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Learning strategic cooperative behavior in industrial symbiosis: A game-theoretic approach integrated with agent-based simulation

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Abstract

This paper investigates the negotiation phase of industrial symbiosis relationships, where companies exchanging wastes for inputs need to develop strategies on how to share the additional costs to operate the industrial symbiosis business. The business behavior is approached as a "coopetition" problem where companies need to *cooperate* to reduce waste discharge costs and traditional input purchase costs and dive into comp*etition* to pay a minimum share of additional costs (i.e., waste treatment, waste transportation, and transaction costs) of operating industrial symbiosis. A noncooperative game-theoretical model for sharing the additional costs is proposed that highlights the two strategies that companies can adopt aimed at sharing costs: a *fair* strategy and an *opportunistic* strategy. Then, an agent-based model is used to simulate the game iterated over time and investigate how the players can adapt their strategies according to their past experience. Simulation results show that players learn that playing the fair strategy is beneficial in the long period, despite in the short period they can gain more benefit by playing the opportunistic strategy. Findings of the paper are critically important to reduce the business and managerial barriers against the formation of industrial symbiosis networks and to stimulate innovative thinking of company managers to foster the development of the circular economy. The paper proposes theoretical, managerial, and policy implications, which are discussed in detail in a comparative manner between linear and circular economy.

KEYWORDS

agent-based simulation, circular economy, game theory, industrial symbiosis, strategy management

1 | INTRODUCTION

Industrial symbiosis (IS) is a subfield of industrial ecology that engages separate industries in physical exchanges of waste materials, water, and energy (Chertow, 2000; Lombardi & Laybourn, 2012). Two companies implement an IS relationship (ISR) when at least one waste produced by the former is used to replace production inputs by the latter. By exchanging wastes for inputs, companies can reduce the amounts of wastes disposed of in landfills and the amounts of traditional primary inputs and raw materials used by production processes, thus generating environmental benefits for the collectivity and reducing their production costs at the same time (ElMassah, 2018; Jacobsen, 2006). Thanks to such a reduction, companies implementing IS can gain a competitive advantage compared with other companies not adopting IS (Chertow & Miyata, 2011; Esty & Porter, 1998; Yuan & Shi, 2009). For these reasons, IS is recognized as a key practice to support the transition towards the circular economy (e.g., Centobelli, Cerchione, Chiaroni, Del Vecchio, & Urbinati, 2020; Kirchherr, Reike, & Hekkert, 2017; Korhonen, Honkasalo, & Seppälä, 2018; Perey, Benn, Agarwal, & Edwards, 2018; Prieto-Sandoval, Ormazabal, Jaca, & Viles, 2018; Stewart & Niero, 2018; Zucchella & Previtali, 2018), and policymakers of many countries are pushing companies to adopt such a practice (European Commission, 2015; European Environmental Agency, 2016; Ministero dell'Ambiente e della Tutela del Territorio e del Mare and Ministero dello Sviluppo Economico, 2017). In this view, IS can be seen as a business-making practice, aimed at implementing the circular economy paradigm in the context of industrial relations. Therefore, in the following, we may refer to an ISR as a (transitional) "business" or a (circular economy) "practice." Moreover, it is crucial to note that implementing IS practices involves various phases prior to its operationalization, for example, the market search and identification phase (e.g., van Capelleveen, Amrit, & Yazan, 2018), as well as the evaluation and opportunity assessment phase (e.g., Yazdanpanah, Yazan, & Zijm, 2019). Thus, our references to "implementing" IS relations refer to various phases as a whole while "operating" such relations is the final phase of engaging with the business aspects and dealing with involved costs. In the following, we elaborate on the nature of such costs.

From the business perspective, despite allowing to reduce production costs, operating an ISR requires that companies pay three additional costs compared with their main businesses, which have been defined as 3T costs (Yazdanpanah et al., 2019): (a) waste transportation costs, related to moving the wastes from the producer to the user; (b) waste treatment costs, related to making wastes available to be used as inputs, for example, due to filtration, sorting, grounding processes; and (c) transaction costs, related to organizing and coordinating the IS business. If these additional costs are lower than the saved costs thanks to replacing inputs with wastes, the ISR is economically feasible. Companies interested in establishing an ISR are required to share these additional costs among them. This is a crucial phase, driven not only by operational conditions (Yazan & Fraccascia, 2020) but also by business strategies developed by company managers. In fact, Yazdanpanah and Yazan (2017) conceptualize the IS practice as a form of "coopetition," that is, something in between pure cooperation and pure competition (Manzhynski & Figge, 2019; Osarenkhoe, 2010a; Osarenkhoe, 2010b). Indeed, companies need to *coop*erate to reduce their production costs (i.e., waste discharge costs and traditional input purchase costs) and dive into comp*etition* to pay a minimum share of 3T additional costs. Hence, to operate an ISR sustainably over time, both companies must gain an economic benefit higher than their respective minimum expected benefits. However, real cases investigated by the authors raised the fact that companies might adopt opportunistic behavior during the cost-sharing negotiation phase, aimed at capturing the greatest part of the overall economic benefit while leaving a scant part to the other company (Handley & Benton, 2012; Huo, Ye, & Zhao, 2015). When this happens, an incentive misalignment problem arises (Cachon, 2003; Narayanan & Raman, 2004): accordingly, the company that would gain the scant part of the benefit might be not motivated enough to cooperate with the symbiotic partner, and it might prefer to reject the relationship. Furthermore, even if the relationship is not immediately rejected, such a misalignment is responsible for reducing trust in the symbiotic partner, which can hamper the stability of the relationship in the long period (Lambert & Boons, 2002). In fact, high trust between the involved companies is recognized as a key facilitator for ISRs (Baas, 2011; Doménech & Davies, 2011; Fichtner, Tietze-Stöckinger, Frank, & Rentz, 2005; Hewes & Lyons, 2008).

So far, the literature focused on studying the cooperation phase of ISRs, for example, by assessing the overall economic benefits that can be created by a given ISR, but it has reserved scant attention to investigate the competition phase. In particular, there are no studies that investigate how companies negotiate aimed at sharing the additional costs of IS. This paper is aimed at filling this gap by investigating how firms can develop long-term ISRs and whether their strategies evolve over time.[1] First, noncooperative game schemes (Nash, 1951) are used to model strategies that companies can adopt in the benefit-sharing phase. Second, agent-based simulation (Axelrod, 1997b; Duffy, 2006; Liu, Yang, & Xu, 2017) is employed to explore the iterated game and its evolution over time, that is, the behavior of the companies in the long period.

