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Research Article

Impact of Business Interoperability on the Performance of Complex Cooperative Supply Chain Networks: A Case Study

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This paper proposes an agent-based model for evaluating the effect of business interoperability on the performance of cooperative supply chain networks. The model is based on insights from the Industrial Marketing and Purchasing network approach and the complex systems theory perspective. To demonstrate its applicability, an explanatory case study regarding a Portuguese reverse logistics cooperative supply chain network is presented. Face-to-face interviews and forms were used to collect data. The findings show that the establishment of appropriate levels of business interoperability has helped to reduce several non-value-added interaction processes and consequently improve the operational performance of the Valorpneu network. Regarding the research implications, this paper extends the current knowledge on business interoperability and an important problem in business: how business interoperability gaps in dyadic organizational relationships affect the network of companies that the two companies belong to—network effect. In terms of practical implications, managers can use the proposed model as a starting point to simulate complex interactions between supply chain network partners and understand better how the performance of their networks emerges from these interactions and from the adoption of different levels of business interoperability.

1. Introduction

It has been widely recognized that, in an era in which the traditional competition between companies has been replaced by competition between supply chain networks (SCNs) [1, 2], individual companies no longer compete as independent entities [3, 4] with unique brand names but instead as integral parts of SCN relationships [5, 6]. As a consequence of this change of the business context to a network-driven economy, companies have been increasingly forced to establish cooperation with SCN partners and other external entities [7] in order to obtain mutual benefits by sharing or partitioning work [8], increase efficiency, improve environmental performance [9], resolve common problems [10], enable market creation [11], provide superior value [12, 13], and establish a superior competitive position [14–16]. This in turn leads to cooperative SCNs, which are defined in this research as set of three or more companies with symbiotic interests that join and efficiently combine the most suitable set of skills and resources (e.g., knowledge, capital, and assets) for a time interval in order to achieve a common set of objectives [17].

However, because systems that support the operations in many companies were created independently [18], some challenges that SCN managers may face when it comes to establishing cooperation are misaligned and conflicting business goals, misaligned management approaches, misaligned business processes, misaligned methods of work, misaligned legal bases, multiple sources of data, heterogeneous and incompatible information technology, and so on (see [4, 19, 20]). To address these problems, business interoperability, often referred to as enterprise interoperability (e.g., [4, 21, 22]), has been widely pointed out as one of the main disciplines that has enabled companies to establish effective cooperation [23]. Its relevance to cooperative SCNs is evident. For example, Brunnermeier and Martin [24] estimated that, in the US automotive supply chain (SC), inadequate business interoperability delays the introduction of new models by at

least two months and costs the members of this industry at least US $1 billion per year. Business interoperability can be defined as *"the ability of two or more business units, as well as of all systems within their boundaries and the external systems that they utilize or are affected by, to work together"* (adapted from [25]).

An analysis of the current literature reveals that, despite the high expectations concerning the effects of business interoperability on the performance of organizations, research in this field focuses mainly on developing architectures (e.g., [26, 27]), frameworks (e.g., [20, 28–30]), maturity models (e.g., [22, 31]), and methods/standards (e.g., [19, 32–35]). Indeed, as shall be discussed further below, only very little empirical research has been carried out regarding the analysis of the effects of business interoperability on the performance of companies, particularly in complex cooperative SCN contexts (see, e.g., [24, 36–39]).

An examination of these studies reveals that, despite their significance to the development of theory on business interoperability, they do not provide insights on how different levels of business interoperability in dyadic organizational relationships affect the performance of the two companies in the dyads and, more importantly, how different levels of business interoperability in dyadic organizational relationships influence the performance of the network that the two companies in the dyad belong to. In this research, the spread of the effects of different levels of business interoperability over the cooperative SCN is called network effect—a phenomenon that occurs in complex systems where the actions or behavior of a system's component have effects on the other system's components. Addressing the network effect in the analysis of the impact of business interoperability on the performance of cooperative SCNs is important because, as emphasized by Håkansson and Snehota [40], the impacts of a dyad relationship are not limited to the two companies in the dyad; that is, other entities and dyads may be impacted. Limiting the analysis only to the performance of the two companies involved in the dyads does not allow a great understanding of the true effect of business interoperability on the performance of cooperative SCNs. In addition, they do not provide any guideline about how to predict the effect of business interoperability on the performance of a new cooperative SCN for being designed and how improvements in the level of interoperability affect the network performance over time. A level of business interoperability is a concept that is used to characterize the state at which a business system can be situated in terms of interoperability with other business systems [31], that is, a measure of how interoperable two or more connected business systems are [28]. Defining certain levels of business interoperability in the analysis of the effects of business interoperability is important to distinguish different interoperability requirements and to serve as a guideline for improving the business interoperability performance of business systems [28, 41].

Another relevant gap is that those studies addressed the analysis of the impact of business interoperability by investigating the companies individually, assuming that no specific links are supposed to exist among the companies in the network. Put differently, the unit of analysis was set at the organizational level instead of at the dyad relationships level. As Johnston [42] (cited in [43]) emphasized, grounding on any individual company/dyad cannot offer any great understanding of the business interactions. To overcome the research gaps identified above, this research presents a model that can be used to analyze the effect of business interoperability on the performance of complex cooperative SCNs. In seeking to achieve this goal, the following research question was posed:

How can we analyze the effect of business interoperability on the performance of complex cooperative supply chain networks?

To address this research question, the following research stance was defined:

Agent-based simulation provides an effective set of tools for analyzing the effect of business interoperability on the performance of complex cooperative supply chain networks.

Agent-based simulation (ABS) is a modeling tool used by researchers from different areas of knowledge to understand and analyze complex patterns that result from the interaction of many individuals within an environment [44]. The justification for choosing ABS as the modeling tool to address the above research question is provided in Section 4.1.

The remainder of this paper is structured as follows: the following section discusses the concept of business interoperability and the aspects of the complex system theory (CST), following the development of an extended business interoperability framework and research hypotheses. The rationale for using ABS and the details of the ABS model are provided in the section thereafter. The paper goes on to test the applicability of the model through a case study regarding a Portuguese reverse logistics (RL) cooperative SCN and ends with the conclusions and suggestions for the forthcoming work.

2. Theoretical Foundations

2.1. Business Interoperability: An Overview. Interoperability has been mostly defined and addressed from the technical perspective (see [45]). This is revealed in one of the most cited definitions of interoperability [46]: *"the ability of two or more systems or components to exchange information and use the information that has been exchanged."* However, interoperability is not only an issue of exchanging information through information and communication technology (ICT) systems (e.g., [18, 45]). There are other dimensions such as interorganizational processes, culture, and the management of contractual issues between the business partners [8]. As a result, the concept of interoperability has been increasingly replaced by business interoperability in order to include the human and organizational elements (e.g., [28, 29, 32]). The definition of business interoperability adopted in this paper is the one provided in Section 1.

2.2. Business Interoperability Frameworks. The current literature includes many elements that have been identified in and around the business interoperability (e.g., [4, 26, 28, 29]), supply chain management (SCM) (e.g., [47–50]), business relationships (e.g., [51–53]), complex SCNs (e.g., [54–58]),

and collaboration (e.g., [59–62]) literature as responsible for the relationships between two or more companies. In the context of this research, the elements of these literature strands are grouped into categories that are named dimensions of business interoperability. A dimension of business interoperability can be defined as the different aspects of business interaction that two or more companies can engage in (e.g., business strategy, management of external relationships, cooperative business processes, business semantic, and information systems) [29]. As implied in this definition, business interoperability is a multidimensional concept that can be viewed and approached from various perspectives, and therefore many frameworks have been proposed to reconcile all the perspectives, approaches, and directions, which are frequently different [63].

A review of the business interoperability literature suggests that there is no shortage of frameworks for modeling interoperability in different business contexts. Among the frameworks published so far, the Levels of Information Systems Interoperability (LISI) [41] is often regarded as the first significant initiative carried out to address interoperability (e.g., [31, 64]). However, it is often criticized due to its "strong" focus on the technical aspect of interoperability [31, 65]. Acknowledging this limitation, frameworks such as the IDEAS interoperability framework [66], the European Interoperability Framework [67], the ATHENA interoperability framework [68], the E-health interoperability framework [69], and the Framework for Enterprise Interoperability [70] have been developed to capture other aspects of business interoperability such as business strategy, business processes, and knowledge management. Although these have been pointed out as some of the most relevant interoperability frameworks (e.g., [22, 26]), they do not incorporate a number of factors associated with the network complexity, which limit their use or make it difficult in the analysis of interoperability in complex business network contexts. In the attempt to overcome this limitation, ATHENA [28] developed the business interoperability framework to support the analysis of collaboration between networked organizations, which has been used as the reference to develop the Zutshi et al.'s [29] framework. This framework captures eight dimensions of business interoperability, called business interoperability parameters, and further identifies subdimensions to allow measuring performance for each parameter (see [29]). In comparison with the frameworks mentioned above, ATHENA's [28] and Zutshi et al.'s [29] frameworks enable a more holistic approach to business interoperability as they incorporate a greater number of business interoperability factors, which are also better organized into five and eight categories, respectively. However, despite recognizing their contribution to the business interoperability literature, we argue that, in order to examine the interactions among companies in complex cooperative SCNs, a more holistic framework is needed. This is in line with Corella et al. [71], who stress that there are scarce practical examples of an SC interoperability framework that can be applied as a reference, and therefore more holistic frameworks must be designed to support the improvement of business interoperability performance. Zutshi et al. [29] also recognized that as the effects of business interoperability across multiple companies in a network need to be further explored, future investigations should adapt their framework in order to be used in a network-based context.

From our perspective, ATHENA's [28] and Zutshi et al.'s [29] frameworks have two relevant limitations. First, they do not capture all relevant dimensions of business interoperability and even those that are incorporated do not include all relevant subdimensions. For example, in the dimension business strategy, issues such as alignment and visibility of cooperation goals are missing. Trust and transparency are missing in the dimension of management of external relationships. Alignment, coordination, integration, flexibility, and monitoring are also missing in the dimension cooperative business processes. Also, they do not incorporate elements related to one essential dimension of business interoperability, that is, Information Quality (see [72]). With regard to this, note that the subdimensions of information quality (e.g., accuracy, timeliness, and completeness) were not incorporated in any of the business interoperability frameworks published so far. The second limitation is related to the design of these frameworks, which was not supported on any relevant network or complexity theory. We argue that as business interoperability in network-based contexts is a multidimensional construct consisting of many related dimensions and subdimensions, making the network even more complex, a network theory is needed to address such complexity. For this reason, this research is grounded on the CST, which advocates that complex systems, as are the examples of cooperative SCNs, should be analyzed in a holistic and systemic way (e.g., [73]) (see the next section).

2.3. Complex Systems Theory. As a relatively new research discipline, CST can be seen as a metatheory that deals with the research of complex systems [74, 75]. For example, in the SCM literature, it has been widely used as a theoretical lens for analyzing complex SCNs [76], providing theoretical frameworks for a number of SCN related publications (see, e.g., [54–58, 73, 77–80]).

The rationale for addressing CST in this research is not limited to the design of our business interoperability framework, which is associated with the aspect of decomposability. From the perspective of CST, as SCN systems are embedded in an open and dynamic environment and interact with it [54], there are eight major aspects that must be taken into account when modeling this type of systems (see [54, 81, 82]): decomposability, dimensionality, reflexivity, nonlinearity, emergence, ability to learn, self-organization, and quasi-equilibrium. Indeed, these aspects have a number of implications for this research. For example, the aspect decomposability, which helps to separate subsystems from one to another [81], is important to decompose the business interoperability construct into detailed dimensions and subdimensions that can be clearly understood, measured, and managed. This facilitates the design of the extended business interoperability framework (see Figure 1) as well as the measurement of its constructs through a maturity model. Dimensionality addresses the degree of freedom that individual companies within the cooperative SCN have to

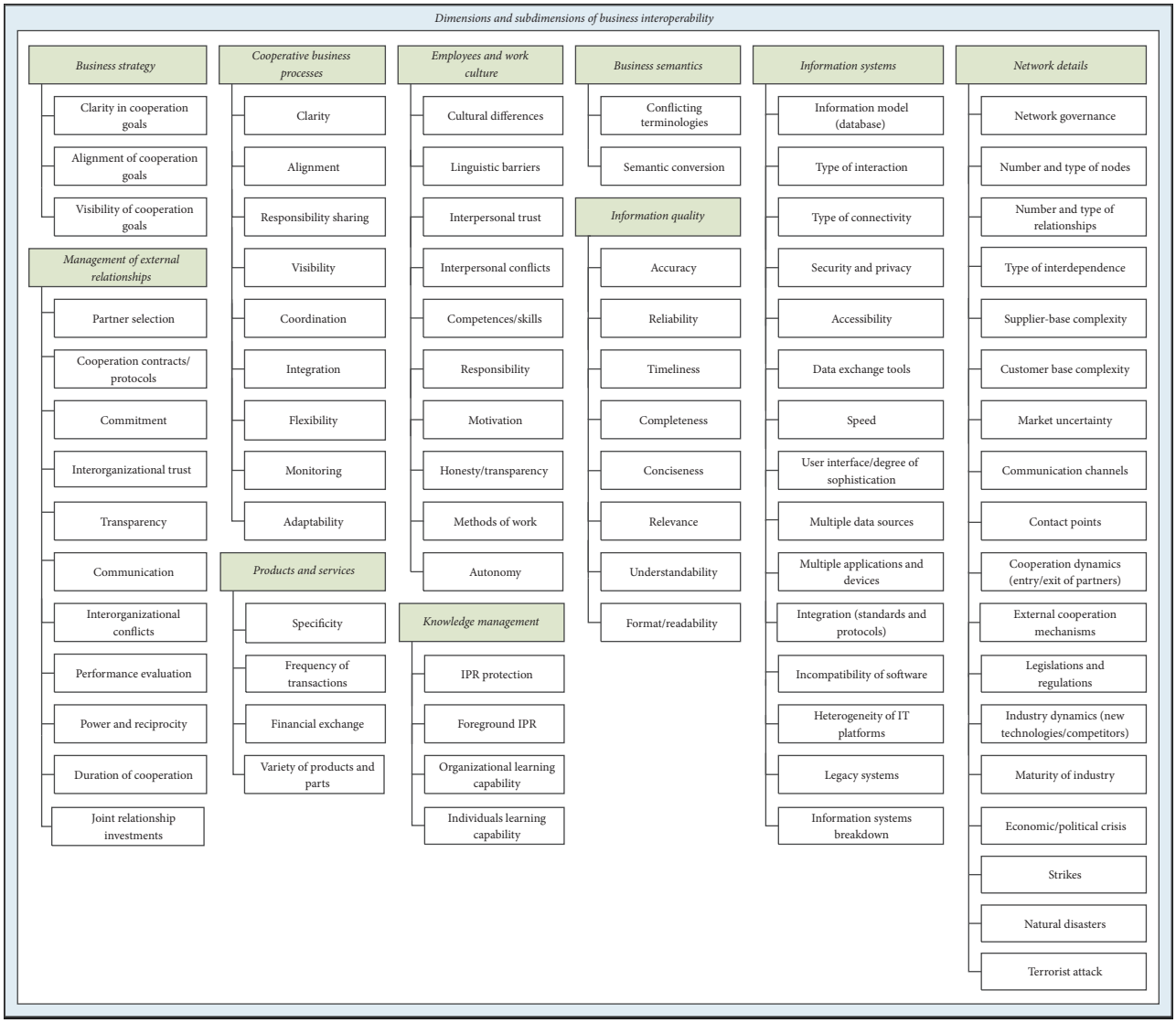


Figure 1: Extended business interoperability framework (adapted from [29]).

behave autonomously [81]. In the scope of this research, it is important to understand the dimensionality of the cooperative SCNs because [81] (1) SCNs with high dimensionality tend to be difficult to control and tend to be too uncooperative harnessing the achievement of the cooperation goals and (2) too less dimensionality implies lees autonomy to invest on innovative cooperation mechanisms, also hampering the value that business interoperability can provide to the whole SCN. Therefore, it is important to measure and maintain cooperating partners freedom in efficient levels.

