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To cooperate, or not to cooperate, that is the question. Strategic analysis for the implementation of industrial symbiosis

Melissa Mollica [a,b,*], Luca Fraccascia [a,c,**], Alberto Nastasi [a]

[a] Department of Computer, Control, and Management Engineering "Antonio Ruberti", Sapienza University of Rome, Italy
[b] Department of Mechanical and Aerospace Engineering, Sapienza University of Rome, Italy
[c] Department of High-Tech Business and Entrepreneurship, University of Twente, The Netherlands

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ABSTRACT

The lack of adequate support in strategic decision-making hampers the widespread of industrial symbiosis (IS). Although various business models for IS are available, existing literature focuses solely on cooperation between waste producers and waste users to replace primary inputs with waste. This paper proposes a strategic analysis for waste producers introducing IS, comparing the traditional cooperative approach with a competitive new product development strategy. Using a game-theoretical model, a third hybrid strategy is defined. The paper examines the impact of market characteristics, investment requirements, IS costs, and primary input purchase costs on the strategic choices of waste producers, providing insights for managers and decision-makers. Results suggest that the characteristics of the market where to enter significantly affect the final strategic behavior. Specifically, the main strategic discriminating factors are the market size, the consumers' willingness to pay, and the investment extent.

1. Introduction

The introduction of this manuscript is divided into three subsections. Section 1.1 concerns the concept of IS. Section 1.2 introduces the business strategies that companies can adopt to implement IS. The latter section is operational to clearly present the gap in the literature and the aim of the paper, which is discussed in Section 1.3.[1]

1.1. Industrial symbiosis

Facilitating the transition of the economy toward more sustainable production and consumption models stands as one of the primary objectives to be attained on a global scale, and IS represents an effective tool to support this goal (D'Amato et al., 2019; Bressanelli et al., 2022). IS is a practice of circular economy (CE) that enables the reuse of by-products and production wastes as inputs in other production processes rather than dispose of them in the landfill (Gertler, 1995; Chertow, 2000). Accordingly, two companies establish an industrial symbiosis relationship (ISR) when the waste producer transfers one or more production wastes to the waste user — the waste exchange can happen (1) free of charge, (2) with the waste producer paying the waste user to dispose of its waste, or (3) with the waste user paying the waste producer for buying the waste (Fraccascia and Yazan, 2018). Implementing IS reduces the amount of wastes disposed of in the landfill, as well as the usage of primary inputs, (Jacobsen, 2006; Dong et al., 2022; Sourmelis et al., 2024). Moreover, economic benefits for companies involved in IS stem from the trade-off between ceasing and emerging costs. In fact, IS allows the waste producer and the waste user to reduce the waste disposal costs and the input purchase costs, respectively, while some additional costs – known in the literature as 3T costs, i.e., Treatment, Transportation, and Transaction costs (Yazan et al., 2020) – arise. At the social level, IS contributes to the creation of new jobs and career opportunities (Domenech et al., 2019; Martin and Harris, 2018), as well as to the enhancement of collective well-being. Since the adoption of the IS practice results in environmental, economic, and social benefits, IS seems a promising tool to pursue sustainable development and policymakers strongly encourage its implementation (European Commision, 2018; European Commission, 2020).

Nevertheless, the spread of the IS practice among companies is still scant compared to the theoretical potentials (Lombardi, 2017),

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* Corresponding author.
** Corresponding author at: Department of Computer, Control, and Management Engineering "Antonio Ruberti", Sapienza University of Rome, Italy.
E-mail addresses: melissa.mollica@uniroma1.it (M. Mollica), luca.fraccascia@uniroma1.it (L. Fraccascia).

[1] The section regarding the business strategies for implementing industrial symbiosis (IS) could have been framed as a literature review section, ideally positioned immediately following the introduction. However, we posit that integrating these concepts within the introduction serves to elucidate the existing gap in the literature and consequently substantiates the aim and scope of this manuscript.

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mainly because of technical, economic, and organizational barriers (Agudo et al., 2023; Corsini et al., 2024; Turken and Geda, 2020). Partly, organizational inertia and resistance to change (Christensen et al., 2003; Christensen, 1997) are responsible for that Setyawan et al. (2024). Moreover, lacking support in strategic decision-making plays an important role in restraining the transition (Kumar et al., 2021; Gupta et al., 2020): without proper guidelines, companies find it challenging to introduce IS in their business practices.

1.2. Business strategies for industrial symbiosis

The literature underlines several strategies supporting the adoption of IS (Fraccascia et al., 2019, 2016). Specifically, companies producing wastes can decide whether to send their by-products to other companies (Jacobsen, 2006; Jensen et al., 2011) or to exploit them within their own boundaries, thus establishing ISRs among different production processes internal to the company (Zhu et al., 2007; Shi and Chertow, 2017; Yang and Feng, 2008). Similarly, companies interested in receiving wastes can decide whether the wastes will be used to replace production inputs or to generate new products, which will be sold on the market (Fraccascia et al., 2016). The literature identified different business models supporting IS for both the waste producer and user: concerning the waste producers, the strategies of (1) internal exchange and (2) external exchange can be distinguished, while the waste users can choose between the strategies of (1) input replacement and (2) new product development (Fraccascia et al., 2016).

Despite the different opportunities proposed in the literature, the strategic approach most widely diffused and studied consists of originally independent companies engaged in physical exchanges of waste materials, water, and energy, i.e., waste producers often opt for an External Exchange (EE) strategy. Several examples of companies implementing the EE can be found in the literature — see, e.g., the Industrial Symbiosis Network (ISN)[2] of Kalundborg (Denmark) (Jensen et al., 2011). The implementation of the EE strategy by the waste producer translates into a cooperative approach toward IS, as both the companies involved can obtain several advantages. For example, the emerging costs of IS – i.e., (1) additional waste treatment costs, (2) costs for transporting the waste, and (3) investments in infrastructures – can be shared (Fraccascia et al., 2017; Albino et al., 2016). Nevertheless, several challenges arise: market research for a partner, contracting negotiations for sharing benefits and costs, coordination, adapting to the use of non-traditional resources are recognized as the major weaknesses of this strategy (Albino et al., 2016; Lambert and Boons, 2002).

The literature provides examples of IS implemented at the firm level, too. For instance, Guitang Group, a Chinese company whose original business was producing sugar, has decided to implement IS by adopting an “internal exchange” and “new product development” business model: instead of sending wastes from sugar production to other companies, the company started to reuse them internally to generate new products (toilet paper, alcohol, and fertilizers) (Zhu et al., 2007). Indeed, by exploiting wastes or by-products within the firm’s boundaries, new production lines can be built to realize new products: this IS strategy is defined NPD (Fraccascia et al., 2016) and leads to competition with the otherwise symbiotic partners. The adoption of the NPD strategy allows novel business opportunities to be grasped by the waste producer, which has the chance to enter into new markets with a competitive advantage over companies not implementing IS. In particular, companies including IS in their business practices might benefit from lower production costs rather than traditional companies, *ceteris paribus*, as the new product is (partially) generated by exploiting internal wastes. Compared to the EE strategy, all IS costs related to cooperation and negotiation disappear. However, as all the benefits are grabbed by the firm, neither the additional costs from IS can be shared. Typically, high investments in new infrastructures and processes are required. Thus, this strategy is hardly sustainable for small firms (Fraccascia et al., 2016).

The main differences between the cooperative and the competitive approaches to IS are displayed in Table 1.

It is worth noting how the NPD strategy can be related to the encroachment phenomenon in supply chains, i.e., when a manufacturer competes with its independent intermediaries by adding a wholly-owned direct sales channel (Zhang et al., 2023; Ponnachiyur Maruthasalam and Balasubramanian, 2023; Zhang et al., 2021). Indeed, we can compare the manufacturer’s encroaching strategy to the waste producer’s choice of competing with an otherwise symbiotic partner.

1.3. Gap in the literature and aim of the paper

Given the different opportunities and challenges stemming from the adoption of the cooperative or competitive approach toward IS, a practical business problem arises for companies: *which is the best business model to adopt when approaching IS*? Indeed, the business models mentioned in Section 1.2 differ from both the strategic perspective – e.g., what to do with wastes – and the economic perspective – e.g., different costs and investments must be sustained. In this regard, companies producing wastes should decide whether to establish an ISR with a symbiotic partner or, conversely, to exploit the waste themselves, producing new products for the market. Note that the strategic decision-making process between cooperation and competition for companies has been analyzed in different contexts, e.g., in traditional markets (Chen et al., 2019; Cheng and Fan, 2021) and in Information and Communications Technology (ICT) markets (Liu et al., 2024): however, it is still unexplored in the field of IS.

In the literature, a few studies developed theoretical models aimed at helping companies to behave properly in the case of approaching IS. These studies adopted game theory, which is an effective tool to model the strategic interaction of firms involved in IS, where the decisions of one player significantly affect the economic performance of the other (Yazan et al., 2020; Yazdanpanah and Yazan, 2018; Ahmad Fadzil et al., 2022). In particular, Tang et al. (2021) investigated the optimal pricing and production strategies of two manufacturers potentially involved in an ISR. Zhang et al. (2022) introduced a three-stage game to model the interaction between a waste producer and a waste user, in which the agents negotiate the waste trading price and share the fixed investment cost required for the ISR through Nash bargaining to define their optimal production quantities. Xiong et al. (2017) proposed a mathematical model for studying the interactive behavior of different waste treatment operators in a symbiotic environment. Yazan et al. (2020) investigated the negotiation phase of an ISR through a non-cooperative game-theoretical model. The authors compared the adoption of a fair strategy and an opportunistic strategy to share the additional costs of IS. Erlier, Yazdanpanah and Yazan (2018) introduced a game-theoretical formulation for an ISR, which consisted of a cooperative cost-allocation game. The aim was to find a cost allocation both fair and stable. Nevertheless, the above-mentioned studies focused on the same model of IS, i.e., the cooperation between two companies, aimed at using wastes to replace production inputs — i.e., the “external exchange” and “input replacement” business model. To date, a framework considering the different business models and suggesting which strategy to adopt for a given company in a specific context is still missing in the literature.

This paper aims to fill this gap by developing a game-theoretical model in which a waste producer, aiming at maximizing its economic benefit (Ferguson, 2016), has to choose between a cooperative and a competitive approach toward IS. Specifically, given the competitive advantage provided to the symbiotic partner whether deciding for a cooperative IS, the waste producer may consider exploiting the waste

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[2] An ISN is a network made of at least three companies exchanging at least two wastes (Chertow, 2007).

Table 1
Main differences between the cooperative and the competitive approaches to IS.

Cooperation	Competition
External Exchange	New Product Development
Cost-sharing	High investments required
Benefit-sharing	Overall benefit appropriability
Need for trust and information sharing	No need to disclose sensible information
Transportation costs arise	Transportation costs do not arise
Transaction costs arise	Transaction costs do not arise

itself and competing with them in the market. Insights from the model are derived and discussed through a simulation conducted with MATLAB. The proposed analysis provides suggestions for managers to help them in approaching IS and for policymakers to design proper policies.

The remainder of this paper is structured as follows. Section 2 presents the methodological framework, the assumptions, and the development of the theoretical model. In Section 3 the results of the simulation are provided and discussed, while Section 4 explains which are the major factors affecting the strategic decision-making process and derives implications from the managerial and policy perspectives. Finally, conclusions are reported in Section 5.

2. Model formulation

This section provides the methodological framework and the development of a model aimed at analyzing the behavior of a waste producer in front of the strategic choice between cooperation and competition. It is divided into two subsections: in Section 2.1 an enterprise input–output approach will be used to model the strategic scenarios available for the waste producer, while in Section 2.2 a game-theoretical model will be developed to investigate its strategic behavior.

2.1. Modeling cooperation and competition strategies

The theoretical framework proposed in this paper has been developed according to the Enterprise Input–Output (EIO) approach. Many studies in the literature of IS have been supported by the EIO approach (e.g., Fraccascia et al., 2017; Albino and Kühtz, 2004; Fraccascia and Giannoccaro, 2020) and practitioners have recognized it as an appropriate tool to represent monetary, material, and emissions flows in IS (Demartini et al., 2022).

The EIO approach allows to model a single firm or production process as a black box that transforms primary inputs into one main output and generates wastes (Lin and Polenske, 1998). Let us consider a company indexed by i, which produces x_i units of its main output. For the sake of simplicity, let us assume that the company requires only one input and produces only one waste. The amount of primary input required (denoted as r_i) and the amount of waste generated (w_i) can be computed as follows:

$$r_i = R_i \cdot x_i \tag{1}$$

$$w_i = W_i \cdot x_i \tag{2}$$

where R_i and W_i are two technical coefficients, representative for the production technologies adopted, denoting the amount of primary input required and the amount of waste generated per unit of main product, respectively.

Let us consider two companies involved in different markets: Company α, which is the focal firm of the analysis, produces product A and sells it in market A, and Company β produces product B and sells it in market B. Let x_A^α and x_B^β be the production quantities of product A produced by Company α and product B produced by Company β, respectively. For the sake of simplicity, it is assumed that each company requires one primary input and generates one waste, whose quantities are dependent on the output production, according to Eqs. (1) and (2), respectively.

If IS does not occur, each company purchases its primary input from traditional suppliers and disposes of its waste in the landfill (Fig. 1(a)).

Let us assume that the waste generated by Company α to produce product A can be used to replace the primary input required by Company β to produce product B, after having received some treatments — hence, we assume a case of imperfect symbiosis[3] — which are undertaken by Company α. In this regard, let us assume that s_{AB} units of input can be replaced by one unit of recycled waste input to produce the same units of output; moreover, let the efficiency of the treatment process – i.e., the percentage of waste that can be used as input after having received the treatment (Fraccascia, 2019) – be equal to one.