The paper is organized as follows. Section 2 describes the theoretical background for the methodologies adopted in this paper, that is, game-theory models and agent-based models. Section 3 presents the game-theory model developed. Section 4 provides the agent-based model developed to simulate the iteration of the game in the long period and shows the simulation results. The paper ends with discussion and conclusions in Sections 5 and 6, respectively.

2 | METHODOLOGICAL BACKGROUND

In this section, the methodological background of this paper is presented. In particular, Section 2.1 addresses the game-theory approach for supply chains and IS research. Section 2.2 addresses the agent-based model approach, focusing on previous applications to IS.

2.1 | Game theory for supply chain and IS research

Game theory is a bag of analytical tools designed to help understanding the phenomena that can be observed when decision makers

[1]In this work, we use the terms "firm" and "company" interchangeably as we are not concerned with how the owners/shareholders share the responsibility for liabilities.

interact among them. A game is a description of the strategic interaction among different players (i.e., the decision makers) that includes the constraints on the actions that the players can take, as well as the players' interests. Two basic assumptions underlie the theory: (a) Players are rational, that is, they pursue well-defined exogenous objectives; and (b) players reason strategically, that is, they take into account their knowledge or expectations of other players' behavior when taking their decisions. The outcome of the game emerges from the combined decisions of players. Decisional states from which no player has interest to depart are called *Nash equilibrium* points. If the players' internal models are known, a Nash equilibrium might be immediately reached at the first iteration of the game. In most real cases, the equilibrium point is not unique, and who plays first (leader) imposes the outcome of the game, so giving rise to a *Stackelberg equilibrium* point (Simaan & Cruz, 1973). Hence, the outcome of the game generally depends on who plays first.

Game theory deals with interactive optimization problems and has been largely applied to study interaction patterns of companies both in the same and in different supply chains. For example, Cachon and Netessine (2006) survey the applications of game theory to supply chain analysis, discussing both noncooperative and cooperative game theory in static and dynamic settings. Hennet and Arda (2008) evaluate the efficiency of different types of contracts between partners within the same supply chain using game theory for decisional purposes. They highlight that a cooperative game approach can be useful to design a supply chain whereas a noncooperative approach is more appropriate to identify the equilibrium points that can be reached in trade conditions. Esmaeili, Aryanezhad, and Zeephongsekul (2009) analyze several seller–buyer supply chain models in the framework of cooperative and noncooperative games. In their study, the noncooperative game is based on the Stackelberg strategy where a seller–Stackelberg (i.e., the seller is the leader player) and a buyer–Stackelberg (i.e., the buyer is the leader) solution concepts are adopted. Even though in the literature, the seller–Stackelberg approach is dominant, there are also works adopting buyer–Stackelberg approach (Chen, Chang, Huang, & Liao, 2006; Maiti & Giri, 2017; Yue, Austin, Wang, & Huang, 2006). Stackelberg game is also used to analyze seller–buyer relationships to find the range of stable profits–costs (i.e., a situation in which buyers and sellers are not economically motivated to change the payment value) (Abad & Jaggi, 2003). Cooperative advertising models are also proposed in manufacturer–retailer supply chains. For instance, by employing game-theoretical analysis, Huang and Li (2001) and Li, Huang, Zhu, and Chau (2002) demonstrate the evolution of marketing strategies as a result of a shift in the retailing power—from manufacturers to retailers. Hence, the application areas of the Stackelberg games in supply chain management are broad containing both noncooperative as well as cooperative approaches. Game-theory models have also been adopted to closed-loop supply chains, in particular to study and estimate price decisions (Yu, Huang, & Liang, 2009; Zhang & Jin, 2011).

Focusing on the application of game-theoretical methods to IS scenarios, Lou, Kulkarni, Singh, and YinlunL (2004) analyze the stability of strategies that firms can apply for implementing a given ISR and integrate such an approach into an emergy analysis framework. To understand which strategy is a stable one to implement, they use solution concepts from noncooperative game theory and consider the fact that various uncertainties are present when evaluating different strategies. This way, their main contribution is a platform that enables realizing win–win IS strategies under uncertainty. Another class of game-theoretical solution concepts that are applicable to the IS research are cost/benefit allocation mechanisms from cooperative game theory (Tan, Andiappan, Wan, Ng, & Ng, 2016). In this regard, Chew, Tan, Foo, and Chiu (2009) and Aviso, Tan, Culaba, and Cruz (2010) develop an implementation framework for integrating relations amongst industrial plants to circulate wastewater. In their game-theoretical model, it is guaranteed that the optimum collective benefit is achievable if all the network members comply with an agreed-upon “wastewater interchange scheme”. In another study focused on the circulation of refillable beverage containers, Grimes-Casey, Seager, Theis, and Powers (2007) apply game theory to model cooperative decision making and capture the heterogeneity of involved stakeholders. They illustrate that cost-based coordination mechanisms are effective for stabilizing ISRs and claim that the applicability of such methods depends on regulative supports from governments, who are in charge of providing incentives (Fraccascia, Giannoccaro, & Albino, 2017; Tao, Evans, Wen, & Ma, 2019). Yazdanpanah and Yazan (2017) present a method rooted in cooperative game theory for the allocation of IS operational costs in bilateral relations such that no firm has an economic incentive to leave the relation—also known as the *stability* property in the game-theory literature (Osborne & Rubinstein, 1994). In their work, taking the traditional costs of each firm into account leads to a cost allocation that also corresponds to the notion of *fairness* in computational economics (Rabin, 1993). Moving to multilateral IS, where multiple firms build symbiotic relations, Yazdanpanah, Yazan, and Zijm (2018) show that guaranteeing long-term collaborations in which no firm has an incentive to defect may require external monetary incentives. In such cases, the regulatory agents (e.g., local or national governments) can allocate coordinative subsidies to ensure the implementation of socio-environmentally desirable collaborations and suppress undesirable ones by means of introducing taxation policies. An approach that employs both cooperative game-theoretic notions for cost allocation and noncooperative solution concepts for analyzing the decisions in IS is proposed by Yazdanpanah et al (2019). Their main aim is to present a formally verifiable decision support tool for evaluating IS relations using logical frameworks from multiagent systems research where operational and epistemic dimensions of IS are emphasized as game changers.

In applying noncooperative game theory to study IS practices, most approaches rely on purely single-shot games where firms have only one chance to play or multiple-shot games with a handful number of rounds (Chew et al., 2009; Grimes-Casey et al., 2007). Such a perspective would be appropriate to see the emergence of IS but limits the chance of studying how a potential IS relation can evolve in the long run, in terms of companies' behavior and strategies adopted. In fact, a missing aspect in the IS literature is the use of analytical methods for “reasoning about stability of ISRs over the long period.”.