Reflexivity suggests that as cooperative SCNs are frequently changing and adapting to new market and/or internal needs, the behaviors of each agent in the network have effects on the other agents around it [81]. For example, by closing emergent interoperability gaps, establishing or eliminating relationships in the cooperative SCN, the performance of the other agents in the network can be affected. This in turn might force the other agents to act in response to those changes, hence causing a reflexive impact on the performance of the whole network. There is an interoperability gap when the current level of business interoperability on a particular situation of interaction does not match the required level. Nonlinearity suggests that cooperative SCNs contain critical nonlinear characteristics where a small change can be magnified to impact the whole network [81]. For example, "changes to the master schedule quantities can have unpredictable, nonlinear impacts on the individual material plans due to differences in planning lead times, lot-sizing rules, and inventory levels for lower level components" [57]. Interoperability gaps in a given dyad relationships may have different impacts on different dyads/companies. Emergence is the arising of new, unexpected patterns, structures, processes, or properties in the whole network [54]. These highly structured collective behaviors, which are not easy to predict by knowing only the

behavior of the individual agents, come from the interactions between these individual agents [83]. With reference to cooperative SCNs, two of the emergent phenomena that can arise are demand amplification and inventory swing. For example, the delays downstream and decisions in an SC often lead to amplifying a nondesirable effect upstream, a phenomenon usually called the "*bullwhip*" effect [82]. Another key idea of emergent properties is that the outcome of those interactions leads to the concept of synergy, suggesting that the sum of the individual parts is more than the system as a whole [84]. Again, with reference to this study, the establishment of appropriate levels of business interoperability in the dyad relationships throughout the cooperative SCN might enable effective interactions between its partners, hence resulting in a performance that might be higher than the sum of the performance achieved in each dyad. Note that this aspect, along with reflexivity and nonlinearity, reinforces the importance of addressing the network effect in the analysis of the impact of business interoperability on the performance of cooperative SCN, as discussed in Section 1.

Ability to learn suggests that intelligent systems, as are the examples of cooperative SCNs, are able to adapt their individual capabilities and improve their performance as experience accumulates [81]. In the ambit of this research, it implies that cooperative SCNs must retain past knowledge on their interoperability experience and use it to learn how to improve their interoperability performance. This requires effective sharing and storage of information on the interoperability experience, which can be used to support decision-making regarding the interoperability mechanisms to be implemented. Self-organization occurs when, based on a certain degree of intelligence, a system uses acquired knowledge to change its internal structure in order to better interact with its environment and adapt automatically to external changes [81]. In the specific case of cooperative SCNs, the interactions among their companies are affected by a set of external events such as the introduction of new legislations and regulations, introduction of new technologies, natural disasters, and economic and political crisis. These events may cause disruptions in the cooperative SCN operations and, in this situation, the cooperative SCN must use its experience to self-organize and recover to a business interoperability state that is equal to or greater than the one when the disruptions occurred.

Last, a system is in quasi-equilibrium when it is prevented from collapsing into randomness but still retains enough freedom to evolve and adapt to the environment whenever needed [81]. In the ambit of this research, it refers to the ability of a cooperative SCN to oscillate between a state of network equilibrium where companies interact normally with interoperable relationships and nonequilibrium characterized by a network with fuzzy relationships or with interoperability issues such as misaligned objectives, business processes and information systems, interorganizational conflicts, and responsibilities not well defined. It is therefore necessary to have in place effective interoperability mechanisms in order to minimize these oscillations and maximize the time cooperative SCNs are operating linearly profiting from a maximum efficiency from the interoperable relationships [81].

2.4. Agent-Based Simulation. ABS is a relatively new computational method that enables a researcher to create, analyze, and experiment with models composed of agents that interact within an environment [85]. It is an approach to modeling complex systems composed of interacting, autonomous agents [86], and to investigating aggregate phenomena by simulating the behavior of individual agents, such as consumers or organizations [44]. In other words, it is a method for modeling Multiagent Systems (MAS) which consist of a set of elements (agents) characterized by some attributes and behaviors, which interact with each other through the definition of appropriate rules in a given environment [87]. Specifically, a MAS is defined by Monostori et al. [88] as a network of agents that interact and typically communicate with each other. Agents refer to any autonomous entity with its own properties, behaviors [44], and decision-making capability [89].

According to Giannakis and Louis [90], the agent-based technology is acknowledged as one of the most promising technologies for effective management of complex systems such as SCNs due to the vital properties of agents, which are summarized, for instance, in Michael and Jennings [91], MacAl and North [86], and Barbati et al. [87]:

(1) *Autonomy*. Agents are able to operate without the direct intervention of humans or others and have some kind of control over their actions and internal state. In other words, agents are aware of their environment operating and control their own actions as well as internal states in order to fulfil their objectives. In particular, the user does not interfere with their decision-making, after they specified their rules.

(2) *Social Ability*. Agents are able to interact with other agents (and possibly humans) via some kind of agent-communication language or common actions.

(3) *Reactivity*. Agents are able to perceive their environment, including other agents, and they are able to react on the basis of these perceptions; that is, they are able to respond in a timely fashion to changes that occur in their environment.

(4) *Proactiveness*. Agents do not simply respond to changes in their environment but can initiate actions in order to satisfy their specified objectives.

3. Hypotheses Development

3.1. Framework of Reference. The framework developed in this research to support the analysis of the effect of business on the performance of cooperative SCNs (see Figure 1) is an extended version of Zutshi et al.'s [29] framework. It was designed to overcome the limitations of the frameworks discussed in Section 2.2. The rationale for choosing Zutshi et al.'s [29] framework as the reference is that it draws upon the literature review of most of the previous interoperability frameworks and because it focuses on the dimensions of

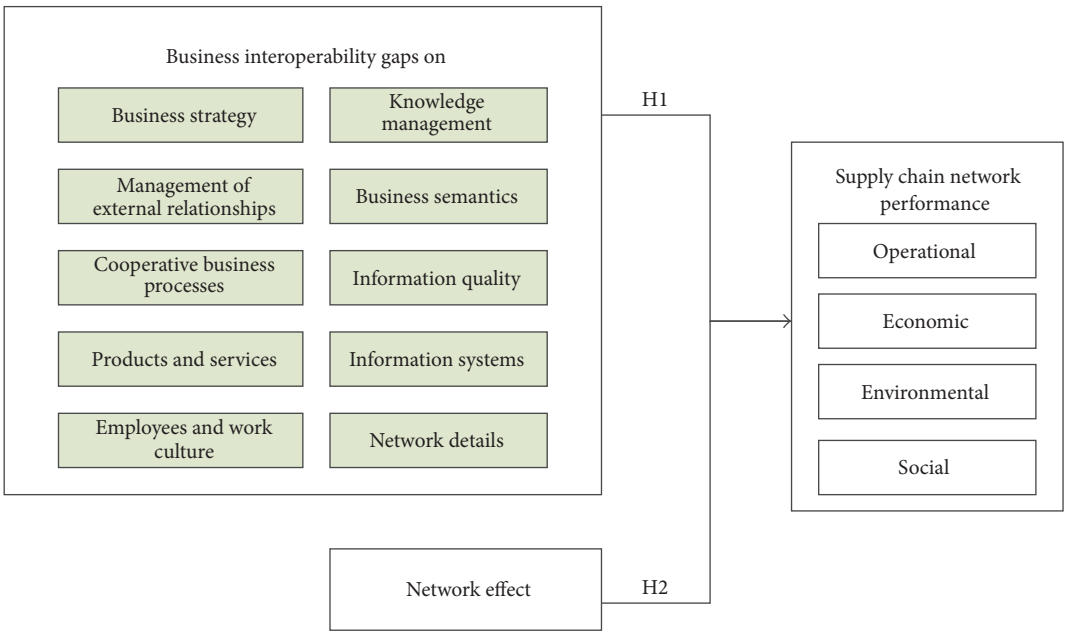


Figure 2: Conceptual framework.

business relationships between collaborating partners, which can also be applied to the context of cooperation. Given that business interoperability is a multidimensional concept, it has been built on the following assumption:

Business interoperability is a multidimension concept that considers not only the information systems configuration characteristics but also other dimensions such as management of external relationships, business strategy, cooperative business processes, employees and work culture, products and services, knowledge management, information quality, business semantics, and network details.

The dimensions of business interoperability included in Figure 1 will be used as constructs in the development of the research hypotheses, the theoretical framework (see Figure 2), and the theoretical ABS model (see Section 4.2). The description of each dimension and subdimension of business interoperability provided in Figure 1 can be found in Cabral [92]. Given that most of the constructs included in that framework are abstract and their integration in the ABS model depends on the business interoperability requirements of the cooperative SCN under analysis, the Axiomatic Design Theory [93, 94] was used to decompose them into detailed constructs that can be easily measured and modeled (see Figure 3). The Axiomatic Design Theory is a design methodology that is used by designers to decompose and structure the components of a complex system in a logical and rational way [94].

3.2. Linking the Levels of Business Interoperability to SCN Performance. Business interoperability has been regarded as an important source of business value [36] and a challenge affecting the success of companies' deployment [95]. For example, Brunnermeier and Martin [24] analyzed the US automotive SC and concluded that imperfect interoperability is very costly and that fixing its problems may help to improve the performance of the industry by minimizing cycle time and cost. Jardim-Goncalves et al. [96] stress that business interoperability is a factor with high impact on the productivity of both the public and private sector, impacting the overall quality, cost of transactions, and yield time, as well as the design of industrial processes and digital public services.

Indeed, empirical evidence shows that business interoperability has a significant effect on the business performance, mainly on the economic and operational dimensions. A classic example is Brunnermeier and Martin's [24] study, mentioned in Section 1. Another example is the Loukis and Charalabidis' [36] study, which concluded that the adoption of information systems interoperability standards such as proprietary, industry-specific, and eXtensible Markup Language- (XML-) based (http://www.w3.org/XML/) ones has a significant positive impact on the four dimensions of performance proposed by the balanced scorecard (customers, learning and innovation, financial, and internal business processes). Additional empirical studies on the impact of interoperability are Gallaher et al. [37], Gallaher et al. [38], and White et al. [39]. These studies suggest a link between business interoperability and economic/operational performance of cooperative SCNs. The performance of a business system refers to how efficiently and effectively it is able to transform the inputs to outputs [28]. Economic performance relates to the SCNs' ability to reduce costs associated with purchased materials, energy consumption, waste treatment, waste discharge, and fines for environmental accidents, while operational performance relates to the SCNs' capabilities to

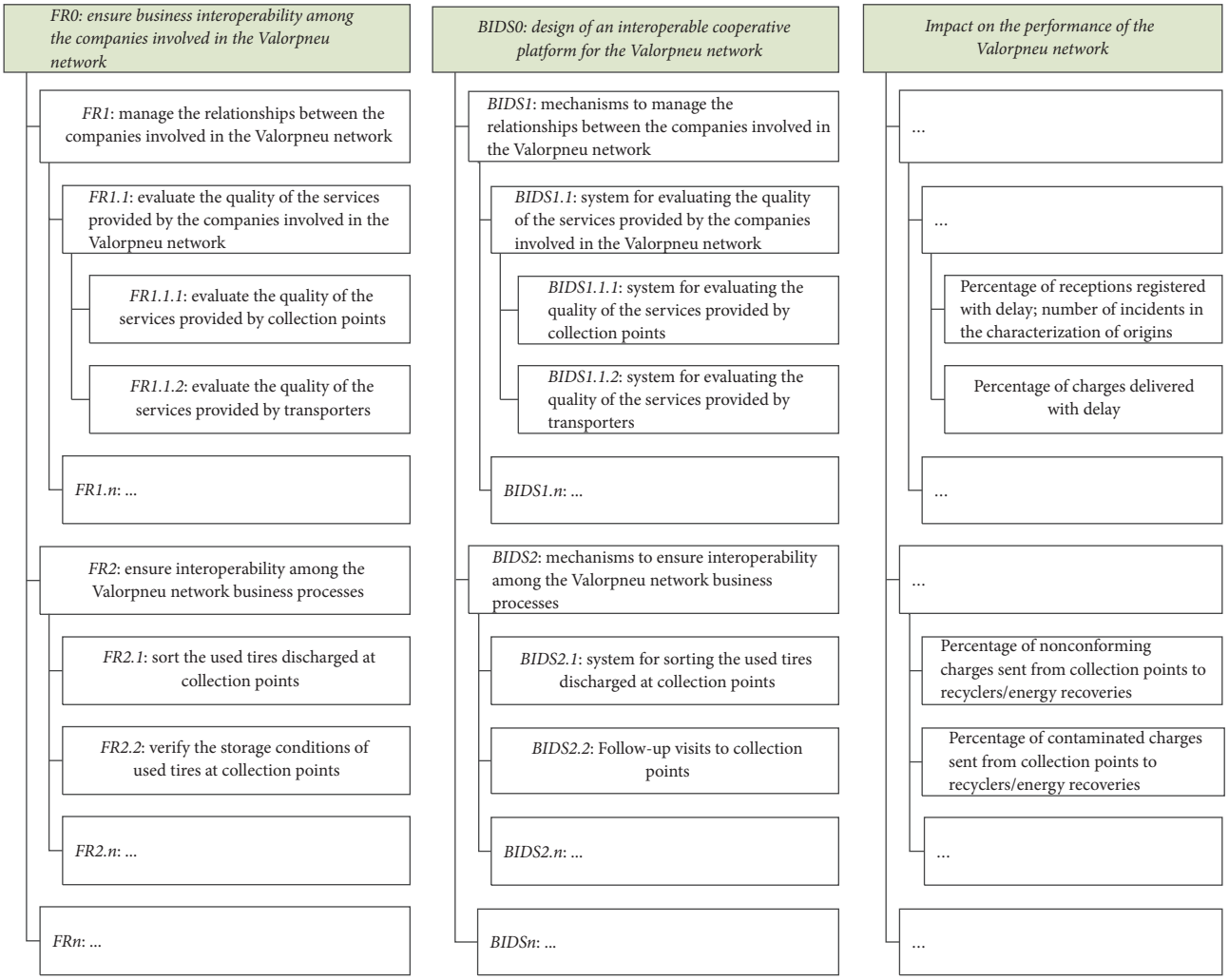


Figure 3: Link between FRs, BIDSs, and performance measures.

more efficiently produce and deliver products or services to customers [9].