From the strategic perspective, Company α can decide which strategy to adopt:

- **Cooperating via implementing the "external exchange" strategy**, by sending its waste to Company β, which will use the waste to replace – totally or partially, depending on the match between waste demand and supply – its primary input (Fig. 1(b)). In this case, the amount of waste exchanged by Company α and Company β, denoted as $e_{A(\alpha)\to B(\beta)}$, can be computed as:

$$e_{A(\alpha)\to B(\beta)} = min\left\{ W_A \cdot x_A^\alpha; \frac{R_B \cdot x_B^\beta}{s_{AB}} \right\} \tag{3}$$

  In the case of a perfect match between waste demand and supply, no waste will be disposed of in the landfill by Company α, while Company β will not purchase any amount of primary input from traditional suppliers. If the demand for waste is higher than the correspondent supply, Company β will purchase additional amounts of input $(R_B \cdot x_B^\beta - W_A \cdot x_A^\alpha \cdot s_{AB})$ from the traditional suppliers. Alternatively, if the demand for waste is lower than the correspondent supply, Company α will dispose of the waste exceeding Company β's demand $(W_A \cdot x_A^\alpha - \frac{R_B \cdot x_B^\beta}{s_{AB}})$ in the landfill.
- **Competing via implementing the "new product development" strategy**, by exploiting the waste to produce itself the product B, which will be sold on the market B. In this case, Company α introduces a second business unit, i.e., Business Unit B, responsible for product B. Hence, Company α will comprehend two business units, i.e., Business Unit A and Business Unit B, in charge of producing product A and B, respectively. Note that, in this scenario, Business unit B becomes an internal customer of Business Unit A, within the boundaries of Company α. Let the amount of waste generated by producing product A and reused by Company α to produce product B be denoted as $e_{A(\alpha)\to B(\alpha)}$, which can be computed as:

$$e_{A(\alpha)\to B(\alpha)} = min\left\{ W_A \cdot x_A^\alpha; \frac{R_B \cdot x_B^\alpha}{s_{AB}} \right\} \tag{4}$$

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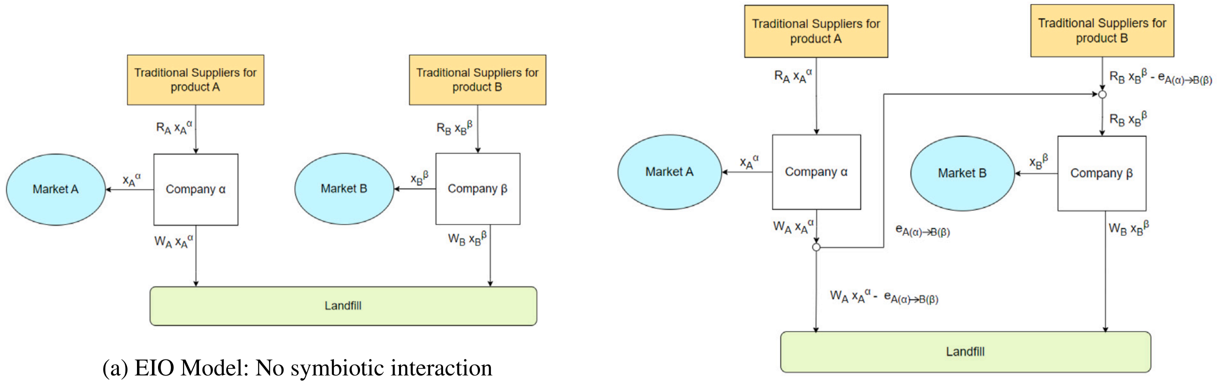
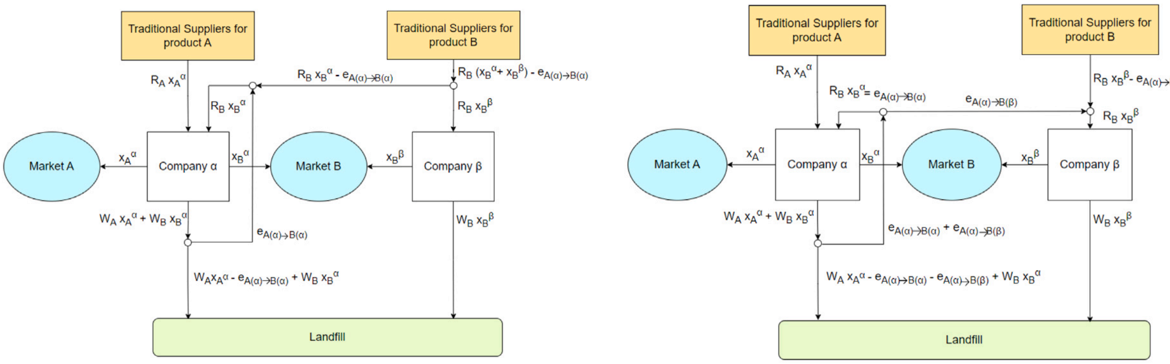
[3] IS is called to be *perfect* when the waste can replace the production input without undergoing additional treatments. Conversely, IS is *imperfect* when some treatments are required before the waste is able to replace the production input (Fraccascia et al., 2017).



(a) EIO Model: No symbiotic interaction

(b) EIO Model: External exchange



(c) EIO Model: New product development

(d) EIO Model: Hybrid strategy

Fig. 1. EIO models.

If there is a perfect match between internal waste demand and supply, Business Unit A of Company α will not dispose of any unit of its waste in the landfill, while Business Unit B will not purchase any amount of input from traditional suppliers. Whether the internal waste demand is higher than the waste supply, Business Unit B of Company α will need to purchase additional amounts of input ($R_B \cdot x_B^\alpha - W_A \cdot x_A^\alpha \cdot s_{AB}$) to produce the product B. Conversely, if the waste internal demand is lower than the waste supply, Business Unit A of Company α will still have a given amount of waste ($W_A \cdot x_A^\alpha - \frac{R_B \cdot x_B^\alpha}{s_{AB}}$) not exploited. In the latter scenario, Company α undergoes a further strategic choice, and can decide whether:

- to dispose of the waste in the landfill, thus **competing via implementing solely the "new product development" strategy** (Fig. 1(c));
- to sell the waste not exploited to Company β, thus **competing via implementing a "hybrid" strategy**. Specifically, Company α further implements the EE strategy in addition to the NPD (Fig. 1(d)).

To summarize: Company α first decides whether to cooperate or compete with Company β; if Company α opts for cooperation, only the "external exchange" strategy (strategy 1) is available ; if Company α opts for competition and the waste internal demand is lower than the waste supply, the company can further choose whether to adopt solely the "new product development" (strategy 2.1) or the "hybrid strategy" (strategy 2.2). Conversely, if the waste internal demand is higher than the waste supply, the hybrid strategy is unfeasible and Company α is forced to adopt the "new product development" (strategy 2.1)

2.2. Development of the game-theoretical model

This subsection concerns the development of a game-theoretical model in which the strategic behavior of Company α – facing the choice between the cooperative or the competitive approach toward IS – is analyzed. In particular, the cooperative approach translates into the implementation of the EE strategy, while the competitive approach leads to the implementation of the NPD strategy or of the Hybrid (HY) strategy.

The model follows the reasoning of Company α. In particular, Company α has to determine (1) whether to cooperate or to compete with Company β, (2) the optimal production quantity for product A (x_A^α), and eventually for product B (x_B^α). The notation used inside the model is provided in Table 2.

The proposed model is based on the following assumptions, consistently with the literature (Zhang et al., 2022; Tang et al., 2021; Ponnachiyur Maruthasalam and Balasubramanian, 2023):

1. At the beginning, Company α operates as a monopolist in market A and Company β operates as a monopolist in market B;
2. Complete information is ensured for both companies;
3. For the sake of simplicity, all the production costs, except for the input purchase and the waste disposal costs, are ignored;
4. For the sake of simplicity, cost functions and production functions are assumed to be linear functions;
5. The inverse demand functions for both product A and product B are linear, i.e., $p_A = a_A - b_A \cdot x$, and $p_B = a_B - b_B \cdot x$;
6. Implementing an ISR between Company α and Company β is economically convenient, i.e., the following condition holds:

$$ct_1 + ct_2 < s_{AB} \cdot pr_B + dc_A \tag{5}$$

Table 2
Notations and explanations.

Notation	Explanation
x_A^α	Amount of product A produced by Company α
x_B^β	Amount of product B produced by Company β
x_B^α	Amount of product B produced by Company α
a_A	Maximum willingness to pay for product A
b_A	Inverse of the demand elasticity for product A
pr_A	Unit input purchase cost for product A
dc_A	Unit waste disposal cost for product A
a_B	Maximum willingness to pay for product B
b_B	Inverse of the demand elasticity for product B
pr_B	Unit input purchase cost for product B
dc_B	Unit waste disposal cost for product B
ct_1	Unit waste treatment cost
ct_2	Unit waste transportation cost
R_A	Technical substitution coefficient of the inputs for product A
R_B	Technical substitution coefficient of the inputs for product B
W_A	technical substitution coefficient of the waste for product A
W_B	Technical substitution coefficient of the waste for product B
s_{AB}	Technical substitution coefficient of the waste for the input of product A
t^α	Company α total transaction cost
t^β	Company β total transaction cost
I	investment required for Company α to enter market B
SV^α	Shapley Value related to Company α
SV^β	Shapley Value related to Company β
SV_A^α	Shapley Value related to the business unit A of Company α
SV_B^α	Shapley Value related to the business unit B of Company α
Π_A^α	Profit of Company α from the business unit A
Π_B^α	Profit of Company α from the business unit B
Π_B^β	Profit of Company β from product B
TC	Company α total costs

Accordingly, the additional cost to exchange one unit of waste is lower than the ceasing costs, i.e., the cost of disposing of one unit of waste in the landfill and the cost to purchase the amount of primary input replaced by one unit of waste.

In the remaining of this section, the model will be developed for the three strategies: EE strategy in Section 2.2.1, NPD strategy in Section 2.2.2, and HY strategy in Section 2.2.3. The logic of the model is resumed in the flowchart proposed in Fig. 2 (for the extended version of the flowchart see Appendix A.1).

2.2.1. External exchange strategy

Problem Description

Whether Company α decides to implement the EE strategy with Company β, the two companies negotiate to share the emerging costs of IS, i.e., waste treatment and transportation costs. Let us assume that the negotiation ends up with the adoption of the Shapley values.[4] Indeed, this cost-sharing mechanism allows the ISR to be fair and stable in the long run (Yazdanpanah and Yazan, 2018; Yazan et al., 2020). The Shapley values represent the unit additional cost for IS that Company α and Company β have to incur. Specifically, Company α will pay SV_A^α and Company β will pay SV_B^β for each unit of waste exchanged.[5]

The optimal production quantity of product A produced by Company α is defined in two stages through backward induction (Aumann, 1995).

In the **first stage**, Company α anticipates Company β's demand via addressing Company β's profit maximization problem (Eq. (6)). The optimal production quantity of product B to realize for Company β (Eq. (7)) allows Company α to know its demand for waste, i.e., $\frac{R_B}{s_{AB}} \cdot x_B^{\beta^*}(EE)$.

$$max_{x_B^\beta}\, \Pi_B^\beta(EE, x_B^\beta) = x_B^\beta \cdot [(a_B - b_B \cdot x_B^\beta) - \frac{R_B}{s_{AB}} \cdot SV_B^\beta - W_B \cdot dc_B] - t^\beta \quad (6)$$

$$x_B^{\beta^*}(EE) = \frac{2a_B \cdot s_{AB} - R_B \cdot (ct_1 + ct_2 - dc_A + pr_B \cdot s_{AB}) - 2dc_B \cdot s_{AB} \cdot W_B}{2b_B \cdot s_{AB}} \quad (7)$$

In the **second stage**, Company α maximizes its own profit (Eq. (8)):

$$\begin{aligned} max_{x_A^\alpha}\, \Pi_A^\alpha(EE, x_A^\alpha) = {} & x_A^\alpha \cdot [(a_A - b_A \cdot x^\beta \alpha_A) - R_A \cdot pr_A] + \\ & - SV_A^\alpha \cdot min\{W_A \cdot x_A; \frac{R_B}{s_{AB}} \cdot x_B^\beta\} - dc_A \cdot max\{0; W_A \cdot x_A^\alpha - \frac{R_B}{s_{AB}} \cdot x_B^\beta\} - t^\alpha \end{aligned} \quad (8)$$

Solving the problem in closed form requires the profit function of Company α to be redefined, according to the match between demand and supply of waste.

Let us define R1EE and R2EE the domain regions of the profit function reported in Eq. (8) such that the constraints $W_A \cdot x_A^\alpha \leq \frac{R_B}{s_{AB}} \cdot x_B^\beta$ (Constraint R1EE) and $W_A \cdot x_A^\alpha > \frac{R_B}{s_{AB}} \cdot x_B^\beta$ (Constraint R2EE) are satisfied, respectively.

If the waste supply is lower than or equal to the waste demand (i.e., Constraint R1EE is satisfied), Company α can send the overall amount of waste generated to Company β, thus avoiding the waste disposal costs entirely. Conversely, Company β needs to purchase additional amounts of primary input from traditional suppliers.

In the domain region R1EE, the profit maximization problem of Eq. (8) can be simplified (see Appendix A.3 Eq. (28)) and the optimal production quantity of product A can be defined as in Eq. (9).

$$x_A^{\alpha^*}(R1EE) = \frac{2a_A - 2R_A \cdot pr_A - W_A \cdot (ct_1 + ct_2 + dc_A - pr_B \cdot s_{AB})}{4b_A} \quad (9)$$

If the waste supply is higher than the waste demand (i.e., Constraint R2EE is satisfied), Company α can satisfy the entire waste demand

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[4] Readers interested to deepen Shapley values in negotiations embedded in ISR are referred to Yazdanpanah and Yazan (2018).

[5] For the computation of SV_A^α and SV_B^β see Appendix A.3 Eqs. (24) and (25).