To fill this gap, we employ agent-based modeling (ABM) and aim for constructing an integrated framework that uses game theory to analyze the emergence of relations and then exploits agent-based simulation to reason about the evolution of such relations.

2.2 | Agent-based modeling

ABM is a suitable technique to study complex systems made by different entities interacting with each other. Each entity is modeled as an agent, which is provided with a given set of goals to accomplish through the interaction with the other agents and the environment, driven by a given set of rules of social engagement (Bonabeau, 2002; Holland, 2002; Weiss, 1999). ABM allows researchers to investigate system dynamics in a way that analytical models cannot do (Axelrod, 1997a) because the system behavior emerges from the interactions among the agents rather than to be defined a priori by the modeler (Macal & North, 2010).

Applications of ABM span a broad range of disciplines. In particular, in the industrial field, the ABM approach was particularly suited to study cooperation dynamics among firms within supply chains and industrial districts (Giannoccaro & Pontrandolfo, 2004; Jiao, You, & Kumar, 2006). Based on the above, such an approach is considered very suited to analyze the dynamics of cooperation in ISRs (e.g., Batten, 2009; Chahla & Zoughaib, 2019; Demartini, Tonelli, & Bertani, 2018; Romero & Ruiz, 2014). Here, agents are the companies that interact amongst each other exchanging wastes, aimed at achieving economic benefits from IS. ABM has been used to investigate the influence of several factors on the emerge of ISRs: different social dynamics and cooperation levels among companies (Bichraoui, Guillaume, & Halog, 2013; Ghali, Frayret, & Ahabchane, 2017), institutional capabilities (Zheng & Jia, 2017), benefit-sharing contracts (Albino, Fraccascia, & Giannoccaro, 2016), policy measures (Fraccascia et al., 2017), operational strategies (Fraccascia, Yazan, Albino, & Zijm, 2019), and information-sharing mechanisms (Fraccascia & Yazan, 2018). Other models have been proposed simulating operations in eco-industrial parks (EIPs). In this regard, Couto Mantese and Amaral (2017) endorse the use of the ABM technique to validate performance indicators for IS through the construction of a model that simulates an eco-industrial park whereas Wang et al. (2017) propose a model to assess the impact of economic disruptions on coal-based ISNs.

3 | THE GAME-THEORETICAL MODEL

In this section, a noncooperative game scheme (Nash, 1951) is used to model the behavior of industrial firms when negotiating how to share the additional costs arising from ISRs.

Two companies are considered, that is, the waste producer (P) and the waste user (U), which try to establish an ISR. The total economic benefit that can be created from such a relationship (π_{max}) can be computed by the following equation:

$$\pi_{max} = CW + CI - AC, \tag{1}$$

where CW denotes the reduction in waste disposal cost gained by the waste producer, CI denotes the reduction in input purchase costs gained by the waste user, and AC denotes the additional 3T costs stemming from the ISR, that is, waste treatment, transportation, and transaction costs (Yazdanpanah et al., 2019). Companies have to share these additional costs and such a sharing affects how the total economic benefits are distributed between them. In this regard, let λ be the share of additional costs that is paid by the waste producer and let $1 - \lambda$ be the share of additional costs that is paid by the waste user. Hence, the economic benefits gained by waste producer (π_P) and the economic benefits gained by waste user (π_U) can be computed as follows:

$$\pi_P = CW - \lambda AC, \tag{2}$$

$$\pi_U = CI - (1-\lambda)AC, \tag{3}$$

where $\pi_P + \pi_U = \pi_{max}$. According to the literature, a minimum net economic benefit that makes the ISR convenient enough exists for each company (Mirata, 2004). The minimum benefit for the waste producer and the waste user is denoted as ε_P and ε_U, respectively. When trying to establish an ISR, the waste producer (user) can play two extreme strategies:

- A *fair* strategy, where he/she settles for gaining its minimum desired benefit ε_P (ε_U). So that the strategy can be considered fair, ε_P (ε_U) should be lower than $0.5 \times \pi_{max}$. In this case, the waste producer (user) will be willing to cooperate $\forall\lambda \le \frac{1}{AC}[CW - \varepsilon_P]$ ($\forall\lambda \ge \frac{1}{AC}[\varepsilon_U + AC - CI]$).
- An *opportunistic* strategy, where he/she tries to capture the greatest part of the economic benefit created, leaving that the waste user (producer) gains its minimum desired benefit ε_U (ε_P). Hence, the waste producer (user) will be willing to cooperate for $\lambda = \frac{1}{AC}[\varepsilon_U + AC - CI]$ ($\lambda = \frac{1}{AC}[CW - \varepsilon_P]$), so that he/she will gain an economic benefit of $\pi_{max} - \varepsilon_U$ ($\pi_{max} - \varepsilon_P$).[2]

The single-shot ISR game can be modeled as a non-zero-sum game[3] simultaneously played by the two above-mentioned companies. Payoffs are evaluated as the net benefits for each player. The resulting payoff matrix is shown in Table 1. Accordingly, the ISR will arise in three of the four scenarios:

1. Both companies play the fair strategy. In this case, they negotiate the value $\in\left[\frac{1}{AC}(\varepsilon_U + AC - CI); \frac{1}{AC}(CW - \varepsilon_P)\right]$, so that $\pi_P \ge \varepsilon_P$ and

[2]Under the assumption that $\varepsilon_P < 0.5 \times \pi_{max}$ ($\varepsilon_U < 0.5 \times \pi_{max}$), it results that $\pi_{max} - \varepsilon_U > 0.5 \times \pi_{max}$ ($\pi_{max} - \varepsilon_P > 0.5 \times \pi_{max}$).

[3]Although in zero-sum games, the total benefit to all players in the game, for every combination of strategies, always adds to zero, in non-zero-sum games, outcomes can have net results greater than zero, so that a gain by one player does not necessarily correspond to a loss by another.

TABLE 1 Payoff matrix for the proposed game-theory model

		Waste user			
		Fair		**Opportunistic**	
Waste producer	**Fair**	$CW - \lambda^{*} \cdot AC$		ε_P	
			$CI - (1 - \lambda^{*}) \cdot AC$		$\pi_{max} - \varepsilon_P$
	Opportunistic	$\pi_{max} - \varepsilon_U$		0	
			ε_U		0

$\pi_U \geq \varepsilon_U$, simultaneously. Hence, the payoff of the waste producer is $CW - \lambda^{*} \cdot AC$, and the payoff of the waste user is $CI - (1 - \lambda^{*}) \cdot AC$.