Common to the above studies is the focus on the information systems' configuration characteristics. The literature mentioned earlier in this paper highlighted the need to take a holistic approach in addressing business interoperability, mainly in the context of cooperative SCNs. This is in line with Loukis and Charalabidis' [36] recommendation to study empirically the value added not only of "technical interoperability" but also of "organizational interoperability" as well and their complementarities. For example, the impact of complexity on the performance of SCNs, which is usually addressed in the SCM literature (see [57]), has never been addressed in the literature on the analysis of the effect of business interoperability on the performance of networked companies.

Also, the research approaches employed in those studies do not allow "pragmatic" testing of the effect of diverse levels of interoperability on the performance of networked companies. Perhaps for this reason, the findings of Loukis and Charalabidis [36] indicated that future research on the business value of information systems should take into account the levels of interoperability that a company's information and communication technology (ICT) infrastructures provide as high-priority variables. Testing the effect of different levels of business interoperability is important because a higher level of interoperability does not necessarily mean a sign of maturity or excellence, since the "optimum level of interoperability" depends on whether the accumulated investments on business interoperability solutions outbalance the benefits, that is, whether it "fits" the interests of the stakeholders [28]. Therefore, the "optimum level of interoperability" has to be judged based on the individual requirement of each situation of interaction; that is, if a low level of business interoperability perfectly matches the situation, costly improvements to existing systems may be unwarranted [28]. In this study, "the optimum level of business interoperability" is reflected in the measure of the gap between the actual level of business interoperability (ALBI) and the required level of business interoperability (RLBI) (see (1)).

Another important limitation of the previous studies is the strong emphasis on the operational and economic

dimensions of business performance. Note that operations management has matured from a field that myopically focused only on these two dimensions to one that comprehensively addresses the broader social and environmental issues that organizations face nowadays [97]. Corresponding to these trends and the fact that SCNs operate in open and dynamic environments (see Section 2.3), we argue that expected performance outcomes of business interoperability are not only operational and economic matters but also environmental and social ones. For example, Gallaher et al. [38] argue that inadequate interoperability in construction industry leads to missed opportunities that could generate valuable benefits for the public at large. In manufacturing industries, business interoperability problems impact society's economic welfare in the following ways: (1) increasing the cost of designing and producing final products and (2) delaying the introduction of new final products—an increase in the cost of designing and producing a new aircraft or automobile may result in an increase in the equilibrium price of their respective markets [37]. These arguments suggest that business interoperability also affects the social performance of SCNs. Social performance relates the ability of cooperative SCNs to meet their legal or social obligations that integrate societal concerns into their business operation and their interactions with their stakeholder groups such as employees, local communities, and the government [98, 99].

Regarding the environmental performance, which is defined as the ability of cooperative SCNs to reduce air emissions, effluent waste, and solid wastes and the ability to decrease consumption of hazardous and toxic materials [9], ATHENA [28] advocates that external contingences such as environmental legislations affect the business relationships and as a result may affect companies' environmental performance. For example, in the case of the Waste Electrical and Electronic Equipment (WEEE) directive, manufacturers are enforced to be responsible for the entire lifecycle of their products [100], contributing to improving their environmental performance. There is also evidence that the implementation of Green Supply Chain Management (GSCM) in Asian countries, such as India, China, Malaysia, Taiwan, South Korea, Thailand, and Indonesia, is partially influenced by a cultural norm called Guanxi, which plays a key role in relationship governance within SC activities by helping companies to better manage their relationships while they green their SCs [101] and improve their environmental performance. In addition, issues such as absence of cleaner production technologies and underdevelopment of recycling technology may inhibit the establishment of GSCM (e.g., [102]) or reverse logistics (e.g., [103, 104]), which in turn might contribute to reducing companies' environmental performance.

An analysis of the SCM literature (e.g., [102, 105]) also reveals that internal business interoperability drivers such as collaborative transportation, coordination of raw materials and components from suppliers to manufacturers, exchange of design specification and environmental requirements, involvement of suppliers in the development and design stage, cooperation with vendors to standardize packaging, integration between focal company engineers and suppliers' designers, certification of suppliers/vendors' environmental management system, organization of environmental seminars and training for suppliers, system for encouraging suppliers to take environmental initiatives, system for rewarding environmental initiatives taken by suppliers, and environmental auditing of suppliers/vendors can help SCN partners to eliminate or at least reduce emissions, energy, hazardous chemical, and solid waste. These arguments suggest that both external contingences and internal business interoperability drivers are related to the environmental performance of SCNs. Underpinned by the above theoretical discussions, the following hypothesis is postulated.

Hypothesis 1. Business interoperability gaps in a dyad relationship are negatively related to the performance of the two companies involved in the dyad.

3.3. Linking Network Effect to SCN Performance. As discussed earlier in this paper, there is a need to address the network effect in the analysis of the effects of business interoperability on the performance of cooperative SCNs. Indeed, the literature on business interoperability and SCM suggests that the effect of the levels of business interoperability in dyad relationships is not limited to the two companies in the dyads, although this aspect has not been empirically investigated. For example, Gallaher et al. [38] argue that inadequate interoperability in dyad relationships increases the cost burden of construction industry and leads to missed benefits for this industry. White et al. [39] stress that small improvements in business interoperability in dyad relationships can produce disproportionately large improvements in SC function. On the other hand, issues such as order cancellations, production problems, shipment delays, and forecast revisions at any step in an SC may interrupt information and physical flows, forcing suppliers to adjust their planning (White et al. [39]), which in turn might have an impact on the whole network. However, although these arguments suggest that the levels of business interoperability in dyad relationships is expected to affect the performance of network of companies to which the dyads belong to, empirical research on the analysis of the effect of business interoperability on performance does not explain how this impact can be analyzed nor which network theories can help to understand such phenomenon [24, 36].

To address this gap, this study takes the perspectives from the Industrial Marketing and Purchasing (IMP) network approach and specific aspects of CST to connect the network effect to the performance of cooperative SCNs (see Hypothesis 2). The IMP network approach was developed in the IMP group [40, 106, 107] in an attempt to account for the complex reality of interorganizational exchanges [108]. It was developed based on the assumption that the initial IMP interaction model (e.g., [109]) is not appropriate to explain the effect of connectedness among dyadic business relationships because its emphasis is generally on a dyad relationship. In short, the basic assumption of the IMP network approach is that relationships should not be viewed as created and developed in isolation but as part of a broader network of interdependent relationships [40]. The implication of this network approach to this study is that in order

to understand better the effect of business interoperability on the performance of networked companies, it is necessary to analyze not only how business interoperability affects the performance of the two companies in the dyad (Hypothesis 1) but also how it affects the whole network. For these reasons, the IMP network approach has been considered as one of the theoretical perspectives supporting the development of Hypothesis 2.

In addition to the IMP network approach, we argue that the principles of CST can also help us to understand the connection between the network effect of interoperability gaps and the performance of cooperative SCNs. Given the complex nature of SCNs (e.g., [54]), Agostinho and Jardim-Goncalves (2015) suggest that some complexity theory is perceived as a means of simplifying them. Indeed, SCNs exhibit emergent or synergistic properties that are difficult to be understood without reference to subcomponent relationships [81]. Putting it in the scope of this study, the emergent impact of business interoperability gaps in dyad relationships cannot be properly understood without an analysis of the network effect. We argue that such analysis must necessarily be grounded on the discipline of complex systems, particularly on the CST. The specific aspects of CST that allow us to transit to Hypothesis 2 and connect network effect to SCN performance are reflexivity, nonlinearity, and emergence (see Section 2.3).

Note that the insights from these three aspects of CST are in line with the principles of the IMP network approach. In sum, the insights from these two network theories suggest that the gaps between the ALBI and RLBI in dyad relationships have a reflexive and nonlinear effect on the performance of other agents belonging to the network and an emergent effect on the performance of the cooperative network as a whole. Therefore, based on the above review of the literature, the following hypothesis is articulated.

Hypothesis 2. Business interoperability gaps in a dyad relationship are negatively related to the performance of the cooperative SCNs that the dyad belongs to.

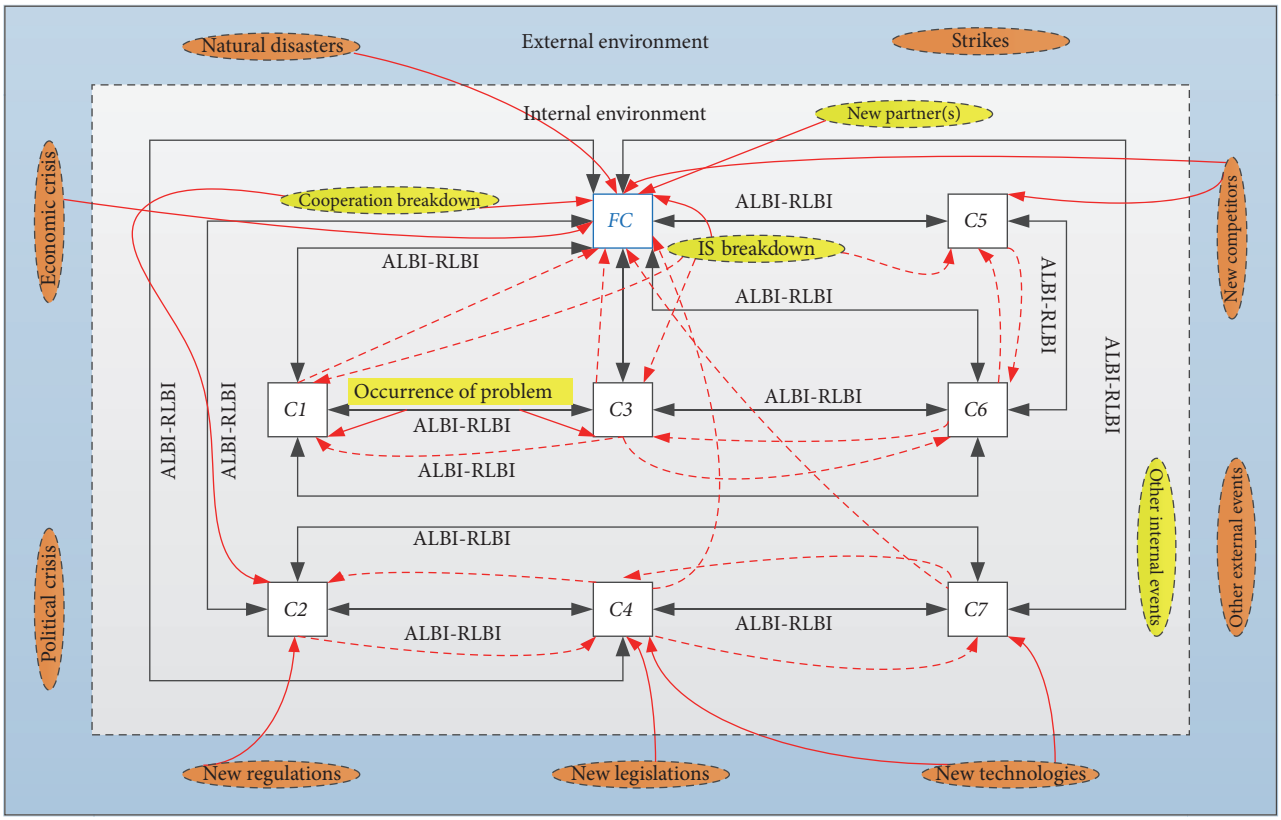
Figure 2 illustrates the theoretical framework that links the construct investigated in this study. Grounded on the theory discussed in Section 3.1 and this section, SCN performance is considered as a multidimensional construct consisting of four dimensions or dependent variables.

4. Model Development

4.1. Rationale for Selecting Agent-Based Simulation. In Section 1, it was stated in the form of a research stance that simulation modeling, more specifically ABS modeling (e.g., [44, 85, 86]), provides an effective set of tools for analyzing the effect of business interoperability on the performance of complex cooperative supply chain networks. The rationale for simulation modeling is that the logical model of the system we are analyzing is not simple enough to be able to use analytical tools to get answer to our research question. Indeed, the high number of dyad relationships usually involved in SCNs, the high number of factors affecting these dyads, the nonlinear interdependencies among them, and the complex network effects that emerge from the interaction of many companies in the SCN make the modeling of such networks too complex for analytical tools. To become analytically tractable, such complexity would require overly simplistic assumptions about the system and companies' behavior, which might bring the validity of the model into question. Although such oversimplifying assumptions could enable us to compute "the exact" effect of business interoperability on the performance of SCNs, they would probably result in an oversimplified model that would not be a valid representation of the system under analysis. We also argue that as the type of systems we are analyzing is pretty complicated, there may not be exact solutions worked out, which is where simulation comes in [110].

