.\frac{d\pi^*(\rho_1,q_1)}{dk_p}\right|_{k_p'}$ because π^* is continuous and differentiable for all values of ρ and q. Because first derivatives show that, for each possible ρ and q, $\frac{d\pi^*}{dk_p} = -\frac{1}{4dR_p^{*2}}$ we do find that $R_p^*(\rho_2, q_2) \le R_p^*(\rho_1, q_1)$ *at* $k_p = k_p'$. So even in this case we find that $R_p^{**}(k_{p2}) \le R_p^{**}(k_{p1})$.

Proof of proposition 2: Because of the assumption regarding κ it suffices to show that $\pi^{**}(k_{r2},\rho_{max2}) - \pi^{**}(k_{r2},\rho_{max1}) \ge \pi^{**}(k_{r1},\rho_{max2}) - \pi^{**}(k_{r1},\rho_{max1})$. Reasoning as in proposition 1, it suffices to show that $\frac{d\pi^{**}(k_{r2},\rho_{max})}{d\rho_{max}} \ge \frac{d\pi^{**}(k_{r1},\rho_{max})}{d\rho_{max}}$ for all ρ_{max}. 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 no-recycling ($\rho=0$) to recycling ($\rho=\rho_{max}$) or from larger recycling areas ($\rho=\rho_{max}$, $q=q_1$) to smaller recycling areas ($\rho=\rho_{max}$, $q=q_2<q_1$). For the first type of shift, $\frac{d\pi^{**}}{d\rho_{max}}$ shifts from zero to a positive value and so this will not break the inequality. If the second type of shift occurs, say at value k_r', $\pi^*(q_2)$ will equal $\pi^*(q_1)$ at k_r', which means that $q_2t_w + r(q_2)t_r < q_1t_w + r(q_1)t_r$ (from (1)). Since $\frac{d\pi^*}{d\rho_{\max}}$ can be written as $\Delta_r - \frac{2}{3}(G + g + \rho\Delta_r - \pi^*(q))\frac{qt_w + r(q)t_r}{t_p + \frac{g}{b} + \rho_{max}(qt_w + r(q)t_r)}$, we can verify that $\frac{d\pi^*(q_2)}{d\rho_{max}} > \frac{d\pi^*(q_1)}{d\rho_{max}}$ at value k_r'. So, even if shifts occur in the optimal values of ρ and q as k_r reduces from k_{r1} to k_{r2}, $\frac{d\pi^{**}(k_{r2},\rho_{max})}{d\rho_{max}} - \frac{d\pi^{**}(k_{r1},\rho_{max})}{d\rho_{max}} \ge 0$ for all ρ_{max}.

Proof of proposition 3: As in proposition 1, it suffices to show that $R_p^{**}(d_2) \le R_p^{**}(d_1)$ for all $g \in [g_1,g_2]$.

It is clear from (2) that if an increase in d does not cause a change in ρ^{**} or in q^{**} that the condition will be met. It is also clear from (1) and (3) that the only change in ρ^{**} or q^{**} that could be caused by an increase in d is a change from $\rho^{**}=0$ to $\rho^{**}=\rho_{max}$. So, for all $g \in [g_1,g_2]$ for which $\rho^{**}(d_1)=0$ and $\rho^{**}(d_2)=\rho_{max}$ we need to confirm that $R_p^{**}(d_2) \le R_p^{**}(d_1)$. From (2) we see that the condition is satisfied if and only if $\frac{d_2}{d_1} \ge (\frac{k_p + k_r/q^{**}(g)^2}{k_p})(\frac{t_p+\frac{g}{b}}{t_p+\frac{g}{b}+\rho_{max}(q^{**}(g)t_w + r(q^{**}(g))t_r)})$. This will hold for all $g \in [g_1,g_2]$ if