2. The waste producer plays the fair strategy, and the waste user plays the opportunistic strategy. In this case, the waste producer gains the minimum benefit ε_P while the waste user gains $\pi_{max} - \varepsilon_P$.
3. The waste producer plays the opportunistic strategy, and the waste user plays the fair strategy. In this case, the waste producer gains $\pi_{max} - \varepsilon_U$ while the waste user its minimum benefit ε_U.

Finally, if both companies play the opportunistic strategy, the ISR does not arise and companies do not gain economic benefits.

As can be noted from Table 1, no dominant strategy exists for any of the actors. The game results in two Nash equilibria, that is, cells *fair–opportunistic* and *opportunistic–fair*. To verify this, we elaborate on the fact that, in both these cases, none of the players can unilaterally increase its payoff by changing strategy. In this regard, let us consider that the waste producer (user) plays the opportunistic strategy and the waste user (producer) plays the fair strategy.[4] In this case, the waste producer (user) would have no interest in changing its strategy because such a change would reduce its economic benefit, whereas the waste user (producer) cannot change its strategy because the relationship would be rejected by the waste producer (user). Therefore, the game stays in either of the two cells. This form of strategic play is also known in the noncooperative games literature as the max–min approach (Aumann & Shapley, 1994), where a player *P* reasons about its strategies, aimed at maximizing its own utility, with the assumption that the opponent player *O* has the same goal (i.e., *O* is aimed to maximize its own utility and accordingly try to minimize *P*'s utility). Due to the noncooperative setting of the game, *P* should select the strategy that maximizes its utility among all the *O*'s minimizing strategies.

All the above is about strategic choices that firms play once. In real-life situations, firms may get involved in multiple symbiotic synergies. Furthermore, companies cooperate between them in the long period; therefore, they can negotiate the economic terms of the ISR over time. This implies that companies have to play the ISR game plenty of times.

To understand the evolution dynamics of ISRs over time, we model ISR behavior in the long run using an iterative ISR game among the involved firms. In this regard, the literature recognizes that path dependence plays a relevant role in long-term ISRs, i.e., that companies are influenced by the historical accumulations resulting from previous operations when taking decisions (Arthur, 1994; Boons & Howard-Grenville, 2009; Doménech & Davies, 2011). The simulation allows to highlight the possible behavior that might emerge in the long period. For example, a company that is cooperating in the *fair–fair* scenario might start to adopt an opportunistic behavior by changing its strategy from fair to opportunistic, aimed at increasing the economic benefits from the ISR, being confident that the symbiotic partner will continue to play the fair strategy. However, opportunistic behavior is responsible for reducing trust between companies (Sako, 1992; Sako & Helper, 1998), which is considered as a key element for the stability of ISRs (Baas, 2008; Baas, 2011; Hewes & Lyons, 2008). In fact, the literature reports cases where ISRs were interrupted because of the lack of trust among the involved companies (Lambert & Boons, 2002). We model such a situation as the possibility for the company that is playing fair in the fair–opportunistic scenario to defect from the ISR. In the next section, a long-term game is explored by employing agent-based simulation.

4 | AGENT-BASED SIMULATIONS FOR LONG-TERM ISRS

This section is divided into three subsections. Section 4.1 presents the agent-based model. Section 4.2 describes the simulation settings. Finally, Section 4.3 shows simulation results.

4.1 | The agent-based model

In this section, multi-rounds of the game described in Section 3 are simulated among multiple industrial firms, where each firm is modeled as an agent. The generic *i*th agent is characterized by the following three idiosyncratic parameters:

- $\varphi(i)$ is the probability that the agent *i* plays the fair strategy when starting a new game.
- $\omega(i)$ is the probability that, if at time $t - 1$ the agent *i* was cooperating playing fair strategy with its partner, at time *t*, the agent *i* changes its strategy and plays opportunistic strategy.
- $\delta(i)$ is the probability that agent *i* interrupts its current relationship because it is playing fair strategy and its partner is playing opportunistic strategy.

[4]Here the reader can read in parallel the role of waste producers in the main sentence and the role of waste users by following parentheses.

Two sets of waste provider and waste receiver agents are considered. In the initial stage, for each agent, the parameters φ, ω, and δ are randomly assigned between zero and one. For any arbitrary time-step t, the generic agent i can be: (1) currently cooperating with another agent j, where both of them played fair strategy at time $t-1$; (2) currently cooperating with another agent j, where i played fair and j played opportunistic strategy at time $t-1$; (3) currently cooperating with another agent j, where j played fair and i played opportunistic strategy at time $t-1$; (4) currently not cooperating with other agents.

In Case (1), that is, if i is currently cooperating with j and both of them played fair strategy at time $t-1$, i (j) changes its strategy from fair to opportunistic with probability $\omega(i)$ ($\omega(j)$). If none of them changes its strategy, both of them play fair strategy at time t, and the ISR is kept. Both agents learn that not changing strategy from fair to opportunistic strategy is convenient in order to keep an ISR; hence, $\omega(i)$ is decreased by $\Delta\omega(i,t)$, and $\omega(j)$ is decreased by $\Delta\omega(j,t)$, where both $\Delta\omega(i,t)$ and $\Delta\omega(j,t)$ are randomly defined between zero and 0.01. Otherwise, if both of them change strategy playing opportunistic, the ISR is interrupted. In this case, both agents learn that changing strategy from fair to opportunistic is detrimental for keeping an ISR; hence, $\omega(i)$ is decreased by $\Delta\omega(i,t)$, and $\omega(j)$ is decreased by $\Delta\omega(j,t)$. Finally, if i (j) changes strategy playing opportunistic and j (i) does not change strategy playing fair, j (i) keeps the ISR with probability $\delta(i)$ ($\delta(j)$). If i (j) decides to keep the ISR, j (i) learns that changing strategy from fair to opportunistic is convenient for itself because the economic advantage that it gains from the ISR is increased; hence, $\omega(j)$ ($\omega(i)$) is increased by $\Delta\omega(j,t)$ ($\Delta\omega(i,t)$). Figure 1 shows the flow chart of the dynamics above described.

In Case (2) (Case (3)), that is, if i (j) is currently cooperating with j (i), where i (j) played fair and j (i) played opportunistic strategy at time $t-1$, i (j) decides to interrupt the ISR with probability $\delta(i)$ ($\delta(j)$). If i (j) interrupts the ISR, j (i) learns that in the long period, i (j) is not willing to cooperate if j (i) plays opportunistic strategy. Hence, $\omega(j)$ ($\omega(i)$) is decreased by $\Delta\omega(j,t)$ ($\Delta\omega(i,t)$). If i (j) does not interrupt the ISR, j (i) learns that in the long period, i (j) is willing to cooperate even if it plays opportunistic strategy. Hence, $\omega(j)$ ($\omega(i)$) is increased by $\Delta\omega(j,t)$ ($\Delta\omega(i,t)$). Figure 2 shows the flow chart of the dynamics described above.