The rationale for ABS modeling rests on the nature of the phenomenon that this research seeks to better understand; that is, how different levels of business interoperability in dyad relationships affect the performance of the network of companies that the dyads belong to. The research addresses the network effect resulting from the adoption of different levels of business interoperability in one or more dyad links. The research does not examine how the whole population of companies in the cooperative network reacts to a change in the network environment but investigates how companies belonging to dyads react to that change, individually. Achieving these goals requires a bottom-up approach rather than a top-down approach, which is to say that the dyads that compose the network, the companies that belong to those dyads, and their interactions have to be modeled at the individual level rather than as a whole, as is done in Systems Dynamics (e.g., [111]), for instance. The rationale for this is that if the network is modeled as a whole, it would be more difficult to identify dyads in which the level of business interoperability must be improved and companies in which performance measures must be improved and to understand the network effect. In addition, the need for ABS modeling can be explained by the fact that the phenomenon under analysis involves groups of autonomous and heterogeneous agents that operate in a dynamic environment and our construct of interest (SCN performance) is an emergent outcome of these entities' interactions [44]. We also perceived that as we would need to model the reflexivity, nonlinearity, and emergence aspects of complex cooperative SCNs, traditional discrete simulation tools are not appropriate.

4.2. Description of the Proposed Model. To develop the proposed ABS model, an extended business interoperability framework has been first built to capture the dimensions and subdimensions of business interoperability (see Figure 1). Then, the Axiomatic Design Theory [93, 94] was used to decompose these dimensions and subdimensions into detailed business interoperability functional requirements (FRs) and map them to their respective business interoperability design parameters (DPs)—see details in Cabral [92]. Note that the rationale for using the Axiomatic Design Theory is related to decomposability aspect of CST, discussed in Section 2.3.



FC: focal company
C: company
ALBI: actual levels of business interoperability
RLBI: required levels of business interoperability

Material, information, and financial flows
Direct impact
Indirect impact (network effect)

Figure 4: The theoretical agent-based simulation model.

Drawing upon the principles of the Axiomatic Design Theory, the dimensions and subdimensions of business interoperability have been stated in the form of FRs, which represent the goals or the business interoperability requirements that must be achieved in the design of an interoperable cooperative SCN platform. The dimensions of business interoperability have been stated in the level 1 FR and the subdimensions in the following levels. To satisfy each FR, a DP has been set in a physical domain. DPs are the solutions, mechanisms, methodologies, procedures, and approaches, used to achieve the business interoperability requirements (e.g., electronic data interchange, information systems standards, radio frequency identification, contracts, and specifications). In the scope of this research these DPs are called business interoperability design solutions (BIDSs). Having reached an appropriate level of decomposition, that is, a level where each last level BIDS can be easily comprehensible and implementable, the last level BIDSs have been used as decision variables in the design of the ABS model.

The proposed ABS model consists of a group of companies and a set of dyad links connecting them (see Figure 4). The links are modeled as bidirectional, as information, financial, and material flows in cooperative SCNs typically occur in both directions. Depending on its position or on its role within the cooperative SCN, each company is modeled as an agent with preestablished degree of autonomy to make decisions and characterized by a set of behaviors and attributes—see, for example, [112]. Behaviors are referred to as the way the agents act and react towards their partners, the extent to which they comply with the cooperation rules, the way they react to changes in their business environment, or their willingness to close any emergent interoperability gap. For example, agents may meet the lead-time or not, report the occurrence of a conflict in a timely way or not, provide information on their internal business processes or not, communicate the actual inventory level or not, accept delayed deliveries or not, implement a new information technology/legislation or not, and take initiatives to react to a strike or not. Examples of companies' attributes are production capacity, capacity surplus, safety stock, type of certifications and/or legislation adopted, and so forth.

Based on a preestablished interaction or business rules, the agents interact with each other towards the achievement of the cooperation goals. For example, they negotiate price and conditions, place, and delivery orders, share information on the inventory level, solve conflicts, and so forth. While

Table 1: The proposed business interoperability maturity model.

Maturity level	Description
0-isolated	The BIDS is not implemented and partners are not aware of its importance.
1-initial	The BIDS is not implemented or is implemented but is ad hoc. However, partners are aware of its importance.
2-functional	The BIDS is implemented and imposed by the dominant partner(s) and does not reflect mutual agreements.
3-connectable	The BIDS is implemented reflecting multilateral agreements but not documented.
4-interoperable	The BIDS is well implemented and well documented, reflecting multilateral agreements.

they interact, their interactions and performance are affected by the interoperability gaps that exist in the dyads to which they belong to, the interoperability gaps in the dyads in which they do not belong to, and the interoperability gaps that exist at the network level. As discussed in Section 2.3, cooperative SCNs exhibit interdependence of their components, that is, the agents affect each other in many ways and therefore their behaviors are dependent upon other agents [113] (cited in [114]).

The interoperability gap, for each last level BIDS, may emerge at the dyad or network level. Thus, the BIDSs are modeled as "dyad variables" or as "network variables." A BIDS is modeled as "dyad variable" if it defines the characteristics of a relationship between two companies. Some examples are mechanisms to define cooperation goals, mechanisms to solve conflicts, mechanisms to coordinate collaborative works, mechanisms to provide information on the processing status of the cooperative business processes, and mechanisms to deliver timely, accurate, or complete information. In contrast, a BIDS is modeled as "network variable" if it characterizes the network. Mechanisms to manage the supply-base complexity, mechanisms to manage the customer-base complexity, mechanisms to manage the market uncertainty, and mechanisms to manage external events are some examples.

The approach that drives the analysis of the impact was first proposed in [112] and is explained as follows: considering that the ALBI for a given BIDS is not always the RLBI and vice versa (see Section 3.2), a distance between these two states is proposed to measure the business interoperability gap, that is, how far the ALBI is from the RLBI (see (1)). Consider

$$\text{business interoperability gap} = \text{ALBI} - \text{RLBI}. \quad (1)$$

The assessment of the ALBI and RLBI for each BIDS is grounded on a business interoperability maturity model that has been developed in the ambit of this study. This maturity model, which draws upon earlier literature such as ATHENA [28], Chen et al. [26], Campos et al. [31], and Guédria et al. [22], consists of five maturity levels as shown in Table 1. Note that this maturity model is not linear; that is, the descriptors may differ, depending on the BIDS. For example, some of the BIDSs associated with the dimension of information systems (e.g., speed, accessibility, and user interface) may require a different type of descriptors.

Based on the business interoperability gap, a probability of problem occurrence is estimated, assuming that if there is a gap in a dyad, then there is a *problem-occurrence-chance* probability of problem(s) occurring between the two agents in the dyad. Examples of problems can be inefficient planning and forecasting due to information that is delivered incomplete, inaccurate, or delayed. It is assumed that the greater the business interoperability gap, the higher the probability of problem occurrence. Again, note that the mechanism of the interoperability gap driving behavior (gap versus probability of problem occurrence) is not linear—given the same or different BIDSs, the same gap may have a different impact on different dyads. This is related to the nonlinearity of complex cooperative SCNs, discussed in Section 2.3.

Once an interoperability problem in a dyad occurs (called "problematic dyad"), the model first examines the probability of impact on the two agents in the dyad. The model assumes that the performance of these agents can be directly affected with a *direct-impact-chance* probability. If this probability is greater than or equal to *random-float 1*, the impact is first estimated regarding the agent(s) in the dyad and then spread over the network. Otherwise, there is neither a direct impact nor a network effect. The impact is spread along only established, directed links between two agents. That is, a dyad is only affected if its neighbor(s) has/have been affected. Another rule driving this diffusion is that the nonneighbor dyads have lower chance to be affected than the neighbor ones (given by a variable called *indirect-impact-chance*). If the *indirect-impact-chance* probability is greater than or equal to *random-float 1*, the neighbor agents are indirectly affected, and their performances are updated by assigning the corresponding impact. Note that to assign both direct and indirect impact it is necessary to link each business interoperability gap and the resulting problem to specific performance measures (see Figure 3).

The model can also be used to analyze the impact of external events. The first step is to examine the probability of an external event to occur, given by a variable called *external-event-chance*. An external event occurs when the *external-event-chance* probability is greater than or equal to *random-float 1*. Once an external event occurs, the model first examines the probability of the dyads in the network to be directly affected (given by a variable called *external-event—direct-impact-chance*). An external event affects directly a dyad if the *external-event—direct-impact-chance* probability is greater than or equal to *random-float 1*. This probability is estimated based on the interoperability gaps that exist regarding the BIDSs used to deal with external events. The approach for spreading the effects of these events is similar to the one proposed to spread the effect of an internal interoperability problem.

In the attempt to reduce the probability of occurrence of interoperability problems and make their network more interoperable, agents in cooperative SCNs continuously interact with and react to the network environment in order to create a new version of their network. They analyze their performance, identify dyads where interoperability gaps exist, discuss whether or not to modify their processes in order to close these gaps, and assess whether modifications have improved their performance. Indeed, when an interoperability gap is detected, there is a probability of closing it, and as a result performance might be improved. However, this behavior might be constrained, for instance, by the willingness of agents to modify their internal processes, which may depend on the relationship between investments versus benefits. The model also simulates this decision-making process as well as its impact on performance of the cooperative SCN. To achieve this goal, additional variables and logics are needed to give agents autonomy and intelligence to make informed decisions.

In the ambit of this research, the simple mechanism driving that decision-making process is to outbalance the accumulated investments needed to close an interoperability gap and the potential benefits. The core variables that control the behavior of agents in this process include information regarding relevant business performance, satisfaction level, accumulated investment, potential benefits, willingness to invest, and influencing power an agent has over other agents. For each relevant performance measure, it is assigned an *expected-performance-threshold,* which is later compared with the corresponding *real-performance-score*, given by the plots set in the simulation environment. This comparison, which is supported by a variable called *interoperability-gap-frequency-check*, can be regularly scheduled (e.g., semiannually, quarterly, or annually). If the *real-performance-score* crosses the *expected-performance-threshold*, the *satisfaction-level* regarding the performance measure of interest increases. As a result, the dyad has a *close-interoperability-gap-chance* probability to close the gap. Once the agents in the dyad consider closing the gap, it is necessary to outbalance the *minimum-expected-benefits-threshold* with the *maximum-accumulated-investment-threshold*. If the *minimum-expected-benefits-threshold* crosses the *maximum-accumulated-investment-threshold*, the *willingness-to-close-interoperability-gap* increases.

An interoperability gap is then closed if the *willingness-to-close-interoperability-gap* is greater than or equal to *random-float 1.* Once an interoperability gap is closed, the *real-performance-scores* of time periods t and $t-1$ (t is equal to semester, quarter, year, etc.) are compared, and if the *real-performance-score*$_t$ crosses the *real-performance-score*$_{t-1}$, the agents conclude that the performance has been improved. Otherwise, they conclude that it has not been improved. Depending on the assessment results, their *satisfaction-to-interoperability-gap-closed* becomes the source of positive or negative influence to their neighbors.

5. Case Study: Valorpneu Network

5.1. Case Study Overview. The case study presented in this paper has been conducted in the Valorpneu network and its purpose is to explore and demonstrate the applicability of the proposed ABS model in a specific and real situation, rather than to achieve generalization about the application of the method or the practices [115].

5.2. Characterization of the Network. Valorpneu network is an RL cooperative industrial network that organizes and manages the system of collecting and disposing of used tires in Portugal. The system that supports the activities inherent to this network is called "Integrated System for Management of Used Tires (SGPU)," which started its operation on February 1, 2003. Currently Valorpneu's collection network has 49 collection points, 27 retreaders, 3 recyclers, 4 energy recoveries, and 23 transporters or companies responsible for their subcontracting.

The Valorpneu network is regarded as an important industrial network in Portugal, and its economic, social, and environmental importance is evident. For instance, a study published in 2014 by Valorpneu about management of used tires in Portugal concluded that the system contributes € 78 million to the Portuguese Gross Value Added (GVA) (with reference to 2011) and created 970 direct jobs, 315 indirect jobs, and 698 induced jobs and that, on average, it reduces 1560 kg of CO2 and 46.5 GJ of energy per ton of used tire managed, per year.

5.3. Characterization of the Participants. In this case study, a sample comprising four companies in the Valorpneu network was chosen. For each company participating in the study, a manager was chosen to be the respondent. The profiles of the four companies and the respondents are provided in Table 2.

5.4. Description of the SGPU Model. The SGPU starts with the introduction of new or second-hand tires into the Portuguese market. Any company producing and/or importing new or second-hand tires—and/or vehicles, aircraft, or equipment that contains new or used tires—needs to celebrate a contract with the managing entity (Valorpneu), allowing the Ecovalue due on the imported tires to be charged. This Ecovalue, which pays for the provision of a service and is charged by tire producers, funds Valorpneu's system.

After reaching the end of their life cycle, tires may be delivered by distributors to collection points spread throughout the country (mainland Portugal and the Autonomous Regions of Madeira and the Azores), at zero cost to the tire holders. To locate the most convenient collection point to deliver tires, there is a Network Map available on the Valorpneu website (http://www.valorpneu.pt/). At collection points, the discharged tires are separated through a well-established sorting process, consisting of five categories (see Table 3), and stored temporarily.

Later, grounded on the inventory level of each of the categories shown in Table 3, tires are routed by Valorpneu from collection points to entities where they are processed (essentially energy recovery and recycling). The management of the information inherent to this complex network is supported by an online information system that enables the different agents within the SGPU to interact, while simultaneously allowing Valorpneu to control and manage

Table 2: Companies' and managers' profile.

	Companies			
	Company 1	Company 2	Company 3	Company 4
Name	Valorpneu	Renascimento	Biogoma	Transportes Bizarro Duarte
Position in the network	Managing Entity	Collection point and transporter	Recycler	Transporter
Sector of activity	Waste management industry	Waste management industry	Waste management industry	Road transport of merchandise
Main service provided	Management of the used tires flows in Portugal	Waste management/logistics provider	Production and commercialization of products derived from used tires	Logistics transport
Years in Valorpneu network business	More than 10 years	More than 10 years (from 2003 to present)	Fewer than 10 years (from 2008)	More than 10 years (from 2003 to present)
Turnover (millions €)	10–20	10–20	Fewer than 10	Fewer than 10
Company size (employees)	Fewer than 50	100–200	Fewer than 50	Fewer than 50
Geographic location	Mainland Portugal (Lisbon)	Mainland Portugal (Loures)	Mainland Portugal (Santarém)	Mainland Portugal (Malveira)
	Interviewees			
	Respondent 1	Respondent 2	Respondent 3	Respondent 4
Job title	Logistics manager	Quality, environment, and security manager	Production manager	Top management
Years in business	More than 10	More than 15	More than 20	More than 10
Years in Valorpneu network business	More than 10	More than 10	Fewer than 10	More than 10

Table 3: Categories of tires at collection points.