$\frac{d_2}{d_1} \ge (\frac{k_p + k_r/q^{**}(g_1)^2}{k_p})(\frac{t_p+\frac{g_2}{b}}{t_p+\frac{g_2}{b}+\rho_{max}(q^{**}(g_1)t_w + r(q^{**}(g_1))t_r)})$, which can be verified as follows. Replacing g with g_2 does not make the second factor smaller. Also, if $g_1 \le g$ then $q^{**}(g_1) \le q^{**}(g)$ (from lemma 1), so replacing $q^{**}(g)$ with $q^{**}(g_1)$ does not make the first factor smaller. This replacement also does not make the second factor smaller as long as $q^{**}(g_1)t_w + r(q^{**}(g_1))t_r \le q^{**}(g)t_w + r(q^{**}(g))t_r$. This condition could only be violated if $q^{**}(g_1) < 1$ and $q^{**}(g)=1$ because of the behavior of $r(q)$ at $q=1$. However if the condition is violated it is also easy to see from (1) that $\pi^*(g_1, q=1)>\pi^*(g_1, q<1)$, which contradicts $q^{**}(g_1) < 1$.

Proof of proposition 4: Because of the assumption regarding κ it suffices to show that $\pi^{**}(d_2,\rho_{max2}) - \pi^{**}(d_2,\rho_{max1}) \ge \pi^{**}(d_1,\rho_{max2}) - \pi^{**}(d_1,\rho_{max1})$. Arguing as in the proof of proposition 2, we see that this holds if $\frac{d\pi^{**}(d_2,\rho_{max})}{d\rho_{max}} \ge \frac{d\pi^{**}(d_1,\rho_{max})}{d\rho_{max}}$ for all ρ_{max}. If the optimal values of ρ and q are the same for d_2 and d_1 then it can easily be verified that this inequality will hold. Inspection of (1) shows that an increase in d can also cause a shift from no-recycling ($\rho=0$) to recycling ($\rho=\rho_{max}$) but no shift in the optimal q. If there is a shift to recycling, $\frac{d\pi^{**}}{d\rho_{max}}$ shifts from 0 to a positive value so the inequality will hold.

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Organic Production Systems: An Emerging Operations Strategy?

Lieven Demeester
Mei Qi
Luk N. Van Wassenhove

Electronic Companion Document

EC.1. Allowing plants to locate off-center

When the market areas for production and recycling plants are different in size ($q \neq 1$) the total transportation costs can be reduced further by allowing the plants in the smaller market areas to locate off-center and closer to the plant in the center of the larger market area. Let's consider $q>1$, as in the left side of figure 2. Because we use a Manhattan distance metric we can separate the horizontal and vertical location problems. Let $0 \le x \le R_p$, with x denoting the horizontal distance that a production plant is moved closer to the recycling plant and away from the center of its market area. The average horizontal distance from a production plant to a customer site is then increased from $\frac{R_p}{2}$ to $\frac{R_p}{2}(1+\frac{x^2}{R_p^2})$ and the average horizontal distance from the recycling plant to a production plant is reduced from $\frac{qR_p}{2}$ to $\frac{qR_p}{2}$-x. To find the optimal value of x we minimize $t_p \frac{R_p}{2}(1+\frac{x^2}{R_p^2}) + \rho t_r (\frac{qR_p}{2} - x)$, which is the sum of the per-unit-of-demand horizontal transportation costs for product and recyclate. This expression is minimized when $x = \frac{\rho t_r}{t_p} R_p$ and its minimum can be written as $(t_p + \rho q t_r (1 - \frac{1}{q}\frac{\rho t_r}{t_p}))\frac{R_p}{2}$. Noting that the vertical transportation costs will be identical and performing a similar optimization for $q < 1$, we find that the following expressions replace (1) and (2).

$$\pi^*(\rho,q) = G + g + \Delta_r\rho - 3(\tfrac{1}{2})^{\frac{4}{3}}(\frac{k_p + \lceil\rho\rceil k_r/q^2}{d})^{\frac{1}{3}}(t(q))^{\frac{2}{3}} \tag{6}$$

$$R_p^*(\rho,q) = (\tfrac{1}{2})^{1/3}(\frac{k_p + \lceil\rho\rceil k_r/q^2}{dt(q)})^{1/3} \tag{7}$$

$$\text{with } t(q) = \begin{cases} t_p + \frac{g}{b} + \rho(qt_w + t_r(1 - q\frac{t_r}{t_w})), \text{ if } q < 1 \\ t_p + \frac{g}{b} + \rho t_w, \text{ if } q = 1 \\ t_p + \frac{g}{b} + \rho(qt_w + qt_r(1 - \frac{1}{q}\frac{\rho t_r}{t_p})), \text{ if } q > 1 \end{cases} \tag{8}$$