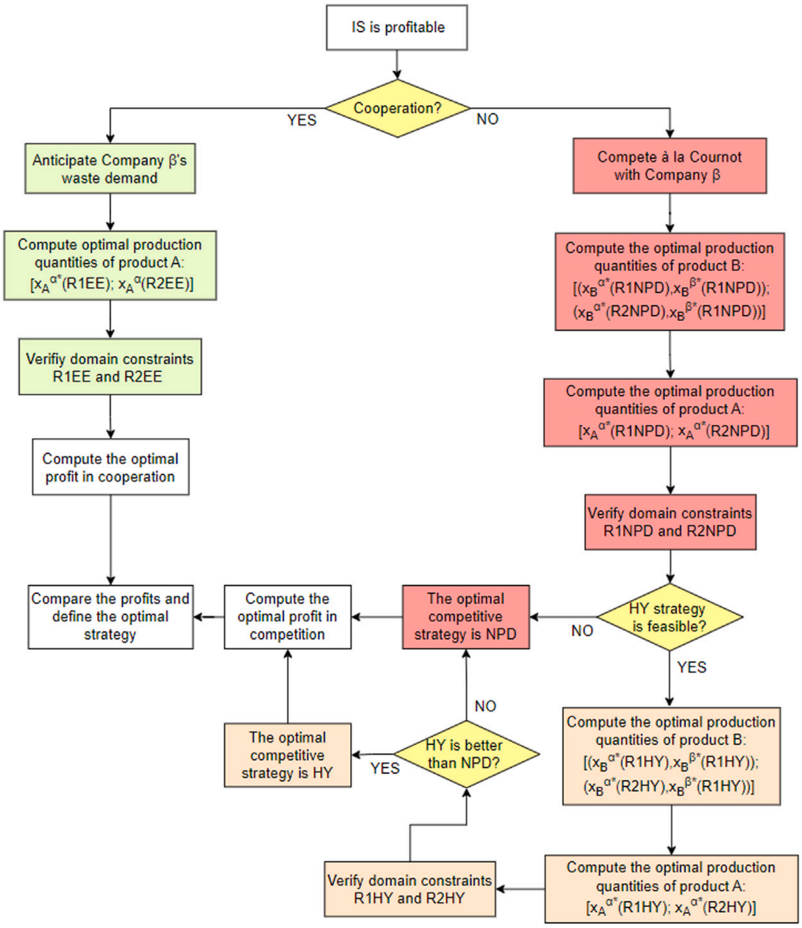

Fig. 2. Model Flowchart.

of Company β, that in turn does not need to purchase any amount of primary input from traditional suppliers. Nevertheless, Company α has exceeding waste (i.e., $W_A \cdot x_A^\alpha - \frac{R_B}{s_{AB}} \cdot x_B^\beta$) to be disposed of in the landfill. In the domain region R2EE, the profit maximization problem of Eq. (8) can be simplified (see Appendix A.3 Eq. (29)) and the optimal production quantity of product A can be defined as in Eq. (10).

$$x_A^{\alpha^*}(R2EE) = \frac{a_A - R_A \cdot pr_A - W_A \cdot dc_A}{2b_A} \tag{10}$$

Problem Solution

The optimal production quantities of product A defined in Eqs. (9) and (10) are admissible if Constraint R1EE and Constraint R2EE are satisfied, respectively. Note that the system of the two constraints admits no solutions.[6] Hence, being the profit function concave under the linearity assumption of demand and cost functions,[7] it is possible to derive that:

- if Constraint R1EE is satisfied, Constraint R2EE must be not satisfied, the optimal production quantity of product A is $x_A^{\alpha^*}(R1EE)$, and Company α yields a profit equal to $\Pi_A^\alpha(R1EE, x_A^{\alpha^*}(R1EE))$;
- if Constraint R2EE is satisfied, Constraint R1EE must be not satisfied, the optimal production quantity of product A is $x_A^{\alpha^*}(R2EE)$, and Company α yields a profit equal to $\Pi_A^\alpha(R2EE, x_A^{\alpha^*}(R2EE))$;
- if neither Constraint R1EE nor Constraint R2EE are satisfied, the optimal production quantity of product A is $\frac{x_B^{\beta^*}(EE)\cdot R_B}{W_A \cdot s_{AB}}$,[8] and Company α yields a profit equal to $\Pi_A^\alpha(R1EE, \frac{x_B^{\beta^*}(EE)\cdot R_B}{W_A \cdot s_{AB}})$.[9]

2.2.2. New product development strategy

Problem Description

Whether deciding for the NPD strategy, Company α starts producing product B and competing with Company β: market B becomes a duopoly. Company α sustains an investment to build a new production line and introduces a novel business unit. In this scenario, Company

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[6] Satisfying the constraints R1EE and R2EE simultaneously implies that:

$$\begin{aligned} &2 \cdot dc_A < ct_1 + ct_2 + dc_A - s_{AB} \cdot pr_B \\ &\quad dc_A < SV_A^\alpha \end{aligned} \tag{11}$$

However, dc_A must be greater than SV_A^α in order for the IS to be feasible.

[7] It is trivial to demonstrate that the second derivative of a profit function of the kind $\Pi(q) = q \cdot (a - b \cdot q - c)$, with a, b, and c positive parameters, is always negative.

[8] The optimal production quantity is on the frontier between the regions R1 and R2. Indeed, since neither solution is admissible, the profit function in the region R1 will be monotonously increasing in the region R1 - hence the maximum falls upon the region's upper limit -, while the profit function in the region R2 will be monotonously decreasing - hence the maximum falls upon the region's lower limit.

[9] The profit function used to compute the final profit is the one relative to the region R1 since the frontier is included in such region.

α comprehends Business Unit A, responsible for producing product A, and Business Unit B, responsible for producing product B. In particular, Business Unit B becomes an internal customer of Business Unit A, within the boundaries of Company α. The emerging costs of IS, i.e., the waste treatment costs.[10] are fairly shared among the two business units according to the respective Shapley values.[11] Company α and Company β are assumed to play a Cournot game to define the optimal production quantities of product B.

Let us define x_B^α and x_B^β the amounts of product B realized by Company α and Company β, respectively. The optimal production quantity of product A produced by Company α is defined in two stages through backward induction.

In the **first stage**, Company α and Company β play *à la* Cournot in market B and Company α anticipates its own internal waste demand. In the **second stage**, Company α maximizes the profit in market A.

The Cournot game played by Company α and Company β is reported in Eq. (12), while the profit maximization in market A is defined in Eq. (13).

$$\begin{cases} max_{x_B^\alpha}\,\Pi_B^\alpha(NPD, x_B^\alpha, x_B^\beta) = & x_B^\alpha \cdot [a_B - b_B \cdot (x_B^\alpha + x_B^\beta) - W_B \cdot dc_B] + \\ & - SV_B^\alpha \cdot min\{W_A \cdot x_A^\alpha; \frac{R_B}{s_{AB}} \cdot x_B^\alpha\} + \\ & - pr_B \cdot max\{0; R_B \cdot x_B^\alpha - W_A \cdot s_{AB} \cdot x_A^\alpha\} + \\ & - dc_A \cdot max\{0; W_A \cdot x_A^\alpha - \frac{R_B}{s_{AB}} \cdot x_B^\alpha\} - I \\ \\ max_{x_B^\beta}\,\Pi_B^\beta(NPD, x_B^\alpha, x_B^\beta) = & x_B^\beta \cdot [a_B - b_B \cdot (x_B^\alpha + x_B^\beta) - R_B \cdot pr_B + \\ & - W_B \cdot dc_B] \end{cases} \tag{12}$$

$$max_{x_A^\alpha}\,\Pi_A^\alpha(NPD, x_A^\alpha) = x_A^\alpha \cdot (a_A - b_A \cdot x_A^\alpha - R_A \cdot pr_A) + \\ - SV_A^\alpha \cdot min\{W_A \cdot x_A^\alpha; \frac{R_B}{s_{AB}} \cdot x_B^\alpha\} - dc_A \cdot max\{0; W_A \cdot x_A^\alpha - \frac{R_B}{s_{AB}} \cdot x_B^\alpha\} \tag{13}$$

Similarly to the EE strategy, to solve the problem in closed form, the profit function of Company α has to be redefined, depending on the match between internal waste demand and supply.

Let us define R1NPD and R2NPD the domain regions of the profit function reported in Eq. (13) such that the constraints $W_A \cdot x_A^\alpha \le \frac{R_B}{s_{AB}} \cdot x_B^\alpha$ (Constraint R1NPD) and $W_A \cdot x_A^\alpha > \frac{R_B}{s_{AB}} \cdot x_B^\alpha$ (Constraint R2NPD) are satisfied, respectively.

If the waste supply is lower than or equal to the internal waste demand (i.e., Constraint R1NPD is satisfied), Company α does not dispose of any unit of waste in the landfill. However, it may need to purchase additional amounts of primary input from traditional suppliers to produce the optimal production quantity of product B.

The Cournot game of Eq. (12) can be simplified (see Appendix A.3 Eq. (30)) to derive the optimal production quantities of product B (Eq. (14)).

$$\begin{cases} x_B^{\alpha^*}(R1NPD) = \frac{a_B - R_B \cdot pr_B - W_B \cdot dc_B}{3b_B} \\ x_B^{\beta^*}(R1NPD) = \frac{a_B - R_B \cdot pr_B - W_B \cdot dc_B}{3b_B} \end{cases} \tag{14}$$

Similarly, the profit maximization problem in market A of Eq. (13) can be simplified (see Appendix A.3 Eq. (31)) to derive the optimal production quantity of product A (Eq. (15)).

$$x_A^{\alpha^*}(R1NPD) = \frac{2a_A - 2R_A \cdot pr_A - W_A \cdot (ct_1 + dc_A - s_{AB} \cdot pr_B)}{4b_A} \tag{15}$$

If the waste supply is higher than the internal waste demand (i.e., Constraint R2NPD is satisfied), Company α has exceeding waste from the production process of product B to dispose of in the landfill.

The Cournot game of Eq. (12) can be simplified (see Appendix A.3 Eq. (32)) to define the optimal production quantities of product B (Eq. (16))

$$\begin{cases} x_B^{\alpha^*}(R2NPD) = \frac{R_B \cdot (dc_A - ct_1) + s_{AB} \cdot (a_B - W_B \cdot dc_B)}{3b_B \cdot s_{AB}} \\ x_B^{\beta^*}(R2NPD) = \frac{R_B \cdot (ct_1 - dc_A - 3pr_B \cdot s_{AB}) + 2s_{AB} \cdot (a_B - W_B \cdot dc_B)}{6b_B \cdot s_{AB}} \end{cases} \tag{16}$$

The profit maximization problem in market A of Eq. (13) can be simplified (see Appendix A.3 Eq. (33)) and the optimal production quantity of product A can be defined as in Eq. (17).

$$x_A^{\alpha^*}(R2NPD) = \frac{a_A - R_A \cdot pr_A - W_A \cdot dc_A}{2b_A} \tag{17}$$

Problem Solution

The optimal production quantities of product A of Eqs. (15) and (17) are admissible if Constraint R1NPD and Constraint R2NPD are satisfied, respectively. Being the profit function concave under the linearity assumption of demand and cost functions, it is possible to derive that:

- if Constraint R1NPD is satisfied and Constraint R2NPD is not satisfied, the optimal production quantity of product A is $x_A^{\alpha^*}(R1NPD)$, and Company α yields a profit equal to $\Pi_{AB}^\alpha = \Pi_A^\alpha(R1NPD, x_A^{\alpha^*}(R1NPD)) + \Pi_B^\alpha(R1NPD, x_B^{\alpha^*}(R1NPD), x_B^{\beta^*}(R1NPD))$.
- if Constraint R2NPD is satisfied and Constraint R1NPD is not satisfied, the optimal production quantity of product A is $x_A^{\alpha^*}(R2NPD)$, and Company α yields a profit equal to $\Pi_{AB}^\alpha = \Pi_A^\alpha(R2NPD, x_A^{\alpha^*}(R2NPD)) + \Pi_B^\alpha(R2NPD, x_B^{\alpha^*}(R2NPD), x_B^{\beta^*}(R2NPD))$.
- if neither Constraint R1NPD nor Constraint R2NPD are satisfied, the optimal production quantity of product A is $\frac{x_B^{\alpha^*}(R2NPD) \cdot R_B}{W_A \cdot s_{AB}}$, and Company α yields a profit equal to $\Pi_{AB}^\alpha = \Pi_A^\alpha(R1NPD, \frac{x_B^{\alpha^*}(R2NPD) \cdot R_B}{W_A \cdot s_{AB}}) + \Pi_B^\alpha(R2NPD, x_B^{\alpha^*}(R2NPD), x_B^{\beta^*}(R2NPD))$.[12]
- if both Constraint R1NPD and Constraint R2NPD are satisfied, the optimal production quantity of product A is $argmax\{\Pi_{AB}^{\alpha^*}\}$, where $\Pi_{AB}^{\alpha^*}$ is the optimal profit, and it such that $\Pi_{AB}^{\alpha^*} = max\{\Pi_A^\alpha(R1NPD, x_A^{\alpha^*}(R1NPD)) + \Pi_B^\alpha(R1NPD, x_B^{\alpha^*}(R1NPD), x_B^{\beta^*}(R1NPD)); \Pi_A^\alpha(R2NPD, x_B^{\alpha^*}(R2NPD)) + \Pi_B^\alpha(R2NPD, x_B^{\alpha^*}(R2NPD), x_B^{\beta^*}(R2NPD))\}$.[13]

2.2.3. Hybrid strategy

Problem Description

Whether Company α has decided for the competitive approach and the waste supply is higher than the internal waste demand required for the new product development (i.e., Constraint R2NPD is satisfied), Company α can decide to sell the exceeding waste to Company β, i.e., its competitor, at a price $pr_B - \varepsilon$.[14] A new feasible strategy comes up:

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[10] In this scenario waste transportation costs do not arise since the waste remains within Company α's boundary.

[11] For the computations see Appendix A.3 Eqs. (26) and (27).

[12] Here, the optimal production quantity of product A is such that the generated waste amount is exactly equal to the internal waste demand for product B. The optimal production quantities of product B are those evaluated in region R2NPD. Indeed, the marginal cost for the business unit B of Company α should account for SV_B^α, which happens in R2NPD, while in region R1NPD the marginal cost accounts for pr_B. However, the correct profit function for the business unit A of Company α is that of R1NPD, since the marginal cost should account for SV_A^α and not for dc_A, as no waste is disposed of.

[13] This scenario is feasible whether $x_B^{\alpha^*}(R2NPD) > x_B^{\alpha^*}(R1NPD)$, which might happen if $SV_B^\alpha < 0$. Indeed, the condition $x_A^{\alpha^*}(R1NPD) > x_A^{\alpha^*}(R1NPD)$ is always verified, as it implies $SV_A^\alpha < dc_A$. The latter is true if $ct_1 < ct_1 + ct_2 < dc_A + s_{AB} \cdot pr_B$, which is verified if IS is feasible.