Category	Dimension/description
Passenger	Diameter ≤ 0.70 m and width ≤ 0.35 m
Heavy	Diameter ≤ 1.20 m and width ≤ 0.35 m
Industrial	Higher dimensions
Damaged	Heavy tires whose structure is damaged to the point that it is not possible to stand them vertically
Massive	All dimensions of massive tires, excluding bandages

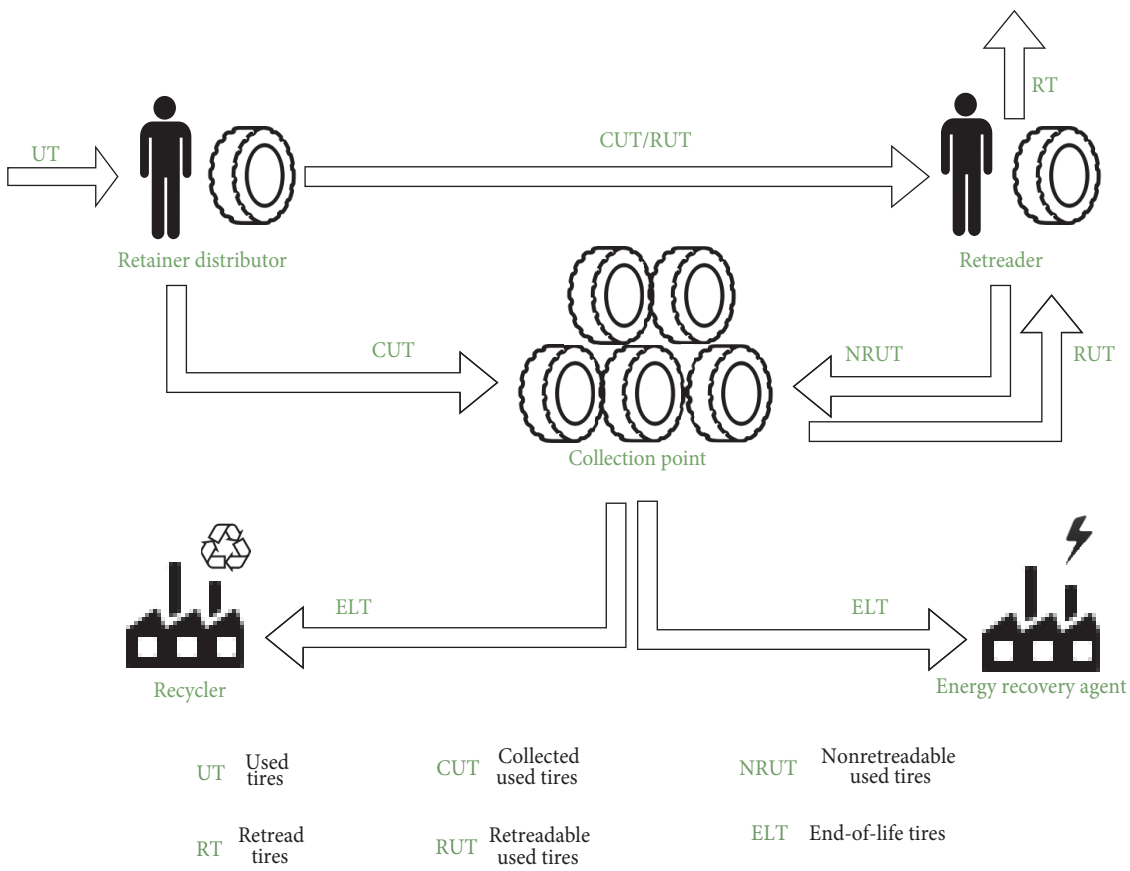


Figure 5: The SGPU working model (source: Valorpneu website).

the whole SGPU. The working model of SGPU is shown in Figure 5.

To help us in the demonstration of the ABS model, a business diagram has been developed to map and systematize the material, information, and financial flows involved in this complex system (see Figure 6).

5.5. Collected Data. Data for this case study were collected primarily through face-to-face interviews. Complementary data were gathered through documents, namely, through the Annual Reports and Newsletter, available on Valorpneu's website. As data were collected through multiple sources, triangulation was used to corroborate the evidence coming from the different sources. These data can be summarized according to two categories: quantitative and qualitative data. Qualitative data are concerned with the characterization of the way that SGPU operators interact (Figure 6), the identification of performance measures and their link to BIDSs and FRs (Figure 3), and the characterization of the ALBI and RLBI (Table 4). Quantitative data are concerned with the SGPU operational performance measures (Table 6) and the numerical quantification of the effect of the BIDSs on the performance measures (Tables 7–10). As the aim is not to provide historical evolution of the SGPU from the beginning of its activity (2003), the time boundaries for data collection were set between 2007 and 2014. The main reason for this is that the annual reports, which contain much of the information needed for this case study, are not available for years prior to 2007.

Note that although the impact of business interoperability has been theoretically linked to the operational, economic, environmental, and social perspectives of business

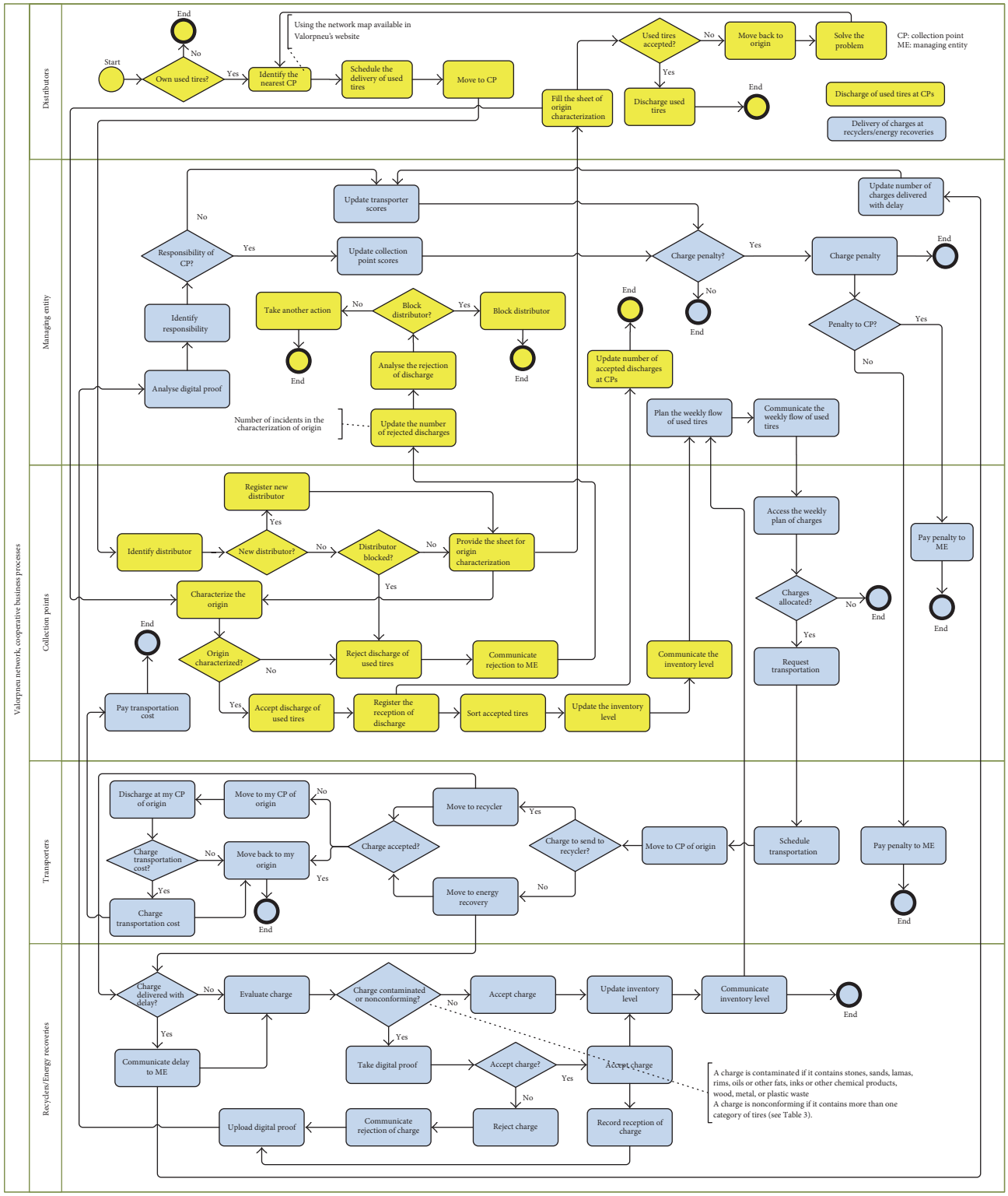


Figure 6: The Valorpneu network business process diagram.

performance (see Figure 2), this case study focuses only on the operational performance of the SGPU, as shown in Figure 3. The rationale for this is that, unlike the operational measures, the other three are more difficult to quantify, in the words of the managers interviewed. Also note that although the developed framework suggests that business interoperability is also multidimensional, many of the dimensions are incompletely or not considered in this case study.

Table 4: ALBI and RLBI for each BIDS.

BIDSs	2007		2008		2009–2014	
	ALBI	RLBI	ALBI	RLBI	ALBI	RLBI
BIDS1.1.1	4	4	4	4	4	4
BIDS1.1.2	0	4	3	4	4	4
BIDS2.1	3	4	4	4	4	4
BIDS2.2	0	4	3	4	4	4

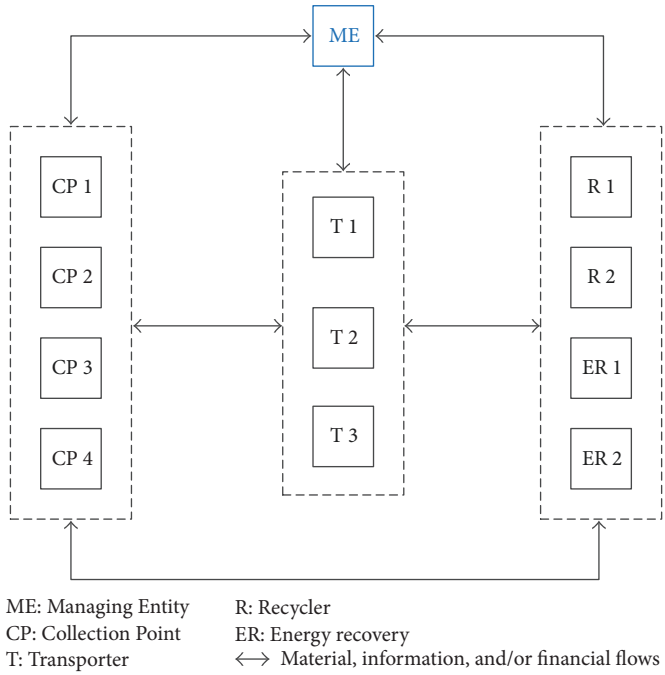


Figure 7: The structure of the considered SGPU.

To be specific, only the BIDSs related to the dimensions "management of external relationships" and "cooperative business processes" are considered. The rationale for this is that, according to the managers interviewed, these two dimensions along with the "information systems" are those with the highest relevance regarding the business interoperability performance of the Valorpneu network. However, the "information systems" dimension is not considered because most of its relevant improvements were achieved prior to the time interval under analysis, that is, prior to 2007. Looking at the extended framework presented in Figure 1, the subdimension considered in the dimension "management of external relationships" is performance evaluation (FR1.1.1 and 1.1.2). In the dimension "cooperative business processes," the subdimensions considered are clarity (clarity in the definition of the system for sorting tires at collection points, FR2.1) and monitoring (FR2.2). The dimension "products and services" is not considered because there is only one product in flow (used tires) and its level of specificity is very low. "Knowledge management" is not modeled because there are no relevant intellectual and property rights (IPR) issues among the SGPU operators. "Employees and work culture" is also not modeled because the interactions among the employees from the different companies within the Valorpneu network are not very frequent. "Business semantics" is not modeled because there are no conflicting terminologies. Last, the dimension business strategy and network details dimension were recognized to be important but not modeled since quantitative data regarding their impact were not available. However, the proposed ABS model is prepared to incorporate constructs related to the ten dimensions of business interoperability and to the four dimensions of performance illustrated in Figure 2.

The values of ALBI and RLBI, in Table 4, were measured through the theoretical business interoperability maturity model provided in Section 4.2. As an example, we use BIDS1.1.2 to show what those values mean (see Table 5).

In 2007, the system for evaluating the quality of the services provided by transporters (BIDS1.1.2) did not exist, corresponding to level zero. In 2008, this system had been implemented but not documented, corresponding to level 3. In 2009, this system was documented, corresponding to level 4. The implications of the improvement of its levels of interoperability are reflected first in the gap between the ALBI and RLBI and then in the performance measures shown in Table 9. For example, in 2007 the gap was equal to minus four and the probability of a charge to be delivered with delay was

Table 5: Measurement of ALBI and RLBI for BIDS1.1.2.

Maturity level	Description
0-isolated	There is no system for evaluating the quality of the service provided by transporters and partners are not aware of its importance.
1-initial	The system for evaluating the quality of the service provided by transporters is not implemented or is implemented but is ad hoc. However, partners are aware of its importance.
2-functional	The system for evaluating the quality of the service provided by transporters is implemented and imposed by the dominant partner(s) and does not reflect mutual agreements.
3-connectable	The system for evaluating the quality of the service provided by transporters is implemented, reflecting multilateral agreements, but not documented.
4-interoperable	The system for evaluating the quality of the service provided by transporters is well implemented and well documented, reflecting multilateral agreements.