Finally, in Case (4), that is, if i is currently not cooperating with other agents, it seeks for another agent k in order to start a new ISR. The agent k is randomly selected. It may happen that (a) the agent k is currently cooperating with another agent and that (b) the agent k is not cooperating with another agent. If k is currently cooperating with another agent, it rejects the cooperation request (Figure 3). In this case, i remains as not cooperating. If at time $t-1$ it interrupted its ISR because it played fair strategy and its partner played opportunistic strategy, the agent i learns that interrupting an ISR can be detrimental for itself even in case of incentive misalignment. In fact, because i does not cooperate now with other agents, it does not gain any economic benefit from IS. Hence $\delta(i)$ is decreased by $\Delta\delta(i,t)$, where $\Delta\delta(i,t)$ is random between zero and 0.01. Alternatively, if k is not cooperating with other agents, agents i and k play fair strategy with probability $\varphi(i)$ and $\varphi(k)$, respectively. If both of them play *fair* strategy, the ISR arises. In this case, both agents learn that playing fair strategy is convenient in order to establish a new ISR; hence, $\varphi(i)$ is increased by $\Delta\varphi(i,t)$, and $\varphi(k)$ is increased by $\Delta\varphi(k,t)$. Furthermore, if agent i (k) interrupted the ISR at time $t-1$ because its partner played opportunistic strategy, it learns that such a decision was convenient for itself. In fact, the economic benefits gained by i (k) are now higher compared with the previous ISR. Hence, $\delta(i)$ ($\delta(k)$) is increased by $\Delta\delta(i,t)$ ($\Delta\delta(k,t)$). Otherwise, if both agents play opportunistic strategy, the ISR does not arise. In this case, both agents learn that playing opportunistic strategy is

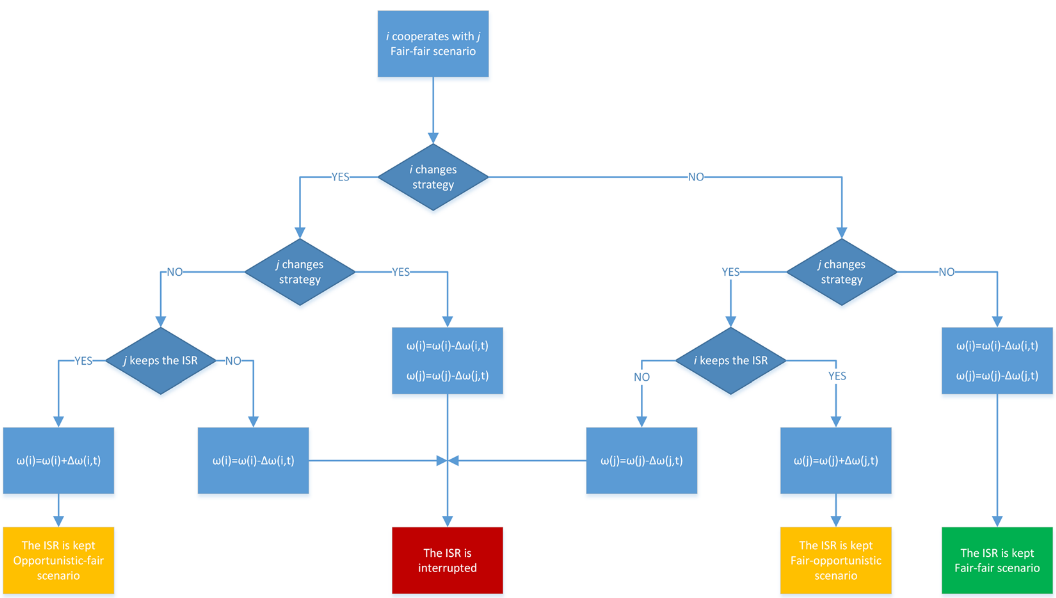

FIGURE 1 Flowchart of decisional rules for Case (1). ISR, industrial symbiosis relationship [Colour figure can be viewed at wileyonlinelibrary.com]

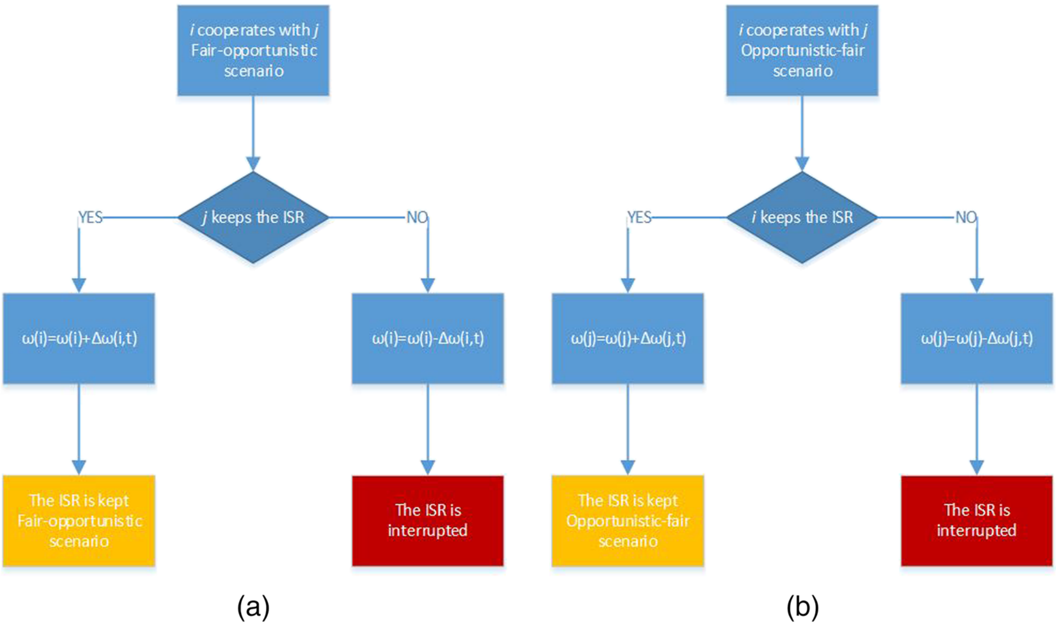

FIGURE 2 (a) Flowchart of decisional rules for Case (2); (b) Flowchart of decisional rules for Case (3). ISR, industrial symbiosis relationship [Colour figure can be viewed at wileyonlinelibrary.com]