[14] The highest possible price, but still convenient for Company β, which reduces its unit production costs by ε.

namely the HY strategy, in which, besides the NPD, also an EE with Company β is implemented. In the cooperative scenario of EE, the benefits from IS are fairly shared between Company α and Company β; conversely, in this case Company α aims at appropriating the benefits from the ISR as much as possible.

Even in this latter strategic approach, the optimal production quantities of both product B and product A to be produced by Company α are defined through backward induction.

As in the NPD scenario, in the **first stage**, Company α anticipates both the internal and the external demand of waste by solving the Cournot game with Company β. In the **second stage,** Company α maximizes the profit in market A. Note that the Cournot game played in market B (see Appendix A.3 Eq. (32)) and the profit maximization problem in market A (see Appendix A.3 Eq. (33)) have to be rewritten to take into account the new flows of waste and revenues between Company α and Company β, as shown in Eqs. (18) and (19), respectively. Indeed, Company β can benefit from a reduction in the input purchase costs, as long as Company α can sell exceeding waste; conversely, Company α's Business Unit B has a reduced advantage in market B because of the reduced gap in the production costs with its competitor. Nonetheless, a novel revenue flow can be grasped by Business Unit A from the sale of the waste.

$$\begin{cases} max_{x_B^\alpha}\, \Pi_B^\alpha(HY, x_B^\alpha, x_B^\beta) = & x_B^\alpha \cdot [a_B - b_B \cdot (x_B^\alpha + x_B^\beta) - \frac{R_B}{s_{AB}} \cdot SV_B^\alpha + \\ & -W_B \cdot dc_B] - I \\ max_{x_B^\beta}\, \Pi_B^\beta(HY, x_B^\alpha, x_B^\beta) = & x_B^\beta \cdot [a_B - b_B \cdot (x_B^\alpha + x_B^\beta) - W_B \cdot dc_B] + \\ & -(pr_B - \varepsilon) \cdot min\{\frac{R_B}{S_{AB}} \cdot x_B^\beta; W_A \cdot x_A^\alpha + \\ & - \frac{R_B}{s_{AB}} \cdot x_B^\alpha\} - pr_B \cdot max\{0; R_B \cdot x_B^\beta + \\ & -W_A \cdot s_{AB} \cdot x_A^\alpha + R_B \cdot x_B^\alpha\} \end{cases} \tag{18}$$

$$max_{x_A^\alpha}\, \Pi_A^\alpha(HY, x_A^\alpha) = x_A^\alpha \cdot (a_A - b_A \cdot x_A^\alpha - R_A \cdot pr_A) + (pr_B - \varepsilon - ct_1 + \\ - ct_2) \cdot min\{W_A \cdot x_A^\alpha - \frac{R_B}{s_{AB}} \cdot x_B^\alpha; \frac{R_B}{s_{AB}} \cdot x_B^\beta\} - SV_A^\alpha \cdot \frac{R_B}{s_{AB}} \cdot x_B^\alpha + \\ - dc_A \cdot max\{0; W_A \cdot x_A^\alpha - \frac{R_B}{s_{AB}} \cdot (x_B^\alpha + x_B^\beta)\} \tag{19}$$

To solve the problem in closed form the profit function of Company α has to be redefined depending on the match between the waste supply and the sum of internal and external waste demand.

Let us define R1HY and R2HY the domain regions of the profit function reported in Eq. (19) such that the constraints $W_A \cdot x_A^\alpha - \frac{R_B}{s_{AB}} \cdot x_B^\alpha \le \frac{R_B}{s_{AB}} \cdot x_B^\beta$ (Constraint R1HY) and $W_A \cdot x_A^\alpha - \frac{R_B}{s_{AB}} \cdot x_B^\alpha > \frac{R_B}{s_{AB}} \cdot x_B^\beta$ (Constraint R2HY) are satisfied, respectively.

If the exceeding waste from Business Unit B's production is lower than or equal to the external waste demand (i.e., Constraint R1HY is satisfied), Company α does not dispose of any unit of waste in the landfill: all the exceeding waste is sent to Company β. Conversely, Company β needs to purchase additional amounts of primary input from traditional suppliers.

The Cournot game of Eq. (18) can be redefined (see Appendix A.3 Eq. (34)), and, accordingly, the optimal production quantities of product B can be computed (Eq. (20)).

$$\begin{cases} x_B^{\alpha^*}(R1HY) = \frac{R_B \cdot (dc_A - ct_1) + s_{AB} \cdot (a_B - W_B \cdot dc_B)}{3b_B \cdot s_{AB}} = x_B^{\alpha^*}(R2NPD) \\ x_B^{\beta^*}(R1HY) = \frac{R_B \cdot (ct_1 - dc_A - 3pr_B \cdot s_{AB}) + 2s_{AB} \cdot (a_B - W_B \cdot dc_B)}{6b_B \cdot s_{AB}} = x_B^{\beta^*}(R2NPD) \end{cases} \tag{20}$$

Company α's profit maximization problem in market A can be simplified (see Appendix A.3 Eq. (36)) and the optimal production quantity for product A can be defined as in Eq. (21).

$$x_A^{\alpha^*}(R1HY) = \frac{a_A - R_A \cdot pr_A - W_A \cdot (ct_1 + ct_2 + \varepsilon - pr_B)}{2b_A} \tag{21}$$

If the exceeding waste from Business Unit B's production is higher than the external waste demand (i.e., Constraint R2HY is satisfied), Company β can replace the overall amount of input required with the waste produced by Company α; Company α has to dispose of exceeding waste in the landfill.

The Cournot game of Eq. (18) can be simplified (see Appendix A.3 Eq. (37)) to define the optimal production quantities of product B (Eq. (22)).

$$\begin{cases} x_B^{\alpha^*}(R2HY) = \frac{s_{AB} \cdot (a_B - W_B \cdot dc_B) - R_B \cdot [ct_1 - dc_A + \varepsilon + pr_B \cdot (s_{AB} - 1)]}{3b_B \cdot s_{AB}} \\ x_B^{\beta^*}(R2HY) = \frac{2s_{AB} \cdot (a_B - W_B \cdot dc_B) + R_B \cdot [ct_1 - dc_A + 4\varepsilon + pr_B \cdot (s_{AB} - 4)]}{6b_B \cdot s_{AB}} \end{cases} \tag{22}$$

Accordingly, Company α's profit maximization problem in market A can be redefined (see Appendix A.3 Eq. (38)) and the optimal production quantity of product A can be computed (Eq. (23)).

$$x_A^{\alpha^*}(R2HY) = \frac{a_A - R_A \cdot pr_A - W_A \cdot dc_A}{2b_A} \tag{23}$$

Problem Solution

The optimal production quantities of product A of Eqs. (21) and (23) are admissible if Constraint R1HY and Constraint R2HY are satisfied, respectively. Being the profit function concave under the linearity assumption of demand and cost functions, it is possible to derive that:

- if Constraint R1HY is satisfied and Constraint R2HY is not satisfied, the optimal production quantity of product A is $x_A^{\alpha^*}(R1HY)$, and Company α yields a profit equal to $\Pi_{AB}^\alpha = \Pi_A^\alpha(R1HY, x_A^{\alpha^*}(R1HY)) + +\Pi_B^\alpha(R1HY, x_B^{\alpha^*}(R1HY), x_B^{\beta^*}(R1HY))$
- if Constraint R2HY is satisfied and Constraint R1HY is not satisfied, the optimal production quantity of product A is $x_A^{\alpha^*}(R2HY)$, and Company α yields a profit equal to $\Pi_{AB}^\alpha = \Pi_A^\alpha(R2HY, x_A^{\alpha^*}(R2HY)) + +\Pi_B^\alpha(R2HY, x_B^{\alpha^*}(R2HY), x_B^{\beta^*}(R2HY))$
- if neither Constraint R1HY nor Constraint R2HY are satisfied, the optimal production quantity of product A is $\frac{(x_B^{\alpha^*}(R2HY) + x_B^{\beta^*}(R2HY)) \cdot R_B}{W_A \cdot s_{AB}}$, and Company α yields a profit equal to $\Pi_{AB}^\alpha = \Pi_A^\alpha(R1HY, \frac{(x_B^{\alpha^*}(R2HY) + x_B^{\beta^*}(R2HY)) \cdot R_B}{W_A \cdot s_{AB}}) + \Pi_B^\alpha(R2HY, x_B^{\alpha^*}(R2HY), x_B^{\beta^*}(R2HY))$.[15]
- if both Constraint R1HY and Constraint R2HY are satisfied, the optimal production quantity of product A is $argmax\{\Pi_{AB}^{\alpha^*}\}$, where $\Pi_{AB}^{\alpha^*}$ is the optimal profit, and it such that $\Pi_{AB}^{\alpha^*} = max\{\Pi_A^\alpha(R1HY x_A^{\alpha^*}(R1HY)) + \Pi_B^\alpha(R1HY, x_B^{\alpha^*}(R1HY), x_B^{\beta^*}(R1HY)); \Pi_A^\alpha(R2HY, x_B^{\alpha^*}(R2HY)) + \Pi_B^\alpha(R2HY, x_B^{\alpha^*}(R2HY), x_B^{\beta^*}(R2HY))\}$.[16]

Table 3 displays the values of the optimal production quantities and the profits of Company α under the three investigated strategies for IS.

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[15] Here, the optimal production quantity of product A is such that the generated waste amount is exactly equal to the overall internal and external waste demand for product B. The optimal production quantities of product B are those of region R2HY. Indeed, the marginal cost of Company β should account for $pr_B - \varepsilon$, which happens in region R2HY. However, the correct profit function for the business unit A of Company α is that of R1HY, since the marginal cost should account for $(ct_1 + ct_2 - pr_B + \varepsilon)$, and not for dc_A, as no waste is disposed of.

[16] This scenario is feasible since the total amount of B produced by Company α and Company β in region R2HY can be higher than in region R1HY. Indeed, x_B^β surely increases as a result of reduced marginal costs, while x_B^α decreases only if $pr_B \cdot (s_{AB} - 1) + \varepsilon > 0$. On the other hand, x_A^α in R2HY is lower than x_A^α in R1HY only if $ct_1 + ct_2 + \varepsilon < pr_B + dc_A$, which might be true if $s_{AB} > 1$.

Table 3
Optimal production quantities and profit (of each business unit) for Company α under the three potential strategies to be adopted (i.e., external exchange, new product development, and hybrid strategy).

Var	Supply $\leq$ Demand	Supply $>$ Demand
	External Exchange Strategy	
$\mathbf{x}_{\mathbf{A}}^{\alpha^*}$	$\frac{2a_A - 2R_A \cdot pr_A - W_A \cdot (ct1 + ct_2 + dc_A - pr_B \cdot s_{AB})}{4b_A}$	$\frac{a_A - R_A \cdot pr_A - W_A \cdot dc_A}{2b_A}$
$\mathbf{\Pi}_{\mathbf{A}}^{\alpha^*}$	$x_A^\alpha \cdot [(a_A - b_A \cdot x_A^\alpha) - R_A \cdot pr_A - SV_A^\alpha \cdot W_A] - t^\alpha$	$x_A^\alpha \cdot (a_A - b_A \cdot x_A^\alpha - R_A \cdot pr_A)+$ $-dc_A \cdot (W_A \cdot x_A^\alpha - \frac{R_B}{s_{AB}} \cdot x_B^\beta) - \frac{R_B}{s_{AB}} \cdot SV_A^\alpha \cdot x_B^\beta - t_\alpha$
	New Product Development Strategy	
$\mathbf{x}_{\mathbf{A}}^{\alpha^*}$	$\frac{a_B - R_B \cdot pr_B - W_B \cdot dc_B}{3b_B}$	$\frac{R_B \cdot (dc_A - ct_1) + s_{AB} \cdot (a_B - W_B \cdot dc_B)}{3b_B \cdot s_{AB}}$
$\mathbf{\Pi}_{\mathbf{A}}^{\alpha^*}$	$x_A^\alpha \cdot (a_A - b_A \cdot x_A^\alpha - R_A \cdot pr_A - W_A \cdot SV_A^\alpha)$	$x_A^\alpha \cdot (a_A - b_A \cdot x_A^\alpha - R_A \cdot pr_A)+$ $-dc_A \cdot (W_A \cdot x_A^\alpha - \frac{R_B}{s_{AB}} \cdot x_B^\alpha) - \frac{R_B}{s_{AB}} \cdot SV_A^\alpha \cdot x_B^\alpha$
$\mathbf{\Pi}_{\mathbf{B}}^{\alpha^*}$	$x_B^\alpha \cdot [a_B - b_B \cdot (x_B^\alpha + x_B^\beta) - W_B \cdot dc_B]+$ $-SV_B^\alpha \cdot W_A \cdot x_A^\alpha - pr_B \cdot (R_B \cdot x_B^\alpha - W_A \cdot s_{AB} \cdot x_A^\alpha) - I$	$x_B^\alpha \cdot [a_B - b_B \cdot (x_B^\alpha + x_B^\beta) - \frac{R_B}{s_{AB}} \cdot SV_B^\alpha - W_B \cdot dc_B] - I$
	Hybrid Strategy	
$\mathbf{x}_{\mathbf{A}}^{\alpha^*}$	$\frac{R_B \cdot (dc_A - ct_1) + s_{AB} \cdot (a_B - W_B \cdot dc_B)}{3b_B \cdot s_{AB}}$	$\frac{s_{AB} \cdot (a_B - W_B \cdot dc_B) - R_B \cdot [ct_1 - dc_A + \varepsilon + pr_B \cdot (s_{AB} - 1)]}{3b_B \cdot s_{AB}}$
$\mathbf{\Pi}_{\mathbf{A}}^{\alpha^*}$	$x_A^\alpha \cdot (a_A - b_A \cdot x_A^\alpha - R_A \cdot pr_A)+$ $+(pr_B - \varepsilon - ct_1 - ct_2) \cdot (W_A \cdot x_A^\alpha - \frac{R_B}{s_{AB}} \cdot x_B^\alpha)+$ $-SV_A^\alpha \cdot x_B^\alpha \cdot \frac{R_B}{s_{AB}}$	$x_A^\alpha \cdot (a_A - b_A \cdot x_A^\alpha - R_A \cdot pr_A)+$ $+(pr_B - \varepsilon - ct_1 - ct_2) \cdot \frac{R_B}{s_{AB}} \cdot x_B^\beta+$ $-dc_A \cdot [W_A \cdot x_A^\alpha - \frac{R_B}{s_{AB}} \cdot (x_B^\alpha + x_B^\beta)] - \frac{R_B}{s_{AB}} \cdot SV^\alpha \cdot x_B^\alpha$
$\mathbf{\Pi}_{\mathbf{B}}^{\alpha^*}$	$x_B^\alpha \cdot [a_B - b_B \cdot (x_B^\alpha + x_B^\beta) - \frac{R_B}{s_{AB}} \cdot SV_B^\alpha - W_B \cdot dc_B] - I$	$x_B^\alpha \cdot [a_B - b_B \cdot (x_B^\alpha + x_B^\beta) - \frac{R_B}{s_{AB}} \cdot SV_B^\alpha - W_B \cdot dc_B] - I$

3. Simulations: which factors do mostly affect the company profit?

The above-presented model has been analyzed through a simulation developed with MATLAB, with the aim to quantitatively assess the impact of the following variables on the profit of Company α:

1. a_B: maximum willingness to pay for product B;
2. b_B: inverse of the demand elasticity for product B;
3. ct_1: unit waste treatment cost;
4. ct_2: unit waste transportation cost;
5. pr_B: unit input purchase cost for product B;
6. I: investment required to enter market B;

In particular, 117649 scenarios have been analyzed by combining seven levels for each investigated variable (see Table 5).