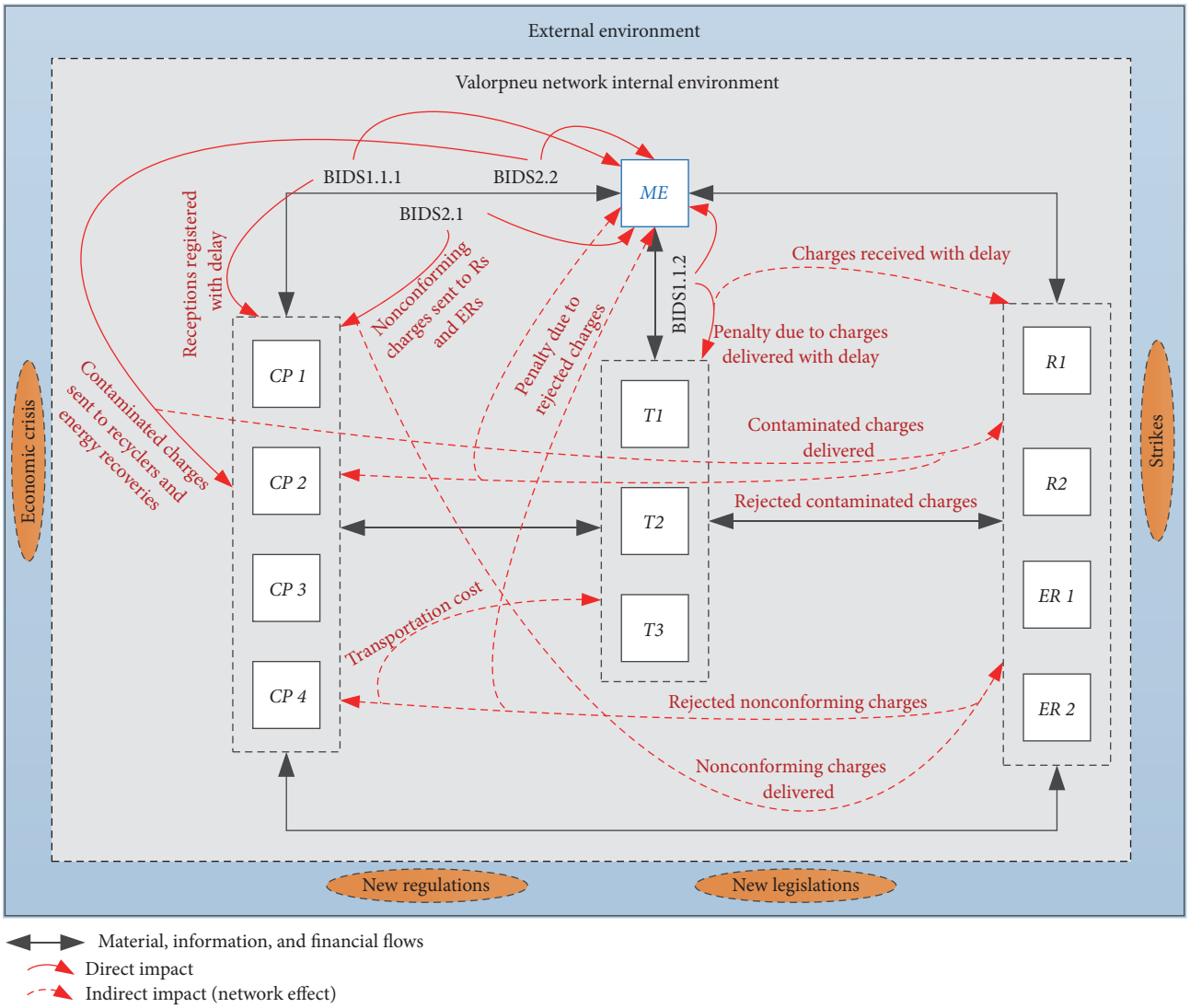


Figure 8: Application of the theoretical agent-based simulation model to the structure of the considered SGPU.

equal to 0.32. In 2008, the gap was equal to minus one and the probability of a charge to be delivered with delay decreased to 0.16. From 2009 to 2014, the gap was equal to zero and the probability of a charge to be delivered with delay was equal to 0.08 in 2009, 0.06 in 2010, 0.02 in 2011, 0.02 in 2013, and 0.012 in 2014.

In addition to the data provided above, some assumptions (A) regarding the performance measures and the impact of

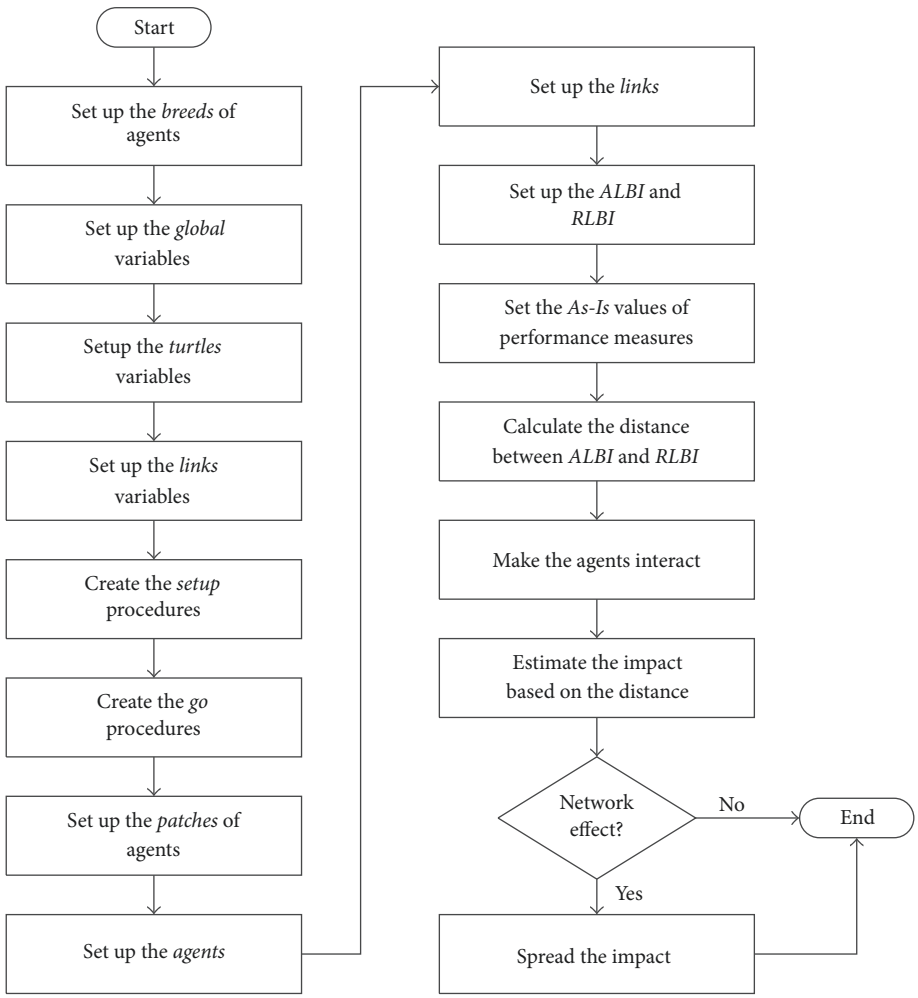


Figure 9: Steps to implement the ABS model.

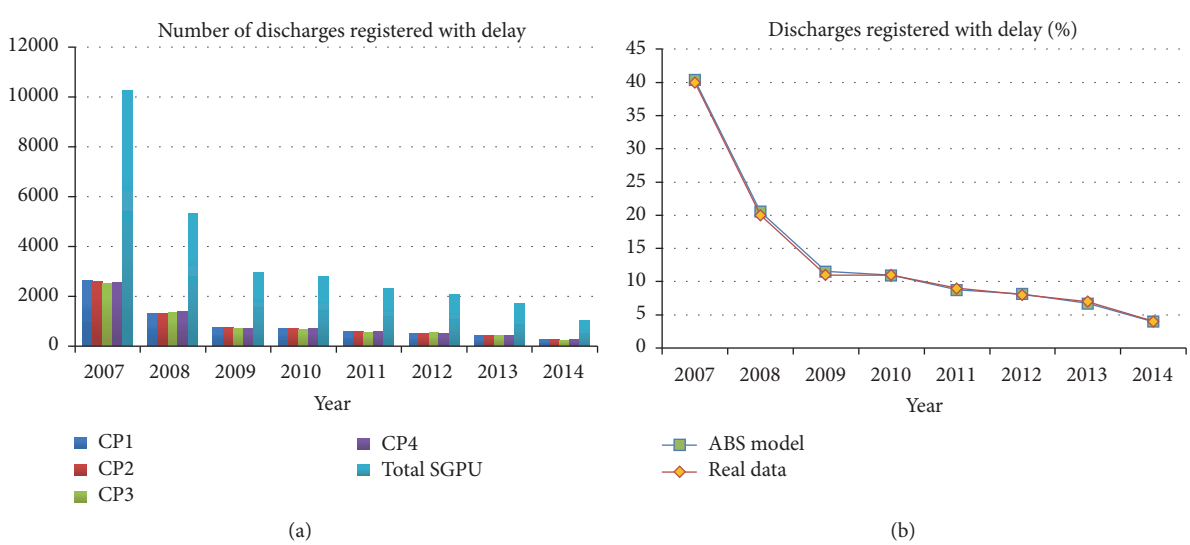


Figure 10: Discharges registered with delay.

Table 6: SGPU performance measures (2007–2014).

SGPU performance measures	2007	2008	2009	2010	2011	2012	2013	2014
Used tires sent to recycling (ton)	43,603	48,332	48,039	49,957	47,595	39,203	38,408	43,779
Used tires sent to energy recovering (ton)	22,897	23,504	21,878	25,759	25,144	24,483	26,132	26,621
Total used tires collected and processed by SGPU (ton)	92,321	96,210	89,574	94,373	90,373	78,268	78,695	84,681
Stock at collection points (ton)	10,153	9,487	9,909	10,193	10,531	11,471	11,480	7,354
Operational expenditures, collection points €)	1,562,739	1,766,300	1,790,308	1,919,697	1,837,568	1,596,483	1,610,799	1,756,842
Operational expenditures, transporters (€)	1,864,954	2,130,661	2,031,665	1,987,633	1,898,601	1,653,207	1,648,926	1,778,545
Operational expenditures, recyclers (€)	3,203,910	3,515,209	3,500,083	3,694,921	3,518,372	2,888,800	2,813,461	3,150,101
Operational expenditures, energy recoveries (€)	1,497,220	1,443,804	1,128,443	705,658	624,354	527,928	370,903	306,222
Average expenditures, storage at collection points (€/ton)	21.90	22.69	24.01	24.20	24.56	24.75	24.67	24.69
Average expenditures, transporters (€/ton)	26.14	27.37	27.25	25.06	25.38	25.63	25.26	24.99
Average expenditures, recyclers/energy recoveries (€/ton)	66.23	64.53	62.47	61.82	61.13	57.99	55.44	54.37

Table 7: Impact of the follow-up visits to collection points.

Performance measure(s)	Impact of BIDS2.2, follow-up visits to collection points							
	2007	2008	2009	2010	2011	2012	2013	2014
Contaminated charges sent from collection points to recyclers and energy recoveries (%)	2	1.20	0.37	0.03	0.23	0.54	0.12	0.23

Table 8: Impact of the introduction of the system for evaluating the quality of services provided by collection points.

Performance measure (s)	Impact of BIDS1.1.1, system for evaluating the quality of services provided by collection points							
	2007	2008	2009	2010	2011	2012	2013	2014
Receptions registered with delay (%)	40	20	11	11	9	8	7	4
Number of incidents in the characterization of the origin (per trimester)	64	51	32	23.80	20.30	18.60	17	15.30

Table 9: Impact of the introduction of the system for evaluating the quality of services provided by transporters.

Performance measure (s)	Impact of BIDS1.1.2, system evaluating and the quality of service provided by transporters							
	2007	2008	2009	2010	2011	2012	2013	2014
Charges delivered with delay (%)	32	16	8	6	4	2	2	1.20

Table 10: Impact of the system for sorting used tires at collection points.

Performance measure(s)	Impact of BIDS2.1, system for sorting used tires at collection points							
	2007	2008	2009	2010	2011	2012	2013	2014
Nonconforming charges sent from collection points to recyclers and energy recoveries (%)	2	0.70	0.13	0.03	0.05	0.06	0.08	0.09

Table 11: Assumptions made.

A	Designation	Assumed value
A1	Probability of contaminated charge to be rejected	0.030
A2	Probability of a nonconforming charge to be rejected	0.020
A3	Probability of contaminated and nonconforming charge to be rejected	0.050
A4	Number of discharges per week	$\sim N$ (500; 50)
A5	Inventory cost for each ton of rejected charge (€/ton)	25
A6	Penalty value charged by managing entity to collection points for each rejected charge (€/charge)	$\sim N$ (120; 10)
A7	Washing fee imposed by recyclers or energy recoveries due to contaminated charges (€/charge)	$\sim N$ (25; 2)
A8	Amount of nonconforming tires per each accepted charge (ton/charge)	$\sim N$ (0.13; 0.015)
A9	Amount of contaminated tires per each accepted charge (ton/charge)	$\sim N$ (0.15; 0.025)
A10	Penalty value charged by managing entity to transporters for each charge delivered with delay (€/charge)	$\sim N$ (25; 2)
A11	Weight of each charge to recyclers and energy recoveries (ton/charge)	$\sim N$ (12.5; 1.2)
A12	Number of working weeks per year	51

business interoperability were made in order to overcome the lack of data (see Table 11). Note that these assumptions were made and validated during the interviews with the manager of the managing entity (Valorpneu).

5.6. Demonstration of the Proposed Model. One of the issues when analyzing SCNs is the need to set the boundaries of the study object, that is, what will be investigated and what will not be. In the context of this case study, retreaders and shredders are not included in the application of the ABS model because according to the managing entity manager, they are not relevant in terms of interaction with the other SGPU operators. Although only one company per each type of agent participated in the study, the ABS model is

demonstrated with the agents illustrated in Figure 7. The rationale behind this is to have more agents in order to better understand the network effect.

As can be seen in Figure 4, the ABS model is generic and incorporates a number of internal and external variables. To show how the constructs defined in Figure 3 have been incorporated in this new scenario, a new version of Figure 4, more simple, has been created—see Figure 8.

To more easily understand how the ABS model is implemented, a detailed simulation process flowchart is provided in Figure 9.

As shown in Figure 9, the first step in implementing the ABS model is to set the *breeds* of agents. *Breeds* are the type of agents involved in the system being modeled. In this study, the system being modeled consists of the five types of agents shown in Figure 7.

Step two consists of defining the *global* variables, that is, those that characterize the network as a whole (e.g., number of collection points, number of transporters, probability of strike, and number of loads a week). Step three is to set up the *turtles*' variables. Turtles here are the agents in the system, that is, the breeds defined previously. These types of variables can be *turtles*' variables or *breeds*' variables. The first can be accessed by any turtle (e.g., type of information system used, time spent in reworking information), while the second can only be accessed by turtles of the same *breed*. Examples of *breeds*' variables, for collection points, are storage capacity, reference stock, and amount of collected tires per day.

The fourth step is to set the *links*' variables, which are those that characterize each dyad relationship. In the scope of this study, these variables are the ALBI, the RLBI, and the gap between ALBI and RLBI. Step five is to create the *setup* and *go* procedures. These are buttons created in the interface to allow the user to initialize *(setup)* and start *(go)* the simulation. Following this, the *patches* of agents are created. Patches are the virtual world where the agents operate and interact.