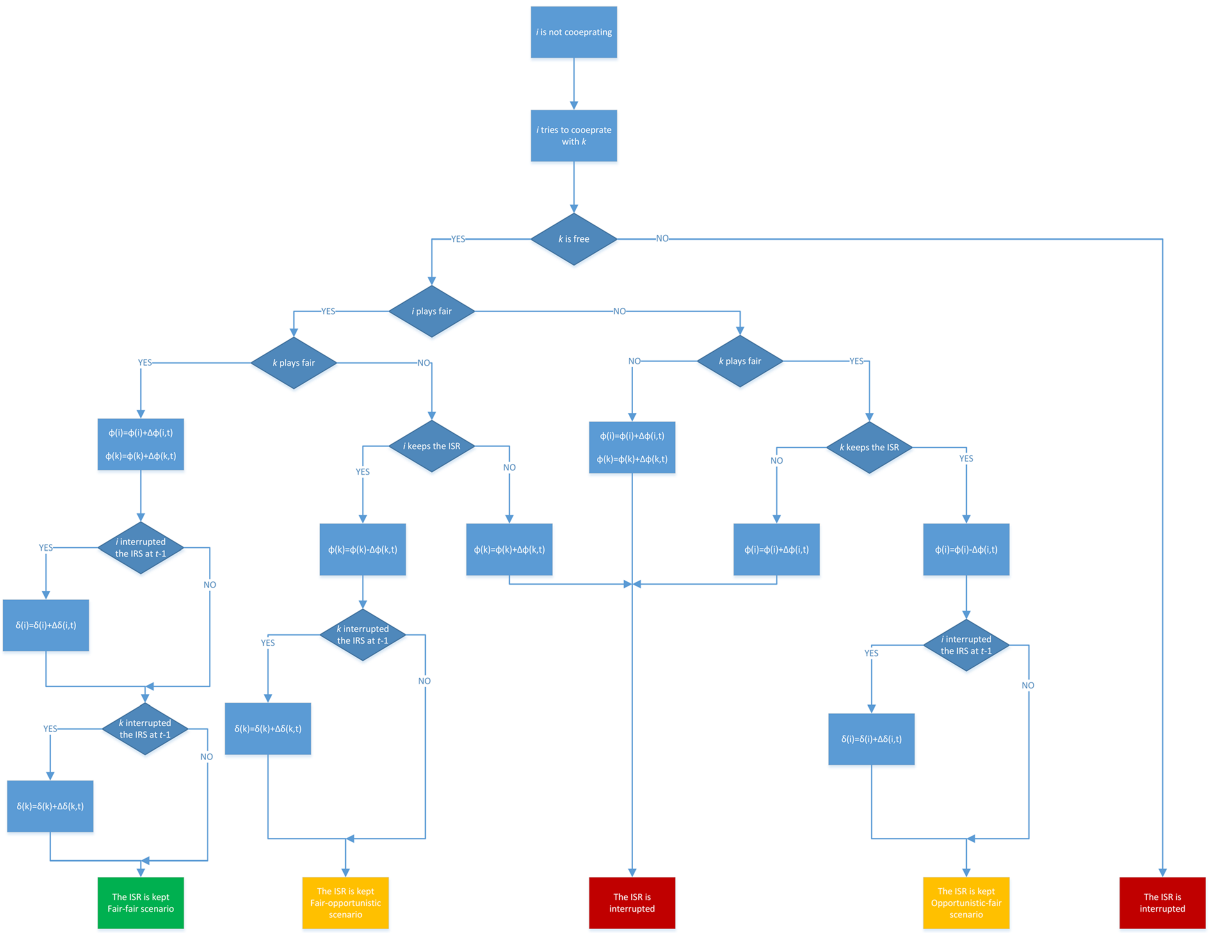

FIGURE 3 Flowchart of decisional rules for Case (4). ISR, industrial symbiosis relationship [Colour figure can be viewed at wileyonlinelibrary.com]

detrimental for establishing a new ISR: it hence $\varphi(i)$ is increased by $\Delta\varphi(i,t)$ and $\varphi(k)$ is increased by $\Delta\varphi(k,t)$. Furthermore, if agent i (k) interrupted its previous relationship, it learns that such a decision was detrimental for itself. Hence, $\delta(i)$ ($\delta(k)$) is decreased by $\Delta\delta(i,t)$ ($\Delta\delta(k,t)$). Finally, if i (k) plays fair and k (i) plays opportunistic, i (k) keeps the cooperation with probability $\delta(i)$ ($\delta(k)$). If i (k) decides to keep the cooperation, k (i) learns that playing opportunistic strategy is convenient in order to establish a new ISRs; hence, $\varphi(k)$ ($\varphi(i)$) is decreased by $\Delta\varphi(k,t)$ ($\Delta\varphi(i,t)$). Furthermore, if agent k (i) interrupted the ISR at time $t-1$ because its partner played opportunistic strategy, it learns that such a decision was convenient for itself. Hence, $\delta(k)$ ($\delta(i)$) is increased by $\Delta\delta(k,t)$ ($\Delta\delta(i,t)$). If the ISR is not kept, the agent i, who interrupted the previous ISR because its partner played opportunistic strategy, learns that such an interruption was detrimental; hence, $\delta(i)$ is decreased by $\Delta\delta(i,t)$. Figure 3 shows the flowchart concerning all of these decision rules.

4.2 | Simulation settings

The simulation considers 100 waste producers and 100 waste users interacting amongst each other for 1,000 runs. At the end of each simulation run, the values of parameters φ, ω, and δ of each company are collected. In particular, the higher the value of φ, the more firms learned that adopting fair strategy is convenient for long-term ISRs. In contrast, the higher the value of ω, the more firms learned that opportunistic behavior resulting from changing strategy from fair to opportunistic strategy when the partner is playing fair strategy is detrimental for long-term ISRs. Finally, the higher the value of δ, the more firms learned to defect the relationship if its partner is playing opportunistic strategy. Simulations are replicated 10,000 times, and values of φ, ω, and δ are averaged across the replications.