For the sake of simplicity, all the technical coefficients have been imposed equal to one. The maximum willingness to pay for product A, i.e., a_A, has been chosen equal to 100, while the transaction costs are equal to 10 for both Company α and Company β. For each scenario, it has been primarily assessed whether IS was feasible (Eq. (5)), and then the optimal production quantities and the profits have been computed in the cases of EE, NPD, and HY strategy — if this last one was admissible. IS was found to be economically feasible in 48707 out of 117649 scenarios. A regression on the profit of Company α with respect to the variables object of analysis has been conducted for each strategy (Table 4). In the following, the results of the regression will be discussed from the analytical and managerial perspectives.

3.1. Willingness to pay and market size

The results of the regressions suggest that the profit of Company α is significantly and positively affected by the willingness of consumers to pay for product B (a_B) and by the size of market B($\frac{1}{b_B}$),[17] whatever the strategy adopted. Nevertheless, the impact of these factors on the NPD and the HY strategies is stronger than the impact in the case of the EE strategy. This is justified by the possibility for Company α to directly gain higher revenues in market B whether deciding to enter such a market, i.e., adopting the NPD or HY strategies. Indeed, if the EE strategy is adopted, these factors only exert an indirect effect, as a higher willingness to pay for product B and a greater size of market B increase the external waste demand, i.e., reduce the amount of eventual exceeding waste to be disposed of in the landfill. From the managerial perspective, this result is worth noting: if a company's waste or by-product can be turned into a high value product (e.g., business bags, as in the case of Kazmok®[18]), or into a product for which a large demand exists (e.g., toilet paper, as in the case of Guitang Group, or more generally a commodity), then it is important to take into account the possibility to exploit the waste in-house rather than give it away.

Table 4
Regression on the profit for each strategy.

Variable	External exchange	New product development	Hybrid strategy
a_B	0,063 ***	130,070 ***	11,322 ***
b_B	−5,866 ***	−6313,531 ***	−121,699 ***
ct_1	−16,689 ***	−51,613	−25,320 ***
ct_2	−16,689***	–	−9,562 ***
pr_B	16,493 ***	−35,838	16,693 ***
I	–	−1 ***	−1 ***
$\mathbf{R^2}$	0,718	0,4627	0,982

Legend: *** = p-value $< 0,001$; ** = p-value $< 0,05$; * = p-value $=< 0,1$.

3.2. Additional costs of industrial symbiosis

The unit waste treatment (ct_1) and transportation costs (ct_2) exert equal, significant, and negative effects on the profit of Company α whether adopting the EE strategy. Indeed, both these factors represent

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[17] The analysis shows a negative correlation with the inverse of the demand elasticity, hence a positive correlation with the demand elasticity. Note that a higher elasticity of the demand implies a greater dimension of the market, being equal all the other conditions.

[18] https://www.kazmok.com/KAZMOK-BUSINESS-briefcase-and-laptop-bags?ProductCategory=15018772&Lng=en.

equal weighting costs for Company α when implementing the EE. Similarly, a negative effect in increasing such costs exists in the case of the HY strategy adoption. Notice that the negative impact of ct_1 is higher in the case of HY strategy rather than in the case of EE, where this cost is shared with Company β. Conversely, the impact of ct_2 is lower in the case of HY strategy, even if the cost is still entirely sustained by Company α. Indeed, only exceeding waste from internal production is delivered to Company β, thus the transportation cost is paid only for a limited amount of waste. In the NPD strategy, ct_2 is not even a cost sustained by Company α — thus it has been excluded from the regression. Conversely, ct_1 results to be non-significant in the case of NPD strategy, which is surprising, as it certainly represents a cost to be incurred. This result might be due to the different effects that ct_1 exerts in regions R1NPD — where ct_1 does not come up in the marginal cost of production, hence it results to be not significant even in the *ad hoc* regression (see Table 6)[19] – and R2NPD – where ct_1 comes up in the marginal cost of production, hence is significant in the *ad hoc* regression. Ultimately, additional costs of IS should be carefully taken into account: if the expense of waste processing is substantial, it is reasonable to surmise that cost-sharing arrangements may be more advantageous, unless the cost of transporting the waste to the partner's facility outweighs this benefit. However, it is important for managers to recognize that the evaluation of the treatment cost of waste might be tricky. Indeed, the analysis shows that the effect of this cost on profits strongly depends on the match between demand and supply: a proper analysis of the expected amount of available waste should be conducted before evaluating the impact of the treatment cost — readers interested to deepen the role of the match between demand and supply for IS are referred to the (non-exhaustive list of) following papers: Herczeg et al. (2018), Fraccascia (2019), Madsen et al. (2015), Bansal and McKnight (2009), Yazan and Fraccascia (2020).

3.3. Input purchase cost

Similar effects to those relative to the waste treatment cost can be found when analyzing the input purchase cost (pr_B). Indeed, when adopting the NPD strategy in the region R1NPD, pr_B exerts both a positive effect (i.e., increases the competitive advantage over Company β) and a negative effect (i.e., increases the cost for purchasing additional inputs from the traditional suppliers) on the profit of Company α. Conversely, in the region R2NPD, the effect of pr_B on the profit of Company α is only positive (i.e., increases the competitive advantage over Company β). These counter-acting effects result in the non-significance of the regression's coefficient for this variable when considering the NPD strategy in its complex, but splitting the analysis between the two regions R1NPD and R2NPD, the positive effect of pr_B in the region R2NPD of the NPD results to be significant (see Table 6). On the other hand, both in the case of EE and HY strategy adoption, pr_B exerts a positive effect on the profit of Company α. Indeed, in the case of EE, increasing pr_B reduces the share of emerging costs for Company α to pay, which is a direct effect of the adoption of the Shapley Values as cost-sharing mechanism between Company α and Company β. Nonetheless, if adopting the HY strategy, other than enhancing the competitive advantage of Company α in the duopoly, increasing pr_B increases the price that Company α can impose on Company β for buying the waste. From the managerial perspective, a higher purchase cost for that input that the available waste can replace is always a good news, since it increases the value of the waste. However, even in this case, the model suggests that managers should carefully reason on the available quantities of waste before choosing how to exploit the competitive advantage provided by pr_B.

3.4. Investment

The effect of the investment was only analyzed in the case of NPD and HY strategies, as it is not sustained by Company α in the case of adopting the EE strategy. The extent of the investment required to enter market B significantly and negatively affects the profit of Company α in both the strategies considered. A proper cost analysis should be conducted to assess the entity of the total investment required: managers should take into account not only the actual investment for building a new production line, a new plant or whatever is physically needed, but also the cost of promoting the novel business both outside and inside the company's boundaries and acquiring adequate technical skills, which might be not present yet inside the company. Finally, but still vital, managers should be in charge of integrating the new business unit with the core business of the company, fighting resistance to change and redesigning organizational routines — readers interested to deepen the organizational and social barriers hampering the adoption of IS are referred to the (non-exhaustive list of) following papers: Fichtner et al. (2005), Golev et al. (2015), Tudor et al. (2007), Hewes and Lyons (2008), Walls and Paquin (2015).

4. Implications: which factors do mostly affect the company's strategic choices?

Other than showing which is the effect – in absolute terms – of the specific set of investigated variables on the profit, the results of the simulation described in Section 3 allows to derive which factors play a major role in the strategic decision-making process of a waste producer approaching IS. In the following, the results of the analysis will be discussed both from the managerial and the policy perspectives.

4.1. Managerial insights

Let us assume that a company generates a waste that can be used to replace a primary input in a given production process cost effectively: this company is interested in implementing IS. Given the three available strategic options, to exploit the waste at best such a company should decide firstly which strategy is optimal in the case of competition, i.e., NPD or HY strategy, and then, by backward reasoning, whether to compete (by adopting the optimal competitive strategy) or to cooperate. In the following, we will assess (1) when the company should decide to adopt the HY strategy if the waste supply exceeds the amount demanded for the NPD, and (2) when the company should decide for the competitive approach, i.e., the more convenient between the NPD and the HY strategy, rather than for the cooperative one, i.e., the EE strategy.

4.1.1. New product development VS hybrid strategy

From the results of the theoretical model, it is possible to derive that implementing the HY strategy is convenient for a waste producer if the savings from not disposing of the exceeding waste and the profits from selling it are higher than the loss of profits in the newly entered market. Indeed, the profits gained from the sale of the new developed product can be reduced by implementing the HY strategy, as the provision of the waste to a competitor at a reduced price (compared to the primary input purchase cost) decreases the competitive advantage achieved by the company through IS.

In all the 28154 simulation scenarios where the HY strategy was feasible, it was also more convenient than the NPD one. While it is not possible to assess that the HY strategy always dominates the implementation of the NPD alone if there is an excess of waste supply (see Appendix A.5 in the Appendix), it appears that none of the investigated variables plays a major role in this strategic choice. Indeed, the difference between the average profit yielded by the company with the two strategies is not substantial in our simulation (such difference impacts for about 1%–2% of the average total profit in the case of HY

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[19] To further understand the results of the regression reported in Table 4 relative to the NPD, an *ad hoc* regression on the profit in case of NPD in the regions R1 and R2 separately was performed.

strategy). Moreover, such a profit gap does not vary significantly when the investigated variables change. Nevertheless, increasing the waste treatment and transportation costs slightly reduces the convenience of the HY strategy, while increasing the purchase cost of the primary input replaced by the waste slightly increases the HY strategy preferability, *ceteris paribus*. The extent of the investment, which should be sustained either way, is irrelevant, while the size of the market and the willingness to pay for the newly developed product positively impact the HY strategy.

Ultimately, if the difference in profits is not so significant, managers should consider other drivers besides profit maximization to decide whether selling eventual exceeding waste to competitors. For example, higher environmental concerns steer to minimizing waste landfilling, while increased managerial complexity or distrust in the competitor may push the strategic decision toward keeping the waste inside the company's boundaries.

4.1.2. Cooperation VS competition

When a company approaching IS has to decide whether to cooperate or to compete, three variables result in having a major impact. A key role is played by the characteristics of market where to enter: increasing the consumers' willingness to pay for the newly developed product and the demand elasticity[20] boosts the profits that can be gained by entering such a market and makes the competitive approach more convenient (see Fig. 4(a) and Fig. 4(b)). Conversely, the higher the investment required to enter the market, the lower the convenience of adopting a competitive approach will be (see Fig. 4(c)). The additional costs of implementing IS and the purchase cost of the input that can be replaced through IS appear to have a minor role in influencing the optimal strategic choice between cooperation and competition.

Ultimately, the strategic choice of managers may be primarily guided by the characteristics of the market where to enter and by the investments required. To enforce this finding a logistic binary regression was also conducted (see Table 7), where the strategic convenience of the competitive approach over the cooperative one has been analyzed. The regression took as input a binary variable equal to one whether the profits gained by implementing the competitive approach were higher than those gained in case of implementing the cooperative one; zero otherwise. Results are consistent with the previous discussion.[21]

4.2. Policy implications

The developed analysis allows to provide insights not only for managers but also for policymakers. Governments are making efforts to promote the widespread of IS (European Commision, 2018; European Commission, 2020), but they lack awareness about which approach to IS they favor with specific policy interventions. For instance, by lowering the waste transportation costs, policymakers push companies toward cooperative strategies, *ceteris paribus*. Conversely, subsidizing investments in new plants and infrastructures, companies are incentivized to pursue a competitive approach. Note that the specific policy adopted may result in different market responses and governments should be well aware of them. Indeed, providing a competitive advantage to companies, i.e., lowering the input purchase cost or the waste disposal cost through a cooperative IS approach, may result in higher optimal production levels, i.e., to the so called rebound effect (Berkhout et al., 2000; Figge and Thorpe, 2019; Zink and Geyer, 2017), thus hampering the environmental advantages of IS. In contrast, promoting competition may be useful to induce the lowering of prices and increase consumers benefits. Hence, policymakers are strongly encouraged to choose carefully both the specific market where they would like to promote IS and the related measures to adopt.