The next step is to create the agents, their position (can be random or fixed), and their *shape* (factory, truck, person, computer, etc.). Once agents are created, it is necessary to set the links among them. In this work, directed links have been established. The next step is to set the corresponding values of the *links*' variables, which are the ALBI and RLBI measured through the maturity model (see Tables 4 and 5), and the performance measures being analyzed. Grounded on these values, the business interoperability gap is calculated using (1).

The last three steps consist of making the agents interact, estimating, and spreading the impact of business interoperability on performance. To make the agents interact, the interaction and decision rules in Figure 6 have been used. For each type of interaction (e.g., delivery of tires at recyclers and/or energy recoveries) it is necessary to identify the BIDS(s) that affect(s) the interaction and relate the BIDS(s) to performance measures (see Figure 3). For example, in the process of delivering tires to recyclers and/or energy recoveries, upon the arrival of the truck the recovery agent receiving the load should evaluate whether it is contaminated, in conformity, or delayed, and decide whether the charge is accepted or not. The probability of a charge to be delivered with delay depends on the gap between the ALBI and RBI for BIDS1.1.2 (measured using data provided in Table 4), and the performance measure related to this process is "percentage of charges delivered with delay" (see Table 9). Similarly, in Table 10, it was set that the probability of a nonconforming charge sent from collection points to recyclers and energy recoveries is dependent on the BIDS2.1. To model whether a charge is contaminated or not, the following condition has been used:

```
if (random-float 1) < probability-of-a-charge-to-be-contaminated
    set contaminated-charge true
    set number-of-contaminated-charges number-of-contaminated-charges + 1
else
    set contaminated-charge false
end
```

The approach used to model whether a charge is not in conformity or delivered with delay is the same as shown above. In the event that a charge is contaminated, nonconforming, or delivered with delay, the probability of rejection, as well as the potential impact, is modeled on the basis of the assumptions made in Table 11. For example, when a charge is contaminated, the decision on its rejection is dependent on the A1—probability of a contaminated charge to be rejected. For this purpose, the following condition has been used:

```
if (random-float) 1 < probability-of-a-contaminated-charge-to-be-rejected
    reject charge
    set number-of-rejected-charges number-of-rejected-charges + 1
else
    accept charge
    set number-of-accepted-charges number-of-accepted-charges + 1
    end
```

Once a charge is rejected, the impact is then spread to the agents that to some extent are involved in the process of delivering the charge. The assumptions used to estimate the impact of this scenario are A5, A6, and A7. For example, the penalty value charged by the managing entity to collection points due to each rejected charge is assumed to be normally distributed, with mean and variance equal to 120 and 10, respectively. The transportation cost charged by transporters to the collection point responsible for the rejected charge is the round trip cost of the value paid by the managing entity to transporters (€/ton—see Table 6).

5.7. Simulation Experiment and Results. One of the issues that is not yet consensual regarding the execution of ABS models is the number of replications that are needed. For example, North and Macal [116] consider the need for designing sets of

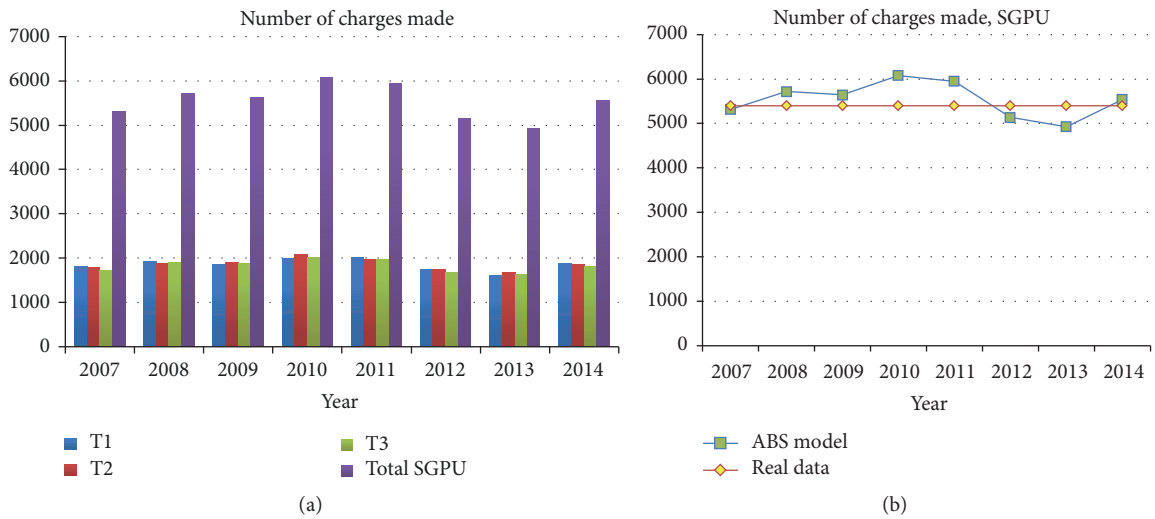


Figure 11: Number of charges made.

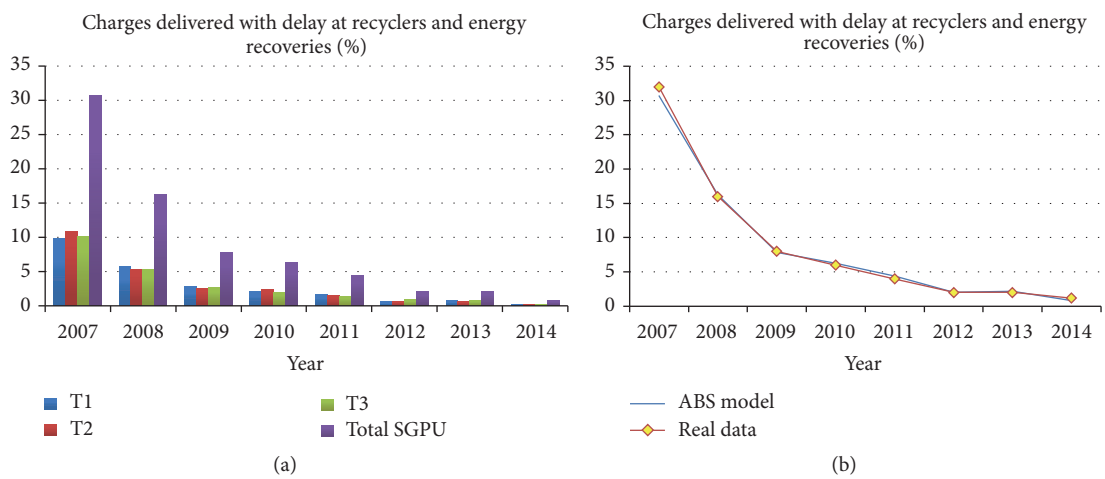


Figure 12: Percentage of charges delivered with delay.

many simulation runs, many more than is the usual practice for standard simulation models, to fully understand system and agent behaviors. However, they do not specify a concrete number. In this research, the model has been replicated 100 times, although, for example, Rand and Rust [44] suggest that 30 runs are acceptable. NetLogo 5.0.5 [117] was used to simulate the model, which was run on a weekly basis. The most relevant simulation outputs are reported in Figures 10–17. First, Figure 10 summarizes the simulation outputs related to the process of discharging tires at collection points.

Second, Figures 11–14 show the simulation outputs for transporters regarding the process of delivering charges at recyclers and energy recoveries.

Third, Figures 15–17 summarize the simulation outputs for collection points regarding the process of delivering charges at recyclers and energy recoveries.

The simulation outputs for collection points due to contaminated, nonconforming, and rejected charges at recyclers and energy recoveries are provided in Figures 18–21.

Before analyzing the case (see the next section), it is important to compare the results from the ABS model to the system output data in order to ensure that valid conclusions are drawn. In other words, it is important to ensure that the model simulated is a reasonable representation of the real system—model validation. An analysis of Figures 10, 12, 16, and 17 suggests that the model behaves as the same as the real system. However, statistical validity is needed to support this assumption. Statistical techniques, such as Z-test and t-test to compare the means and F-test to compare the variances, are usually applied for this purpose. A fundamental requirement to apply these tests is the normality of the two data sets. However, in this case study, the output performance measures from the model and the real system are nonnormal. In addition, it is not reasonable to assume that the two data sets are normally distributed because the sample size is small (8 years). Therefore, a nonparametric test is applied to verify, for a given significance level, whether the medians of populations of the model output data and the system output data are

Table 12: Decision values for the Mann–Whitney–Wilcoxon test.

Parameter	Test parameters Designation	Receptions registered with delay (%)	Charges delivered with delay (%)
$U_{\text{Real System}}$	Rank sum test of the real system	38	20
$U_{\text{Simulation Model}}$	Rank sum test of the simulation model	37	20
U	Rank sum test	37	20
$\bar{n}$	Mean of U	32	32
S	Standard deviation of U	10,99	10,99
Z_{test}	Computed test statistic Z	−0,32	−1,26
α	Level of significance	5%	5%
	$Z_{0,975}$	1,96	1,96
	Decision rule	$\lvert Z\rvert = 0{,}32 < Z_{0,975}$	$\lvert Z\rvert = 1{,}26 < Z_{0,975}$
	Decision	Do not reject the null hypothesis	Do not reject the null hypothesis

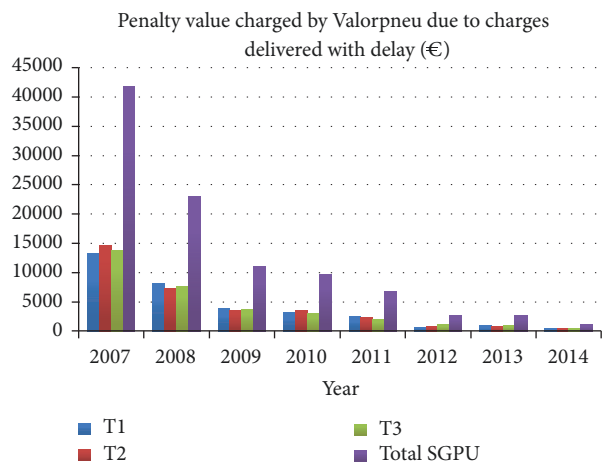


Figure 13: Penalty value charged by Valorpneu due to charges delivered with delay.

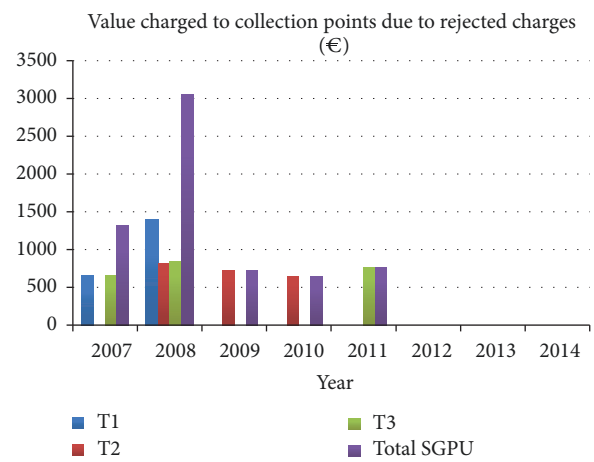


Figure 14: Value charged to collection points due to rejected charges.

significantly different. The statistical technique applied is the Mann–Whitney–Wilcoxon test (for details on how to apply this test, see, e.g., [118]), and the performance measures evaluated are "receptions registered with delay" and "charges delivered with delay." Table 12 shows the computed values for the Mann–Whitney–Wilcoxon test and the conclusions drawn.

As can be seen in Table 12, the Z_{test} values for the two performance measures evaluated are between −1,96 and 1,96. Thus, for a significance level of 5%, there is no evidence to reject the null hypothesis, suggesting that there is no statistically significant difference between the model output data and the system output data. This suggests that the simulated model behaves the same as the real system; that is, it is valid.

5.8. Analysis of the Case. According to one of the managers interviewed, Valorpneu network is known as one of the industrial networks with the best business interoperability performance in Portugal. Taking a look at the simulation outputs, it is possible to state that indeed the implementation of appropriate levels of business interoperability has helped to reduce several non-value-adding processes and consequently improve the operational performance of the Valorpneu network. For example, the existence of a well-defined system for sorting used tires at collection points—defined in the document "Collection Point: Rules and Procedures" (BIDS2.1)—has helped to maintain a low number of nonconforming charges sent to recyclers and/or energy recoveries. This document was created in 2007, and therefore its level of business interoperability was considered to be 3 in that year and 4 from 2008 to 2014. As can be seen in Figure 17, the effect of this BIDS is evident. From the 5400 charges performed every year (see Figure 11), fewer than 2% of nonconforming charges are sent from collection points to recyclers and energy recoveries. In 2007, the number of nonconforming charges was around 2%. Since 2008, this number has decreased year after year. For example, in 2008 it was around 0.7% and in 2014 around 0.07%.

Despite the significance of the impacts discussed above, the most important improvements achieved in the last seven years in the Valorpneu network are related to the introduction of the BIDS1.1.1 and BIDS1.2.2. The main impacts of these systems are in the percentage of charges delivered with

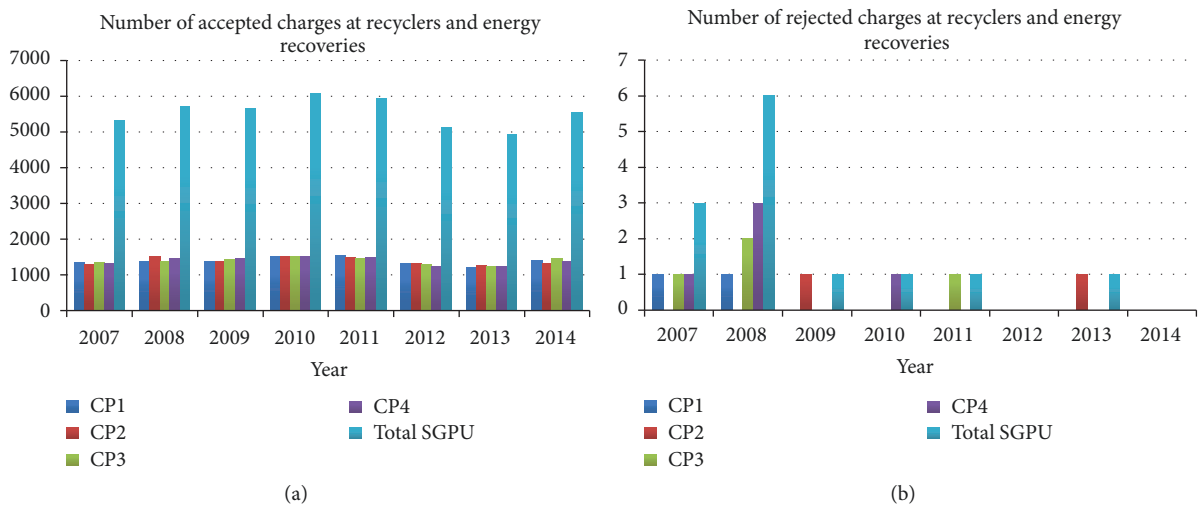


Figure 15: Number of accepted/rejected charges-recyclers and energy recoveries.