4.3 | Simulation results

Simulation results are shown in Figure 4. Let us first consider the parameter δ. It grows from 0.5007 at t = 1 to one at t = 449 and keeps this value until t = 1,000. Such a growth denotes that, if a waste producer (user) plays opportunistic strategy, in the long term, the waste users (producers) that are cooperating with the company learn that they can benefit more by defecting from the relation. In fact, they can establish new ISRs with other firms playing fair strategy and gain higher economic benefits. Such a collapse of relation might be costly for the waste producer (user) because immediately reduces the economic benefits it gains from the ISR. As a result, firms learn that playing the fair strategy is beneficial in the long term. In fact, the values of φ and ω support such an issue. In particular, as can be noted from the parameter φ, in the long period, the probability that companies play the fair strategy when starting a new game increases: φ grows from 0.4997 at t = 1 to one at t = 414 and keeps such a value until t = 1,000. The parameter ω shows two opposite trends over time: It grows from 0.5003 at t = 1 to 0.5442 at t = 153 and then decreases to 0 at t = 1,000. This is representative of the fact that, initially, firms try to take advantage from adopting opportunistic behavior, in particular by changing strategy from fair to opportunistic when both players are adopting the fair strategy. In fact, the company changing strategy increases its own economic benefits from the ISR if its partner is available to keep the relationship despite its economic benefits are reduced. However, as the values of the parameter δ show, in the long period, such a partner is more willing to interrupt the ISR with an opportunistic player because it learns that it can benefit more by defecting the relation. As a result, firms learn that opportunistic behavior aimed at taking more advantage from existing ISRs are detrimental for their economic results.

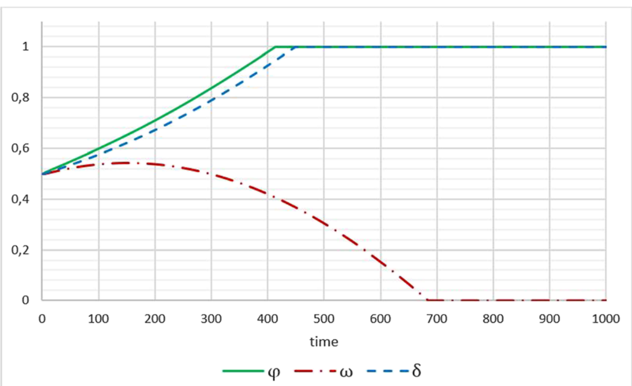

FIGURE 4 Simulation results [Colour figure can be viewed at wileyonlinelibrary.com]

5 | DISCUSSION

Findings of this paper show that companies enter in a learning process on how to develop business strategies while assessing IS opportunities. In particular, it is highlighted that playing the opportunistic strategy is not a stable solution for companies, as it only provides short-term benefits. Moreover, an opportunistic strategy results in a higher chance of losing partners; hence, playing this strategy makes it challenging to keep a symbiotic relation—and its related benefits—over time. Changing from opportunistic to fair behavior enables companies to find a *fair-playing* partner quicker and therefore implementing IS business becomes easier. This also indicates a *fair play* strategy for companies when they first launch the negotiation phase. On an abstract level, our results show that to implement IS (and in the long run to comply with sustainability goals), it is not necessary to expect that firms should suffer financially. In contrast, we are showing that firms can learn to achieve a collectivity-oriented perspective and at the same time contribute to sustainability goals in a profitable manner.

These results are in line with the literature highlighting the key role of cooperative strategies for the success of the IS practice in the long period (e.g., Ashton & Bain, 2012; Chertow, 2000; Lambert & Boons, 2002). Our results show that the willingness to adopt opportunistic behavior is reduced in the long period, although it might rise in the short–medium period. In this regard, opportunistic behavior can be discouraged by developing trust between the companies involved in ISRs (Baas & Huisingh, 2008; Hewes & Lyons, 2008). According to Yazdanpanah et al. (2019), this might be a challenge particularly when the number of potential cooperators is limited in the geographic proximity, which is a game changer. In contrast, implementing trust with other potential cooperators might be easier when there is a sufficient number of potential cooperators in the given geographical proximity.

From the methodological perspective, agents learn because path dependence is recognized as a driving factor of the current decisions of companies (Doménech & Davies, 2011). Considering the two ISR strategies presented in Section 3, that is, fair and opportunistic strategies, the results highlight that in the long term, firms learn to implement the fair strategy. This is because in case the generic firm *A* applies the opportunistic strategy, in the long term, other firms that are in relation with *A* learn that they can benefit more by defecting the relation. Such a collapse of relation might be costly for *A*, as it has to establish new ISRs and pay further penalty costs. This learning process is in line with the role of *path dependence* in the context of IS. In fact, firms are strongly influenced by their past ISRs when taking decisions about their current relationships (Boons & Howard-Grenville, 2009; Doménech & Davies, 2011). Considering Table 1, in any time step, ISRs can either take place in a fair–fair form or in a fair–opportunistic form (and never in an *opportunistic–opportunistic* manner). As we discussed above, while in single-shot ISRs, an opportunistic strategy results in higher benefit for industrial firms, in the long term, the opponent firms (on the other side of the relation) may defect the relation and establish new relations. The proposed ABM can be used as an illustrative tool for managers of industrial clusters as well as regional policy makers, aimed at showing them that companies should be pushed through a sustainable behavior (for a case study that supports this finding, readers are referred to Albino, Dangelico, & Yazan, 2010).

The findings of this paper have also implications from the perspective of agent-based computational economics (Leigh Tesfatsion, 2002). For this account, we first focus on—as phrased by Schelling (2006)—*linking micro-motives to macro-behavior* and then discuss the ability to reach a social equilibrium through learning processes.

In ISRs, understanding the relation between motives of individual industrial agents and the failure/establishment of long-time relations calls for methods to link motives in the firm-level (micro-motives) and the global behavior of a collection of firms (macro-behavior). This is basically because the macro-level behavior of ISRs, for example, that all firms *play* fair over time, is not a straightforward extension of micro-level motives, for example, to maximize the benefits regardless of the opponent's benefits. This is a challenge that Schelling (2006) calls the lack of descriptive concepts to explain such counterintuitive macro-behavior and relate them to micro-motives. Our results show that the ability of industrial decision makers to “learn from their experiences and history” is a link to explain the dominance of fair–fair ISRs in the long term. Therefore, although a selfish company may implement opportunistic strategies to maximize the (short-term) benefit, in the long run, the society of agents learns from the past and tends to implement fair–fair strategies. In a nutshell, in case of ISRs, learning would be a candidate to answer Schelling's concern about linking individual motives to social behavior (see more on the concept of learning in cooperative multi-agent settings; readers interested to the concept of learning in cooperative multi-agent settings are referred to Panait & Luke, 2005).

As shown in Section 4, there are two Nash equilibria in the single-shot ISR games. However, as discussed in Aumann (1990), Nash equilibria are not situations that could be reached effortlessly among a population of agents. In this work, we simulate the evolution of ISR games and show that the ability to learn can act as a self-organizing mechanism and enriches the agents involved in ISRs, leading to self-organizing ISRs that reach the fair–fair equilibrium as a social equilibrium (in the sense of Gilboa & Matsui, 1991) in the absence of external interventions. Note that self-organizing mechanisms are well studied in communication networks (e.g., Dressler, 2008). Therefore, this paper opens a new research line for studying such mechanisms for IS research.