One should note that the described optimization involved an assumption about the impact of off-center plant location on the localization advantage. We have described localization advantage as a combination of adaptation and proximity leverage. With an off-center plant location, the adaptation effect would remain unchanged because the size of the market area is not changing. However, the proximity leverage will be affected as the average distance to the customer is increasing. From the derivation above it is clear that we have assumed that the localization is an adaptation effect only, not influenced by the off-center location. This assumption, as can be observed easily, maximizes the effect of off-center location on *t(q)* and thus provides an upper bound for this effect.

From (1), (2), and (6)-(8) it can be seen that the effect of this optimization on $R_p^*(\rho,q)$ or $\pi^*(\rho,q)$ is small, especially if $t_r < t_w$ and $t_r < t_p$, which is often the case as we have argued when we introduced the numerical example in section 5 of the paper. For the results in table 2 and 3, for example, allowing off-center location affects investment option (1) in table 2 and combined investment (1) + (3) in table 3. In both cases the resulting supply chain has q=2. Using (6)-(8) instead of (1)-(2) in these two scenarios leads to savings of no more than €0.07 per ton and so the impact on results is minimal.

EC.2. Discussion of mixed interactions

We shortly discuss the mixed interaction between the other six pairs of parameters that relate to organic production systems (charts that illustrate these mixed interactions are available from the authors). For the pairs (k_p,d) and (k_r,d), a quick inspection of (1) reveals that, with respect to *unit profit*

(π^{**}), mini-scaling (a decrease in k_p or k_r) and range flexibility (d), are *supplementary*; in other words, mini-scaling reduces the unit profit benefits of increased range flexibility. However, to offer a general proposition regarding the supplementarity with respect to *net unit profit* as defined in (5), we would have to argue that mini-scaling and range flexibility are *complementary* with respect to the unit investment costs κ, and this seems unreasonable. Mini-scaling often involves a reduction in the number of processing steps and might actually simplify the efforts to increase range flexibility. The remaining four parameter pairs, (k_r,g), (k_r, k_p), (ρ, k_p,), and (ρ,g), each have one recycling, and one production-related parameter. We find that complementarity exists in certain regions where ρ^{**} and q^{**} do not change. For q^{**} >1 or q^{**} <1, this seems due to the restrictions on q, and therefore is not very interesting. However, for q^{**}=1, these conditional complementarities are more meaningful. We discuss this interesting interaction between production and recycling in section 4.2 of the paper.

EC.3. Allowing the supply chain to set price

One simplification of our model is that the supply chain is considered a price-taker. As discussed in Erlenkotter (1989), and applied effectively for reverse logistics in Wojanowski et al (2007), a simple algorithm that identifies the optimal price for a price-setting firm is easily added to the optimal market area model. Closed-form solutions are then no longer achievable but we can easily conjecture, though, that the complementarities in question will not be weakened because any investment strategies that are adopted lead to higher per unit profits, and the advantage of price-setting typically increases with the unit profit under price-taking. We confirmed this for the numerical example in table 2 and 3. The magnitude of the complementarity, with respect to overall profit in this case, increased when post-investment price optimization was allowed, as opposed to pre-investment price optimization only (we used d_1=0.16-0.001*G and d_2=0.32 -0.002*G; the optimal value of G pre-investment was €96, and post-investment it was €60).

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Europe Campus
Boulevard de Constance,
77305 Fontainebleau Cedex, France
Tel: +33 (0)1 6072 40 00
Fax: +33 (0)1 60 74 00/01

Asia Campus
1 Ayer Rajah Avenue, Singapore 138676
Tel: +65 67 99 53 88
Fax: +65 67 99 53 99

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