5. Conclusions

This paper aims to define the optimal strategic behavior of a waste producer when deciding between a cooperative and a competitive approach toward IS and contributes (1) to filling a gap in the existing knowledge over IS, and (2) to providing managerial and policy insights on a complex business problem. Indeed, the lack of a framework guiding companies in a proper approach toward IS represents a barrier to its potential widespread. Despite the literature suggesting several business models and related strategies, practitioners focused mainly on a single way of implementing IS, which consists in the cooperation between a waste producer and a waste user, aimed at replacing production inputs with wastes, i.e., the external exchange strategy (EE). Nevertheless, IS can be implemented at the firm level, by exploiting the waste within the firm's boundaries and entering into new markets, i.e., adopting a new product development strategy (NPD), In this paper, a model supported by the EIO and based on a game-theoretical approach has been developed to investigate the optimal choice between cooperation and competition for a waste producer willing to approach IS. The model enables the introduction of a second competitive approach to IS, which consists of a hybrid strategy (HY) between NPD and EE: since the waste producer may not reuse the overall amount of its available waste in the case of NPD, the exceeding waste may be profitably sold to a competitor. The analysis suggests that the characteristics of the market where to enter significantly affect the strategic behavior of the waste producer. In particular, a higher willingness to pay for the newly developed product and a higher market size boost the convenience of the competitive approach, thus suggesting managers who have to deal with (1) high valuable waste or (2) waste that can be turned into products with high demand (e.g., commodities) to carefully consider the idea of exploiting the waste themselves, as the Guitang Group did by starting producing itself paper from sugar waste (e.g., Zhu et al. (2007)). Conversely, the higher the investment required to enter such a market, the lower the advantage of competition will be. Moreover, the analysis highlights that the HY strategy – when feasible – can be more advantageous than the NPD alone, as earnings from selling the waste and savings in disposal costs may offset losses in the market. However, none of the investigated variables appeared to play a major role in determining the optimal choice between NPD and HY, which then may be easily guided by other reasonings rather than profit maximization (for example environmental concerns or increased managerial complexity).

This paper provides several theoretical contributions. Specifically, it enhances the state of the art by shedding light on a complex strategic problem for waste producers willing to adopt IS. It emphasizes the need for further investigations in the strategic decision-making of companies approaching IS to define a comprehensive framework guiding for managers and decision-makers in the transition toward IS. Finally, it introduces a strategic option in the field of IS currently disregarded, i.e., the HY, that opens up novel chances of revenues for firms adopting IS. Despite these advantages, the developed model is not without limitations. First, the model assumes complete information, which may not reflect real-world context. Additionally, it treats the two companies as monopolists in their relative markets, whereas firms involved in IS may operate in various market structures, such as perfect competition or oligopolies. The model assumes the price as the sole decision variable for consumers, neglecting their potential preference for products from sustainable processes. Furthermore, the model considers only a one-to-one interaction between two firms. It would be interesting to examine more complex scenarios involving multiple waste users and/or producers. Future research should address these limitations to develop a robust strategic framework to support managers and decision-makers and to explore the effect of different policy measures on the strategic choices of companies.

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[20] Demand elasticity is related to the market size, as previously discussed, i.e., it is the inverse of b_B.

[21] The variables a_B, b_B and I showed a higher level of significance.

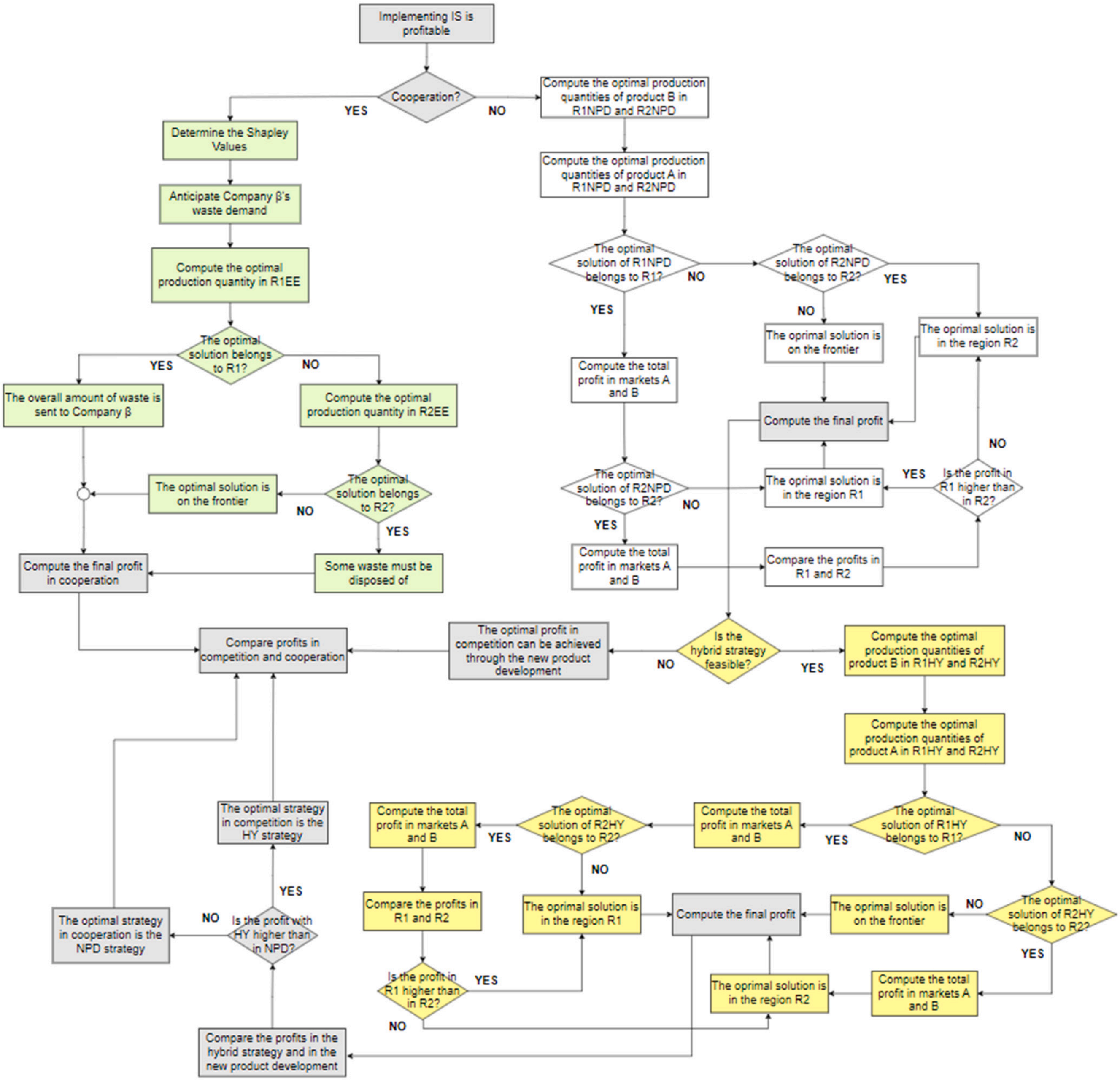

Fig. 3. Extended Model Flowchart.

CRediT authorship contribution statement

Melissa Mollica: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **Luca Fraccascia:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Conceptualization. **Alberto Nastasi:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials. Additional data are available on request from the corresponding author.

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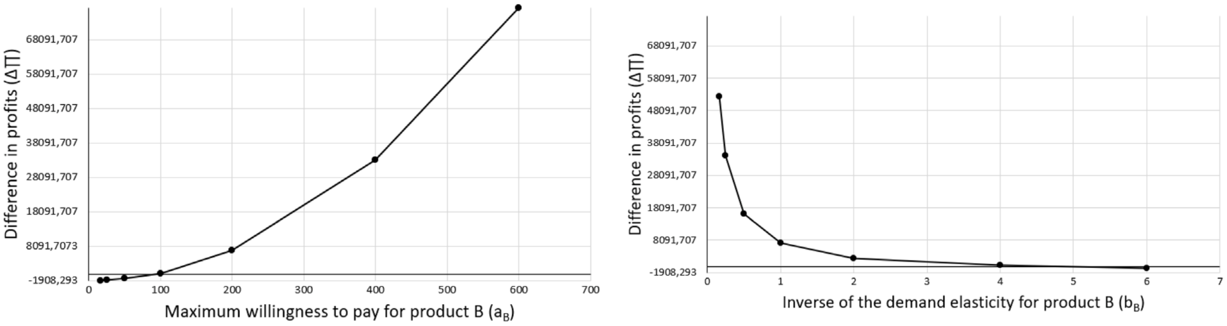
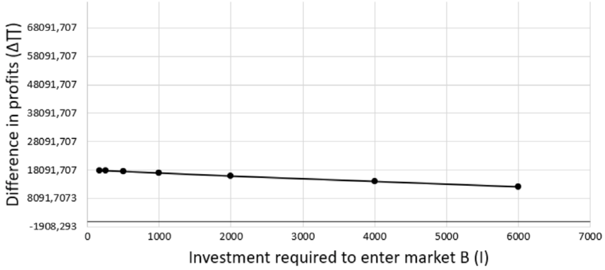


(a) Difference in Company α average profits ($\Pi(competition) - \Pi(cooperation)$), variation of a_B

(b) Difference in Company α average profits ($\Pi(competition) - \Pi(cooperation)$), variation of b_B



(c) Difference in Company α average profits ($\Pi(competition) - \Pi(cooperation)$), variation of I

Fig. 4. Difference in Company α average profits: competition and cooperation.

and Research, CUP B53C22004130001, MICS (Made in Italy - Circular and Sustainable).

Appendix

A.1. Extended flowchart

The extended flowchart of the model is reported in Fig. 3.

A.2. Additional tables and figures

Additional regressions performed by the authors for deeper investigation are reported in Tables 5–7. While Fig. 4 displays the difference in the profits of Company α in the case of competition and cooperation subject to variations of maximum willingness to pay, demand elasticity ad investment extent.

A.3. Additional equations

The Shapley values in the case of EE have been computed as follows:

$$SV_A^{\alpha} = \frac{1}{2} \cdot (ct_1 + ct_2 + dc_A - s_{AB} \cdot pr_B) \tag{24}$$

$$SV_B^{\beta} = \frac{1}{2} \cdot (ct_1 + ct_2 - dc_A + s_{AB} \cdot pr_B) \tag{25}$$

The Shapley values in the case of NPD have been computed as follows:

$$SV_A^{\alpha} = \frac{1}{2} \cdot (ct_1 + dc_A - s_{AB} \cdot pr_B) \tag{26}$$

$$SV_B^{\alpha} = \frac{1}{2} \cdot (ct_1 - dc_A + s_{AB} \cdot pr_B) \tag{27}$$

Table 5
Levels (L_i) per variable.

Variable	L1	L2	L3	L4	L5	L6	L7
a_B	$\frac{100}{6}$	$\frac{100}{4}$	$\frac{100}{2}$	100	$100 \cdot 2$	$100 \cdot 4$	$100 \cdot 6$
b_B	$\frac{1}{6}$	$\frac{1}{4}$	$\frac{1}{2}$	1	$1 \cdot 2$	$1 \cdot 4$	$1 \cdot 6$
ct_1	$\frac{1}{6}$	$\frac{1}{4}$	$\frac{1}{2}$	1	$1 \cdot 2$	$1 \cdot 4$	$1 \cdot 6$
ct_2	$\frac{1}{6}$	$\frac{1}{4}$	$\frac{1}{2}$	1	$1 \cdot 2$	$1 \cdot 4$	$1 \cdot 6$
pr_B	$\frac{1}{6}$	$\frac{1}{4}$	$\frac{1}{2}$	1	$1 \cdot 2$	$1 \cdot 4$	$1 \cdot 6$
I	$\frac{1000}{6}$	$\frac{1000}{4}$	$\frac{1000}{2}$	1000	$1000 \cdot 2$	$1000 \cdot 4$	$1000 \cdot 6$

Table 6
Regression on the profit for the regions R1 and R2 of the NPD.

Variable	R1NPD	R2NPD
a_B	254,438 ***	11,23 ***
b_B	−42803, 9 ***	−117, 318 ***
ct_1	−256, 846	−16, 207***
ct_2	–	–
pr_B	13,151	7,7***
I	−1 ***	−1 ***
R²	0,690	0,981

Legend:
*** = p-value $< 0,001$; ** = p-value $< 0,05$; * = p-value $=< 0,1$.

Table 7
Regression cooperation VS competition.

Variable	Regression coefficients
a_B	0,0016***
b_B	−0,061***
ct_1	−0,0044**
ct_2	0,00008
pr_B	0,00019**
I	$-6{,}2E^{-05}$***
R²	0,56

Legend:
*** = p-value $< 0,001$; ** = p-value $< 0,05$; * = p-value $=< 0,1$.

Table 8
Numerical examples dataset.

Variable	Case 1	Case 2	Case 3
a_A	100	100	100
b_A	1	1	1
pr_A	2	2	2
dc_A	5	5	5
a_B	100	200	50
b_B	1	0,5	2
pr_B	5	5	5
dc_B	2	2	2
R_A	1	1	1
R_B	1	1	1
W_A	1	1	1
W_B	1	1	1
s_{AB}	1	1	1
t_α	10	10	10
t_β	10	10	10
ct_1	1	1	1
ct_2	1	1	1
ε	0,1	0,1	0,1
I	1000	1000	1000

In the following, the simplifications of the profit maximization functions and the Cournot games in each scenario (according to the match between waste supply and demand) for all the investigated strategies will be reported.