6 | CONCLUSIONS

This paper has theoretical, managerial, and policy implications.

In terms of theoretical implications, the integration of ABM with game theory for analyzing ISRs is an innovative approach, as to our knowledge, no studies took place in the literature integrating two approaches in the field of IS. Organizational learning for (particularly self-emergent) IS networks is not in-depth analyzed in the literature of IS; hence, this paper extends the applicability of game theory integrated ABM for organizational learning of companies to achieve sustainable behavior.

With regard to the managerial implications, this paper highlights different dynamics that can take place in the construction of ISRs and explains them through a game model. This model is useful for managers to take more precise decisions with as much information as possible referring to cooperation between companies. The results of this paper suggest that managers play fair when establishing or operating ISRs. Ashton and Bain (2012) observe that IS synergies resemble product sales more closely than informal relations, that is, that ISRs are primarily economic transactions and are embedded within social relations to a lesser degree. In this context, playing fair means “do not manage IS synergies as arm's length relationships,” for example, trying to capture the greatest part of the value overall created by the synergy. In fact, in this case, the (potential) partner would capture a scant value from the relationship and, therefore, he/she would have a limited willingness to cooperate. This is detrimental for ISRs. Moreover, playing fair should be associated with developing trust with the symbiotic partner. High trust between two companies means that companies might be sure that their partners will not put in practice opportunistic behavior over time. This allows both companies to make joint investments in the relationship, for example, in logistical and operational issues that increase the efficiency of the ISR and further contribute to reducing the 3T costs (see Section 1). Such a practice would highly contribute to the further development of self-organized ISNs.

The transaction between firms involved in ISRs results in undoubted environmental benefits, in the form of reduction of landfill saturation, as well as a decrease in the environmental impacts related to the use of conventional raw materials. However, because the transaction is highly dependent upon actors' behavior (or simply IS additional costs do not allow better payoff), policy makers may encourage the establishment of the transaction, providing incentives to the involved actors—either to both of them or to just to the one with the lower contractual power—because this actor could be the most motivated to not enter or leave the transaction. In this way, positive externalities could be internalized by actors contributing to the improvement of environmental benefits. Taking into account the *local* character of sustainable supply chains, such incentives may also be used within regional and interregional environmental policy frameworks. However, there is still a need for efficient tools, which can integrate the accounting of externality reduction in the computation process in decision making. In this sense, this paper might be a leading one to indicate research need for such tools facilitating the application of environmental accounting and (economic-oriented) decision making simultaneously. Furthermore, policy makers could contribute to developing the culture of trust among companies already or potentially involved in ISRs, for instance, by spreading examples of successful ISRs driven by the fair play between the partners.

This paper proposes also a novel business strategy development as *circular economy* calls for new business models that would facilitate the operation of the waste-based businesses to gain value-added while preserving primary resources. Further research may include the optimization of the payoffs for companies involved in ISRs taking into account the instable character of reusable end-of-life products (whose supply chains structurally differ from ISR-based supply chains), in terms of quality level and continuity of supply. Moreover, in future agent-based simulations, we aim to take into account other operations-oriented dynamic parameters, that is, physical quantity of resources, presence of environmental regulations, and alternative buyers/suppliers. Such factors may affect the companies' contractual power, as well as their willingness to cooperate. Our future research avenue is modeling actors' behavior through multi-player iterative games, where firms are involved in multidimensional ISNs. Finally, future investigation is required to shed light on the role of IS online platforms (e.g., Fraccascia & Yazan, 2018) in assisting companies when negotiating the economic terms of symbiotic synergies, aimed at driving companies towards the fair play. This is also associated with the modality of the use. For example, SHAREBOX platform[5] proposes two cost- and benefit-sharing tools, namely, Cost Allocation in Industrial Symbiosis Relations (COSTIS) and Evaluating Industrial Symbiosis Opportunities (EVALIS), which assist business managers to filter the promising IS opportunities and to fairly negotiate the cost and benefit sharing. The tools can be used as single or dual mode, which offers also secure data sharing. Such tools might be spread more in the future as they are needed to properly operate circular business models (Fraccascia, 2020).

[5]SHAREBOX is an online platform for IS whose design has been funded by the European Union's Horizon 2020 research and innovation program.

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APPENDIX A.

Figure 5 shows results of the simulation obtained by changing the values of the parameters $\Delta\varphi$, $\Delta\omega$, and $\Delta\delta$. It can be noted that the outcome of the simulation does not change. This contributes to confirm the validity of the simulation model.

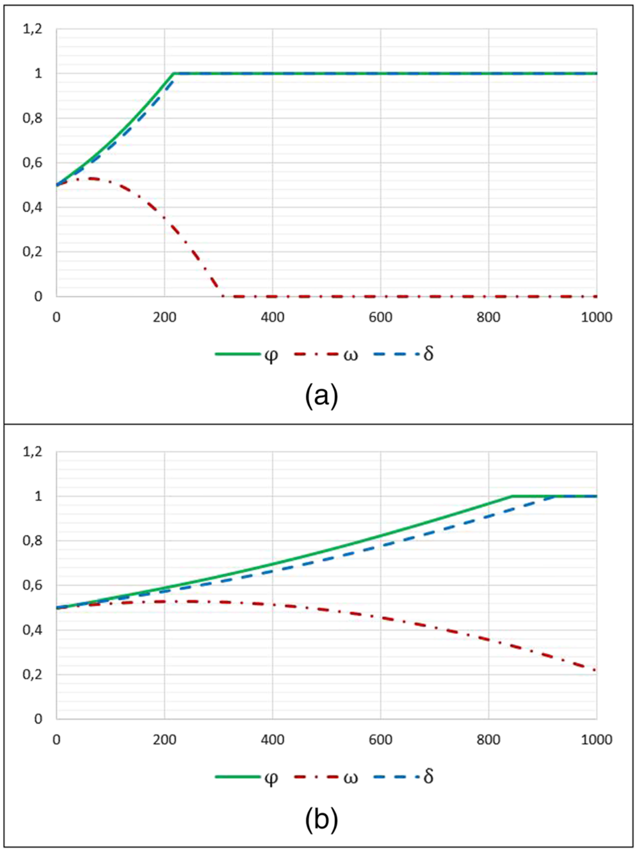

FIGURE 5 Simulation results with (a) Δ ranging between 0 and 0.02; (b) Δ ranging between 0 and 0.005 [Colour figure can be viewed at wileyonlinelibrary.com]