External Exchange Strategy:

Profit maximization problem in the region R1EE:

$$max_{x_A^\alpha}\Pi_A^\alpha(R1EE,x_A^\alpha)=x_A^\alpha\cdot[(a_A-b_A\cdot x_A^\alpha)-R_A\cdot pr_A-SV_A^\alpha\cdot W_A]-t^\alpha \tag{28}$$

Profit maximization problem in the region R2EE:

$$\begin{aligned}max_{x_A^\alpha}\Pi_A^\alpha(R2EE,x_A^\alpha)={}&x_A^\alpha\cdot(a_A-b_A\cdot x_A^\alpha-R_A\cdot pr_A)-dc_A\cdot(W_A\cdot x_A^\alpha+\\&-\frac{R_B}{s_{AB}}\cdot x_B^\beta)-\frac{R_B}{s_{AB}}\cdot SV_A^\alpha\cdot x_B^\beta-t^\alpha\end{aligned} \tag{29}$$

New Product Development Strategy:

Cournot game in market B in the region R1NPD:

$$\begin{cases}max_{x_B^\alpha}\Pi_B^\alpha(R1NPD,x_B^\alpha,x_B^\beta)= & x_B^\alpha\cdot[a_B-b_B\cdot(x_B^\alpha+x_B^\beta)-W_B\cdot dc_B]+\\ & -SV_B^\alpha\cdot W_A\cdot x_A^\alpha-pr_B\cdot(R_B\cdot x_B^\alpha+\\ & -W_A\cdot s_{AB}\cdot x_A^\alpha)-I\\ max_{x_B^\beta}\Pi_B^\beta(R1NPD,x_B^\alpha,x_B^\beta)= & x_B^\beta\cdot[a_B-b_B\cdot(x_B^\alpha+x_B^\beta)+\\ & -R_B\cdot pr_B-W_B\cdot dc_B]\end{cases} \tag{30}$$

Profit maximization problem in market A in the region R1NPD:

$$max_{x_A^\alpha}\Pi_A^\alpha(R1NPD,x_A^\alpha)=x_A^\alpha\cdot(a_A-b_A\cdot x_A^\alpha-R_A\cdot pr_A-W_A\cdot SV_A^\alpha) \tag{31}$$

Cournot game in the region R2NPD:

$$\begin{cases}max_{x_B^\alpha}\Pi_B^\alpha(R2NPD,x_B^\alpha,x_B^\beta)= & x_B^\alpha\cdot[a_B-b_B\cdot(x_B^\alpha+x_B^\beta)-\frac{R_B}{s_{AB}}\cdot SV_B^\alpha-W_B\cdot dc_B]-I\\ max_{x_B^\beta}\Pi_B^\beta(R2NPD,x_B^\alpha,x_B^\beta)= & x_B^\beta\cdot[a_B-b_B\cdot(x_B^\alpha+x_B^\beta)-R_B\cdot pr_B-W_B\cdot dc_B]\end{cases} \tag{32}$$

Profit maximization problem in market A in the region R2NPD:

$$\begin{aligned}max_{x_A^\alpha}\Pi_A^\alpha(R2NPD,x_A^\alpha)={}&x_A^\alpha\cdot(a_A-b_A\cdot x_A^\alpha-R_A\cdot pr_A)-dc_A\cdot(W_A\cdot x_A^\alpha+\\&-\frac{R_B}{s_{AB}}\cdot x_B^\alpha)-\frac{R_B}{s_{AB}}\cdot SV_A^\alpha\cdot x_B^\alpha\end{aligned} \tag{33}$$

Hybrid Strategy:

Cournot game in market B in the region R1HY:

$$\begin{cases}max_{x_B^\alpha}\Pi_B^\alpha(R1HY,x_B^\alpha,x_B^\beta)= & x_B^\alpha\cdot[a_B-b_B\cdot(x_B^\alpha+x_B^\beta)+\\ & -\frac{R_B}{s_{AB}}\cdot SV_B^\alpha-W_B\cdot dc_B]-I\\ max_{x_B^\beta}\Pi_B^\beta(R1HY,x_B^\alpha,x_B^\beta)= & x_B^\beta\cdot[a_B-b_B\cdot(x_B^\alpha+x_B^\beta)-W_B\cdot dc_B]+\\ & -(pr_B-\varepsilon)\cdot(W_A\cdot x_A^\alpha-\frac{R_B}{s_{AB}}\cdot x_B^\alpha)+\\ & -pr_B\cdot(R_B\cdot x_B^\beta-W_A\cdot s_{AB}\cdot x_A^\alpha+R_B\cdot x_B^\alpha)\end{cases} \tag{34}$$

Profit maximization problem in market A in the region R1HY:

$$max_{x_A^\alpha}\Pi_A^\alpha(R1HY,x_A^\alpha)=x_A^\alpha\cdot(a_A-b_A\cdot x_A^\alpha-R_A\cdot pr_A)+(pr_B-\varepsilon-ct_1+ \tag{35}$$

$$-ct_2)\cdot(W_A\cdot x_A^\alpha-\frac{R_B}{s_{AB}}\cdot x_B^\alpha)-\frac{R_B}{s_{AB}}\cdot SV_A^\alpha\cdot x_B^\alpha \tag{36}$$

Cournot game in market B in the region R2HY:

$$\begin{cases}max_{x_B^\alpha}\Pi_B^\alpha(R2HY,x_B^\alpha,x_B^\beta)= & x_B^\alpha\cdot[a_B-b_B\cdot(x_B^\alpha+x_B^\beta)+\\ & -\frac{R_B}{s_{AB}}\cdot SV_B^\alpha-W_B\cdot dc_B]-I\\ max_{x_B^\beta}\Pi_B^\beta(R2HY,x_B^\alpha,x_B^\beta)= & x_B^\beta\cdot[a_B-b_B\cdot(x_B^\alpha+x_B^\beta)+\\ & -\frac{R_B}{S_{AB}}\cdot(pr_B-\varepsilon)-W_B\cdot dc_B]\end{cases} \tag{37}$$

Profit maximization problem in market A in the region R2HY:

$$\begin{aligned}max_{x_A^\alpha}\Pi_A^\alpha(R2HY,x_A^\alpha)={}&x_A^\alpha\cdot(a_A-b_A\cdot x_A^\alpha-R_A\cdot pr_A)+(pr_B-\varepsilon-ct_1-ct_2)\cdot\frac{R_B}{s_{AB}}\cdot x_B^\beta+\\&-dc_A\cdot[W_A\cdot x_A^\alpha-\frac{R_B}{s_{AB}}\cdot(x_B^\alpha+x_B^\beta)]-\frac{R_B}{s_{AB}}\cdot SV^\alpha\cdot x_B^\alpha\end{aligned} \tag{38}$$

A.4. Numerical study

Three numerical examples will be used to show the main dynamics of the model and provide an easier comprehension of the model. The input dataset is shown in Table 8.

The first numerical example (Case 1) serves as a baseline, and the full development of the model will be provided only in this case.

According to the setting of Case 1 (Table 8), markets A and B have the same characteristics, i.e., $a_A = a_B$ and $b_A = b_B$, and IS is convenient, indeed:

$$ct_1+ct_2=2<10=dc_A+s_{AB}\cdot pr_B \tag{39}$$

Whether Company α decides to implement the EE strategy, the emerging cost of IS would be shared between Company α and Company β according to the Shapley values. In this numerical example, the marginal benefit gained through IS is equal, thus the costs would be equally shared, too:

$$\begin{aligned}SV_A^\alpha&=\frac{ct_1+ct_2+dc_A-s_{AB}\cdot pr_B}{2}=\frac{1+1+5-1\cdot 5}{2}=1\\SV_B^\beta&=\frac{ct_1+ct_2-dc_A+s_{AB}\cdot pr_B}{2}=\frac{1+1-5+1\cdot 5}{2}=1\end{aligned} \tag{40}$$

In the first stage, company α would be able to anticipate the external waste demand from Company β. Indeed, the profit maximization problem for Company β would be:

$$\begin{aligned} max_{x_B^\beta} \Pi_B^\beta &= x_B^\beta \cdot \left(a_B - b_B \cdot x_B^\beta - \frac{R_B}{s_{AB}} \cdot SV_B^\beta - W_B \cdot dc_B\right) - t^\beta = \\ &= x_B^\beta \cdot \left(100 - 1 \cdot x_B^\beta - \frac{1}{1} \cdot 1 - 1 \cdot 2\right) - 10 \end{aligned} \tag{41}$$

Hence, the optimal production quantity of product B would be $x_B^{\beta^*} = 48,5$ and, accordingly, the waste demand for Company α $\frac{R_B}{s_{AB}} \cdot x_B^{\beta^*} = \frac{1}{1} \cdot 48,5 = 48,5$.

In the second stage, Company α would optimize its production quantity, too. Whether producing in the region R1EE (i.e., waste available lower than or equal to the external waste demand), Company α maximization problem would be:

$$\begin{aligned} max_{x_A^\alpha} \Pi_A^\alpha &= x_A^\alpha \cdot (a_A - b_A \cdot x_A^\alpha - W_A \cdot SV_A^\alpha - R_A \cdot pr_A) - t^\alpha = \\ &= x_A^\alpha \cdot (100 - 1 \cdot x_A^\alpha - 1 \cdot 1 - 1 \cdot 2) - 10 \end{aligned} \tag{42}$$

The optimal production quantity of product A would be $x_A^{\alpha^*} = 48,5$. Since $W_A \cdot x_A^{\alpha^*} = 1 \cdot 48,5 = 48,5 = \frac{R_B}{s_{AB}} \cdot x_B^{\beta^*}$, in this case example the available waste would be equal to the external waste demand and would be entirely delivered to Company β.

Note that, since the optimal solution in the region R1 of the EE strategy is admissible, the optimal solution in the region R2 (i.e., waste available higher than the external waste demand) will be not. Indeed, whether producing in the region R2EE, the optimal production quantity for Company α would be found by solving the following maximization problem:

$$\begin{aligned} max_{x_A^\alpha} \Pi_A^\alpha &= x_A^\alpha \cdot (a_A - b_A \cdot x_A^\alpha - R_A \cdot pr_A) - dc_A \cdot (W_A \cdot x_A^\alpha + \\ &\quad - \frac{R_B}{s_{AB}} \cdot x_B^{\beta^*}) - \frac{R_B}{s_{AB}} \cdot SV_A^\alpha \cdot x_B^{\beta^*} - t^\alpha = \\ &= x_A^\alpha \cdot (100 - 1 \cdot x_A^\alpha - 1 \cdot 2) - 5 \cdot (1 \cdot x_A^\alpha - \frac{1}{1} \cdot 48,5) + \\ &\quad - \frac{1}{1} \cdot 1 \cdot 48,5 - 10 \end{aligned} \tag{43}$$

From which it is possible to derive that $x_A^{\alpha^*} = 46,5$. Since $W_A \cdot x_A^{\alpha^*} = 1 \cdot 46,5 < 48,5 = \frac{R_B}{s_{AB}} \cdot x_B^{\beta^*}$ the optimal solution of R2EE is not admissible. In conclusion, the optimal solution for Company α whether implementing the EE strategy would belong to the region R1EE and Company α would gain a profit equal to:

$$\begin{aligned} \Pi_A^\alpha(x_A^{\alpha^*}) &= x_A^{\alpha^*} \cdot (a_A - b_A \cdot x_A^{\alpha^*} - W_A \cdot SV_A^\alpha - R_A \cdot pr_A) - t^\alpha = \\ &= 48,5 \cdot (100 - 1 \cdot 48,5 - 1 \cdot 1 - 1 \cdot 2) - 10 = 2342,25 \end{aligned} \tag{44}$$

Conversely, whether Company α decides to implement the NPD strategy, a new business unit, i.e., Business Unit B, would be created within the firm's boundaries, and the emerging costs from IS would be shared between the business units according to the Shapley Values as follows:

$$\begin{aligned} SV_A^\alpha &= \frac{ct_1 + dc_A - s_{AB} \cdot pr_B}{2} = \frac{1 + 5 - 1 \cdot 5}{2} = 0,5 \\ SV_B^\alpha &= \frac{ct_1 - dc_A + s_{AB} \cdot pr_B}{2} = \frac{1 - 5 + 1 \cdot 5}{2} = 0,5 \end{aligned} \tag{45}$$

In the first stage, Business Unit B of Company α would compete with Company β in the market B.

The Cournot equilibrium in the case of waste available lower than or equal to the internal waste demand, i.e., in the region R1NPD, would be:

$$\begin{cases} max_{x_B^\alpha} \Pi_B^\alpha & = x_B^\alpha \cdot [a_B - b_B \cdot (x_B^\alpha + x_B^\beta) - W_B \cdot dc_B] + \\ & - SV_B^\alpha \cdot W_A \cdot x_A^{\alpha^*} - pr_B \cdot (R_B \cdot x_B^\alpha - W_A \cdot s_{AB} \cdot x_A^{\alpha^*}) - I = \\ & = x_B^\alpha \cdot [100 - 1 \cdot (x_B^\alpha + x_B^\beta) - 1 \cdot 2] - 0,5 \cdot 1 \cdot x_A^{\alpha^*} + \\ & -5 \cdot (1 \cdot x_B^\alpha - 1 \cdot 1 \cdot x_A^{\alpha^*}) - 1000 \\ max_{x_B^\beta} \Pi_B^\beta & = x_B^\beta \cdot [a_B - b_B \cdot (x_B^\alpha + x_B^\beta) - R_B \cdot pr_B - W_B \cdot dc_B] = \\ & = x_B^\beta \cdot [100 - 1 \cdot (x_B^\alpha + x_B^\beta) - 1 \cdot 5 - 1 \cdot 2] \end{cases} \tag{46}$$

The optimal solutions would be:

$$\begin{cases} x_B^{\alpha^*} = 31 \\ x_B^{\beta^*} = 31 \end{cases} \tag{47}$$

Hence, the internal waste demand would be $\frac{R_B}{s_{AB}} \cdot x_B^{\alpha^*} = \frac{1}{1} \cdot 31 = 31$.

In the second stage, Business Unit A would maximize its profit as follows:

$$\begin{aligned} max_{x_A^\alpha} \Pi_A^\alpha &= x_A^\alpha \cdot (a_A - b_A \cdot x_A^\alpha - R_A \cdot pr_A - W_A \cdot SV_A^\alpha) = \\ &= x_A^\alpha \cdot (100 - 1 \cdot x_A^\alpha - 1 \cdot 2 - 1 \cdot 0,5) \end{aligned} \tag{48}$$

The optimal production quantity of product A would be $x_A^{\alpha^*} = \frac{100-2-0,5}{2} = 48,75$, but since $W_A \cdot x_A^{\alpha^*} = 1 \cdot 48,75 > 31 = \frac{R_B}{s_{AB}} \cdot x_B^{\alpha^*}$, the optimal solution of the NPD strategy in the region R1NPD would be not admissible.

Conversely, the Cournot equilibrium in the case of waste available higher than the internal waste demand, i.e., in the region R2NPD, would be:

$$\begin{cases} max_{x_B^\alpha} \Pi_B^\alpha & = x_B^\alpha \cdot [a_B - b_B \cdot (x_B^\alpha + x_B^\beta) - \frac{R_B}{s_{AB}} \cdot SV_B^\alpha - W_B \cdot dc_B] - I = \\ & = x_B^\alpha \cdot [100 - 1 \cdot (x_B^\alpha + x_B^\beta) - \frac{1}{1} \cdot 0,5 - 1 \cdot 2] - 1000 \\ max_{x_B^\beta} \Pi_B^\beta & = x_B^\beta \cdot [a_B - b_B \cdot (x_B^\alpha + x_B^\beta) - R_B \cdot pr_B - W_B \cdot dc_B] = \\ & = x_B^\beta \cdot [100 - 1 \cdot (x_B^\alpha + x_B^\beta) - 1 \cdot 5 - 1 \cdot 2] \end{cases} \tag{49}$$

The optimal solutions would be:

$$\begin{cases} x_B^{\alpha^*} = 34 \\ x_B^{\beta^*} = 29,5 \end{cases} \tag{50}$$

In the second stage, the profit maximization problem for Business Unit A of Company α would be:

$$\begin{aligned} max_{x_A^\alpha} \Pi_A^\alpha &= x_A^\alpha \cdot (a_A - b_A \cdot x_A^\alpha - R_A \cdot pr_A) - dc_A \cdot (W_A \cdot x_A^\alpha - \frac{R_B}{s_{AB}} \cdot x_B^\alpha) + \\ &\quad - \frac{R_B}{s_{AB}} \cdot SV_A^\alpha \cdot x_B^\alpha = \\ &= x_A^\alpha \cdot (100 - 1 \cdot x_A^\alpha - 1 \cdot 2) - 5 \cdot (1 \cdot x_A^\alpha - \frac{1}{1} \cdot x_B^\alpha) - \frac{1}{1} \cdot 0,5 \cdot x_B^\alpha \end{aligned} \tag{51}$$

From which we derive $x_A^{\alpha^*} = 46,5$. In this case, $W_A \cdot x_A^{\alpha^*} = 1 \cdot 46,5 > 34 = \frac{R_B}{s_{AB}} \cdot x_B^{\alpha^*}$. Hence, the optimal solution in the region R2NPD is admissible. Whether choosing the NPD strategy, the profit gained by Company α would be:

$$\begin{aligned} \Pi_{AB}^\alpha = \Pi_A^\alpha(x_A^{\alpha^*}) + \Pi_B^\alpha(x_B^{\alpha^*}) &= 46,5 \cdot (100 - 1 \cdot 46,5 - 1 \cdot 2) + \\ &\quad - 5 \cdot (1 \cdot 46,5 - \frac{1}{1} \cdot 34) - \frac{1}{1} \cdot 0,5 \cdot 34 + \\ &\quad + 34 \cdot [100 - 1 \cdot (34 + 29,5) + \\ &\quad - \frac{1}{1} \cdot 0,5 - 1 \cdot 2] - 1000 = 2471,2 \end{aligned} \tag{52}$$

Since the waste available exceeds the internal waste demand, the HY strategy is admissible. If deciding to adopt such a strategy, Company α would sell exceeding waste to Company β at a price $p_w = pr_B - \varepsilon =$

$5-0,1=4,9$. If producing in the region R1HY the Cournot equilibrium would be:

$$\begin{cases} max_{x_B^\alpha}\mathit{\Pi}_B^\alpha & = x_B^\alpha\cdot[a_B-b_B\cdot(x_B^\alpha+x_B^\beta)-\frac{R_B}{s_{AB}}\cdot SV_B^\alpha-W_B\cdot dc_B]-I=\\ & = x_B^\alpha\cdot[100-1\cdot(x_B^\alpha+x_B^\beta)-\frac{1}{1}\cdot 0,5-1\cdot 2]-1000\\ max_{x_B^\beta}\mathit{\Pi}_B^\beta = & x_B^\beta\cdot[a_B-b_B\cdot(x_B^\alpha+x_B^\beta)-W_B\cdot dc_B]-(pr_B-\varepsilon)\cdot(W_A\cdot x_A^\alpha+\\ & -\frac{R_B}{s_{AB}}\cdot x_B^\alpha)-\ pr_B\cdot(R_B\cdot x_B^\beta-W_A\cdot x_A^\alpha+R_B\cdot x_B^\alpha)=\\ & = x_B^\beta\cdot[100-1\cdot(x_B^\alpha+x_B^\beta)-1\cdot 2]-(5-0,1)\cdot(1\cdot x_A^\alpha-\frac{1}{1}\cdot x_B^\alpha)+\\ & -5\cdot(1\cdot x_B^\beta-1\cdot x_A^\alpha+1\cdot x_B^\alpha) \end{cases} \tag{53}$$

The optimal solutions would be:

$$\begin{cases} x_B^{\alpha^*}=34\\ x_B^{\beta^*}=29,5 \end{cases} \tag{54}$$

Note that the optimal production quantities of product B would not change compared to the previous strategy, i.e., NPD region R2NPD. However, the optimal production quantity for Business Unit A of Company α would be:

$$\begin{aligned} max_{x_A^\alpha}\mathit{\Pi}_A^\alpha &= x_A^\alpha\cdot(a_A-b_A\cdot x_A^\alpha-R_A\cdot pr_A)+(pr_B-\varepsilon-ct_1+\\ &-ct_2)\cdot(W_A\cdot x_A^\alpha-\frac{R_B}{s_{AB}}\cdot x_B^\alpha)-\frac{R_B}{s_{AB}}\cdot SV_A^\alpha\cdot x_B^\alpha=\\ &= x_A^\alpha\cdot(100-1\cdot x_A^\alpha-1\cdot 2)+(5-0,1-1+\\ &-1)\cdot(1\cdot x_A^\alpha-\frac{1}{1}\cdot x_B^\alpha)-\frac{1}{1}\cdot 0,5\cdot x_B^\alpha \end{aligned} \tag{55}$$

The optimal solution in the region R1 would be $x_A^{\alpha^*}=50,45$, which is admissible. Indeed, $W_A\cdot x_A^{\alpha^*}=1\cdot 50,45=50,45<63,5=\frac{1}{1}\cdot(34+29,5)=\frac{R_B}{s_{AB}}\cdot(x_B^{\alpha^*}+x_B^{\beta^*})$. Conversely, in the region R2HY, the optimal solution for the HY strategy is not admissible. Indeed, the Cournot equilibrium would be:

$$\begin{cases} max_{x_B^\alpha}\mathit{\Pi}_B^\alpha & = x_B^\alpha\cdot[a_B-b_B\cdot(x_B^\alpha+x_B^\beta)-\frac{R_B}{s_{AB}}\cdot SV_B^\alpha-W_B\cdot dc_B]-I=\\ & = x_B^\alpha\cdot[100-1\cdot(x_B^\alpha+x_B^\beta)-\frac{1}{1}\cdot 0,5-1\cdot 2]-1000\\ max_{x_B^\beta}\mathit{\Pi}_B^\beta & = x_B^\beta\cdot[a_B-b_B\cdot(x_B^\alpha+x_B^\beta)-\frac{R_B}{S_{AB}}\cdot(pr_B-\varepsilon)-W_B\cdot dc_B]=\\ & = x_B^\beta\cdot[100-1\cdot(x_B^\alpha+x_B^\beta)-\frac{1}{1}\cdot(5-0,1)-1\cdot 2] \end{cases} \tag{56}$$

The optimal solutions would be:

$$\begin{cases} x_B^{\alpha^*}=33,97\\ x_B^{\beta^*}=29,57 \end{cases} \tag{57}$$

The profit maximization problem for Business Unit A of Company α would be:

$$\begin{aligned} max_{x_A^\alpha}\mathit{\Pi}_A^\alpha &= x_A^\alpha\cdot(a_A-b_A\cdot x_A^\alpha-R_A\cdot pr_A)+(pr_B-\varepsilon-ct_1-ct_2)\cdot\frac{R_B}{s_{AB}}\cdot x_B^\beta+\\ &-\ dc_A\cdot[W_A\cdot x_A^\alpha-\frac{R_B}{s_{AB}}\cdot(x_B^\alpha+x_B^\beta)]-\frac{R_B}{s_{AB}}\cdot SV^\alpha\cdot x_B^\alpha=\\ &= x_A^\alpha\cdot(100-1\cdot x_A^\alpha-1\cdot 2)+(5-0,1-1-1)\cdot\frac{1}{1}\cdot x_B^\beta+\\ &-\ 5\cdot[1\cdot x_A^\alpha-\frac{1}{1}\cdot(x_B^\alpha+x_B^\beta)]-\frac{1}{1}\cdot 0,5\cdot x_B^\alpha \end{aligned} \tag{58}$$

The optimal solution would be $x_A^{\alpha^*}=46,5$. In this case, $W_A\cdot x_A^{\alpha^*}=1\cdot 46,5=46,5<63,54=\frac{1}{1}\cdot(33,97+29,57)=\frac{R_B}{s_{AB}}\cdot(x_B^{\alpha^*}+x_B^{\beta^*})$, hence the optimal solution in R2HY would be not admissible. The optimal solution for the HY strategy would fall in the region R1HY and Company α would yields a profit equal to:

$$\begin{aligned} \mathit{\Pi}_{AB}^\alpha=\mathit{\Pi}_A^\alpha(x_A^{\alpha^*})+\mathit{\Pi}_B^\alpha(x_B^{\alpha^*}) &= 50,45\cdot(100-1\cdot 50,45-1\cdot 2)+(5-0,1+\\ &-1-1)\cdot(1\cdot 50,45-\frac{1}{1}\cdot 34)-\frac{1}{1}\cdot 0,5\cdot 34+\\ &+\ 34\cdot(100-1\cdot(34+29,5)-\frac{1}{1}\cdot 0,5+\\ &-1\cdot 2)-1000=2585,6 \end{aligned} \tag{59}$$

Table 9
Results case 1.

Region	$\mathbf{x}_{\mathbf{B}}^{\alpha^*}$	$\mathbf{x}_{\mathbf{B}}^{\beta^*}$	$\mathbf{x}_{\mathbf{A}}^{\alpha^*}$	Admissible	Profit [EUR]
R1EE	–	48,5	48,5	YES	2342,2
R2EE	–	48,5	46,5	NO	–
R1NPD	31	31	48,75	NO	–
R2NPD	34	29,5	46,5	YES	2471,2
R1HY	34	29,5	50,45	YES	2585,6
R2HY	33,97	29,57	46,5	NO	–

Table 10
Results case 2.

Region	$\mathbf{x}_{\mathbf{B}}^{\alpha^*}$	$\mathbf{x}_{\mathbf{B}}^{\beta^*}$	$\mathbf{x}_{\mathbf{A}}^{\alpha^*}$	Admissible	Profit [EUR]
R1EE	–	197	48,5	YES	2342,2
R2EE	–	197	46,5	NO	–
R1NPD	128,67	128,67	48,75	YES	10 452
R2NPD	134,67	125,67	46,5	NO	–
R1HY	–	–	–	–	–
R2HY	–	–	–	–	–

Table 11
Results case 3.

Region	$\mathbf{x}_{\mathbf{B}}^{\alpha^*}$	$\mathbf{x}_{\mathbf{B}}^{\beta^*}$	$\mathbf{x}_{\mathbf{A}}^{\alpha^*}$	Admissible	Profit [EUR]
R1EE	–	11,75	48,5	NO	–
R2EE	–	11,75	46,5	YES	2199,2
R1NP	7.17	7.17	48,75	NO	–
R2NPD	8,67	6,42	46,5	YES	1351,5
R1HY	8,67	6,42	50,45	NO	–
R2HY	8,65	6,45	46,5	YES	1401,5

The application of the model in this case example suggests that the HY strategy in the region R1HY would the more convenient for Company α (Table 9).

However, whether market B became more attractive, i.e., if the maximum willingness to pay for product B (a_B) and the demand elasticity ($\frac{1}{b_B}$) increased (Case 2), the HY strategy would be not feasible[22] and the optimal strategy would be the NPD in the region where the waste available is lower than the waste internal demand, i.e., R1NPD (Table 10).

Conversely, if market B became less attractive, i.e., if the maximum willingness to pay for product B (a_B) and the demand elasticity ($\frac{1}{b_B}$) decreased (Case 3), the optimal strategy would be the EE in the region R2, i.e., R2EE (Table 11).

These results confirm the predominant effect of the characteristics of market B on the strategic choice of Company α, which is in line with the discussion in Sections 3 and 4.

A.5. Random simulations

To validate the model, the same regressions whose results are provided in Tables 4 and 6 were performed over the outputs of a

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[22] Indeed, there is no waste exceeding the internal waste demand of Company α.

Table 12
Lower and upper limits per variable.

Variable	Lower limit	Upper limit
a_B	$\frac{100}{6}$	$100 \cdot 6$
b_B	$\frac{1}{6}$	$1 \cdot 6$
ct_1	$\frac{1}{6}$	$1 \cdot 6$
ct_2	$\frac{1}{6}$	$1 \cdot 6$
pr_B	$\frac{1}{6}$	$1 \cdot 6$
I	$\frac{1000}{6}$	$1000 \cdot 6$

Table 13
Regression on the profit for each strategy (Validation).

Variable	External exchange	New product development	Hybrid strategy
a_B	0,057 ***	42,263 ***	15,062 ***
b_B	$-3,463$ ***	$-4316,75$ ***	$-422,223$***
ct_1	$-18,79$ ***	49,897	$-38,08$ ***
ct_2	$-18,77$***	–	$-12,091$ ***
pr_B	18,768 ***	20,599	22,93 ***
I	–	$-0,992$ ***	$-0,999$ ***
R^2	0,837	0411	0,956

Legend:
*** = p-value $< 0,001$; ** = p-value $< 0,05$; * = p-value $=< 0,1$.

Table 14
Regression on the profit for the regions R1 and R2 of the NPD (Validation).

Variable	R1NPD	R2NPD
a_B	131,184 ***	15,039 ***
b_B	$-20653,9$ ***	$-422,07$ ***
ct_1	23,61	$-24,285$***
ct_2	–	–
pr_B	11,162	9,202***
I	$-0,963$ ***	-1 ***
R^2	0,617	0,954

Legend:
*** = p-value $< 0,001$; ** = p-value $< 0,05$; * = p-value $=< 0,1$.

simulation of the model run over a random dataset. The random dataset was built by combining randomly generated values within upper and lower limits for each variable of interest (i.e., a_B, b_B, ct_1, ct_2, pr_B, I) as shown in Table 12. The results of the validation analysis (Tables 13 and 14) are in line with the results obtained in the simulation provided in Section 4.2.

Differently from the result obtained in the simulation, in 614 scenarios over 83458 of the model validation (0,736% of scenarios) the NPD in region R2 resulted to be more convenient than the HY strategy, i.e., higher profits for Company α were ensured by the NPD strategy in the region R2.

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