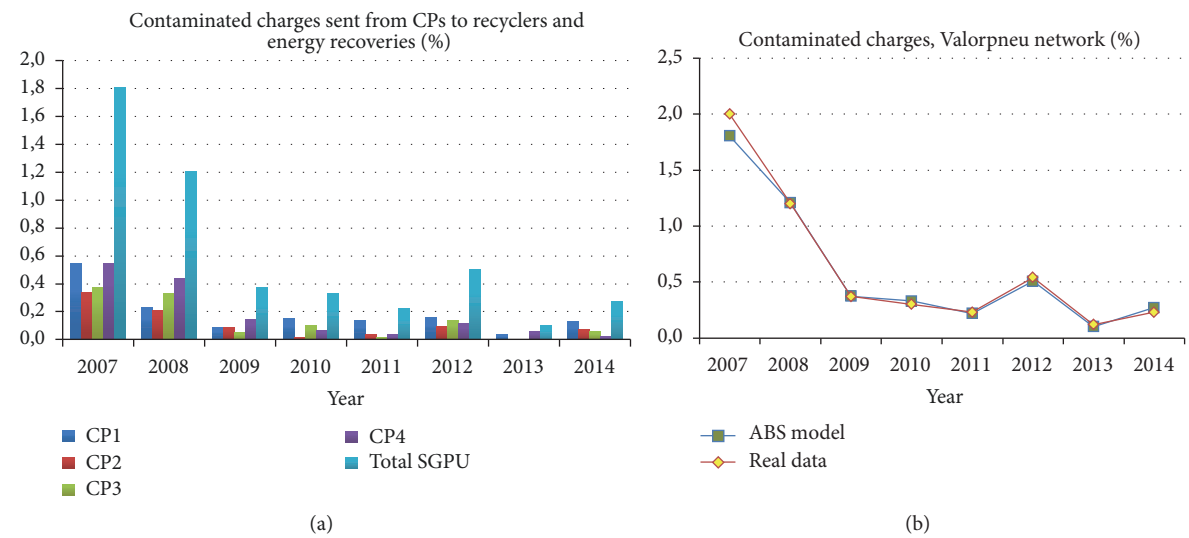


Figure 16: Percentage of contaminated charges sent from collection points to recyclers and energy recoveries.

delay (related to BIDS1.1.2) and the percentage of receptions registered with delay (related to BIDS1.1.1). As can be seen in Figure 12, the percentage of charges delivered with delay fell from 30.71% in 2007 to 0.83% in 2014. The reason behind the high percentage of delays in 2007 is that at that time BIDS1.1.2 did not exist, corresponding to the level zero. With the introduction of this system in 2008, which increased the level of business interoperability to 3, there was a considerable reduction from 30.71% to 16.22%, a reduction of 47.18% (with reference to 2007). However, the system reached the maximum level of maturity (level 4) only in 2009. As a result, a reduction of 53.82% (16.22% in 2008 and 7.49% in 2009) was achieved in 2009. With the maturation of this BIDS1.1.2 in 2009, the amplitude of its impact stabilized and in 2014 the corresponding value was about 0.83%.

Regarding the registration of receptions, Figure 10 shows that the introduction of BIDS1.1.1 has also helped to significantly reduce the percentage of receptions registered with delay. Similarly to the metric number of charges delivered with delay, in the year of the introduction of BIDS1.1.2 (2008), there was a substantial reduction of 49.17% (40.37% in 2007 to 20.52% in 2008) in the percentage of receptions registered with delay. In the same way, in the second year of maturation (2009) the reduction was around 50% with reference to 2008. After 2009, the amplitude of its impact stabilized, as we see with the metric number of charges delivered with delay.

In addition to these impacts, the introduction of BIDS1.1.1 has also helped to reduce the number of incidents in the characterization of origins at collection points. For example, in 2009 the average number of incidents per trimester was around 31. In 2014, this value had fallen to 16, representing a reduction of 48.39% (with reference to 2009). In 2007, before the introduction of BIDS1.1.1, the average number of incidents was estimated to be around 69 per trimester.

Regarding the number of contaminated charges (related to BIDS2.2), the impact is also considerable. Despite the high

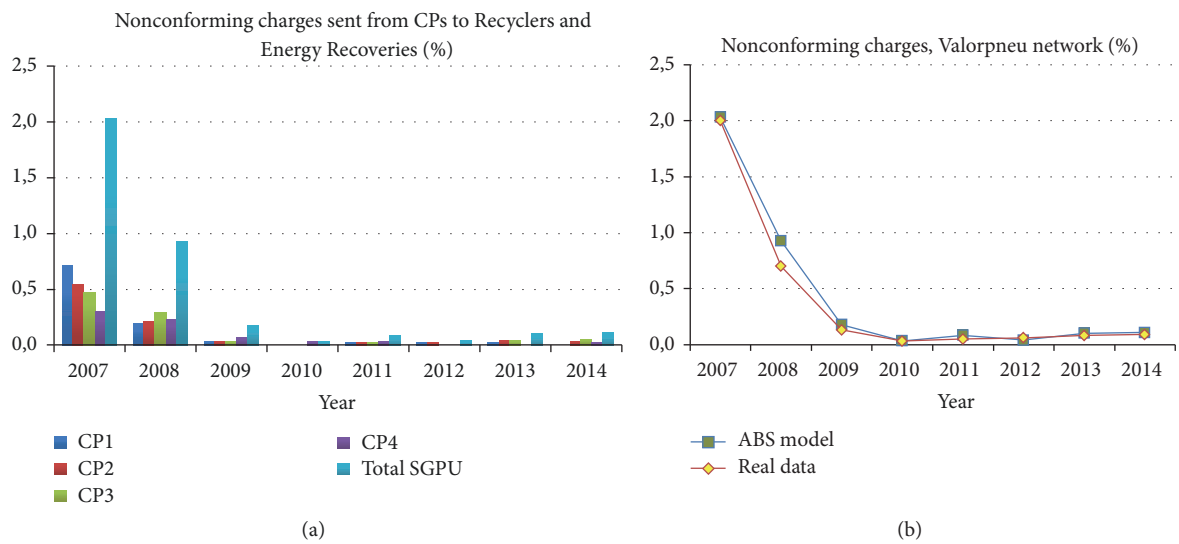


Figure 17: Percentage of nonconforming charges sent from collection points to recyclers and energy recoveries.

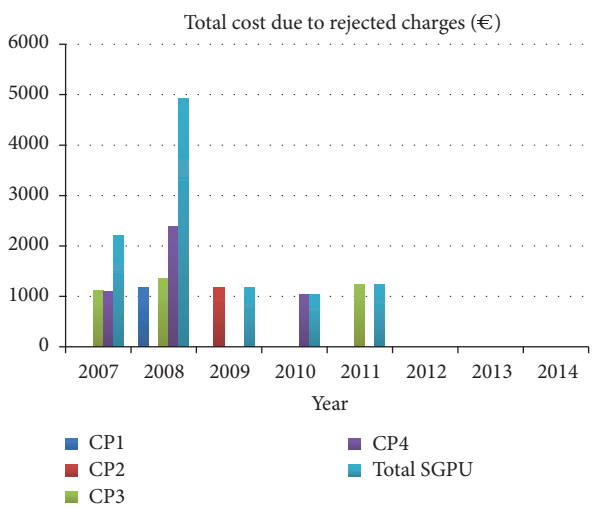


Figure 18: Total cost for CPs due to rejected charges.

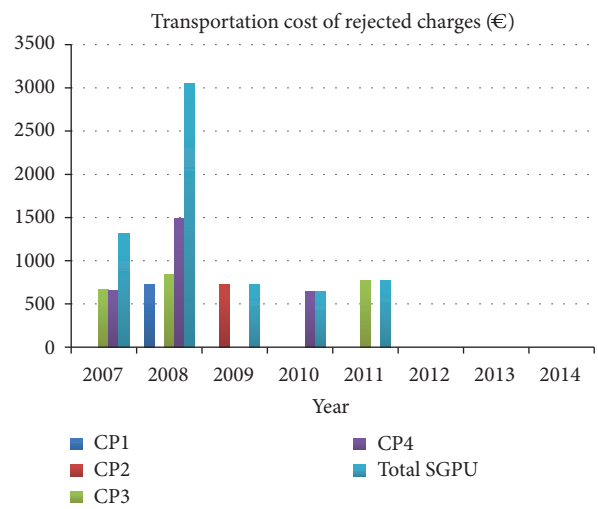


Figure 19: Transportation cost paid to transporters due to rejected charges.

number of loads carried out every year in the scope of SGPU, the percentage of contaminated charges was around 0.27% in 2014. From Figure 16, we see that this value fell sharply after 2008 (69 in 2008 to 15 in 2014). The reason for improvement is that since 2008 the managing entity intensified the follow-up visits to collection points.

The findings discussed here support both Hypotheses 1 and 2. First, the gap between ALBI and RLBI on BIDSs related to the dimensions "management of external relationships" and "cooperative business processes" affected the operational performance of the SGPU operators, as predicted in Hypothesis 1. Second, the gap between ALBI and RLBI in dyads affected the performance of companies in other dyads. The implementation of a system to evaluate the performance of transporters affected the performance of collection points, recyclers, and energy recoveries, thereby supporting Hypothesis 2.

6. Conclusions

6.1. Conclusions on the Research Question. This paper proposed an agent-based model to simulate the interactions among cooperative networked companies and analyzed how business interoperability affects their interactions and performance. The paper addressed a research question defined on the basis of an important gap in business interoperability and operations management (OM) literature: existing works do not explain how to analyze the effect of business interoperability on the performance of networked organizations, taking into account the network effect.

With regard to the research question, the findings of this study suggest that indeed ABS modeling provides a set of effective tools to analyze the effect of business interoperability

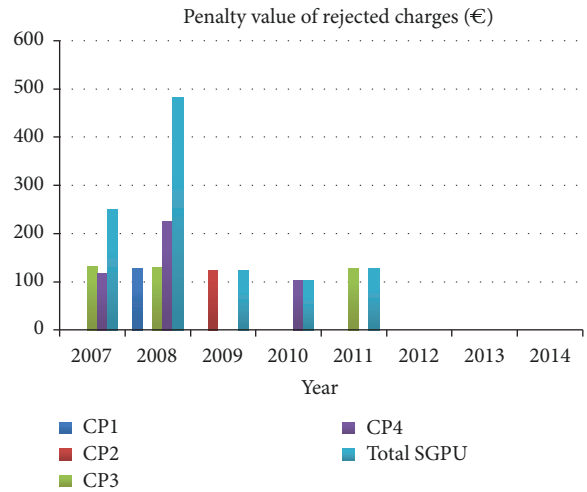


Figure 20: Penalty value paid to transporters due to rejected charges.

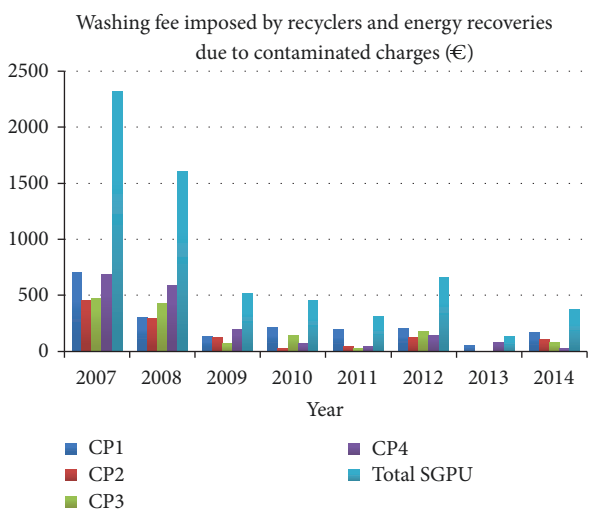


Figure 21: Washing fee imposed by recyclers and energy recoveries due to contaminated charges.

on the performance of cooperative SCNs, as it enabled the researcher to

(1) model the interaction among the SGPU operators;

(2) model the way that each BIDS can affect companies' interaction by linking each interaction process to specific BIDSs;

(3) model the probability of occurrence of business interoperability problems based on the gap between the ALBI and RLBI for each BIDS;

(4) model the occurrence of business interoperability problems when companies interact and spread the impact of such problems to other members of the network;

(5) estimate the effect of the business interoperability problems, first on the performance of the agents belonging to the relationship(s) in which the problem occurred and then on the performance of the other companies.

Summarizing, the main research gap (the network effect) can be effectively captured using the proposed ABS model. For example, in the case study presented here, a situation was modeled in which a charge sent by a collection point to a recycler or an energy recovery is rejected due to contamination and/or nonconformity. The impact of this rejection was first assigned to the collection point responsible for sending the rejected charge and then spread to transporters and the managing entity. The transporter benefits from the transportation cost paid by the collection point (round trip transportation cost) and the managing entity charges a penalty to the collection point due to the rejected charge. This situation could have a considerable effect on the performance of the recycler or energy recovery that rejected the charge if its current inventory level is not enough to ensure that its production is not interrupted. This evidence from the data collected supports Hypotheses 1 and 2.

6.2. Theoretical Implications. This paper proposes a model that can be used by researchers from different areas such as business interoperability, SCM, and OM in general to simulate how organizations interact in business networks and analyze how business interoperability can affect their performance. In terms of relevance to theory, this is the first time that the network effect is taken into account in the analysis of the effect of business interoperability on the performance of SCNs. In short, the main difference regarding the existing studies is that this research addresses the network effect. Testing the effect of the levels of business interoperability on performance is also a novelty and contributes to filling gaps in the current literature. Another relevant contribution of this research is that, unlike earlier works, it explores organizational issues, namely, those of the dimension "management of external relationships." This is in line with Hypothesis 1 and reinforces our assumption that business interoperability is not a technological issue only. The extended business interoperability framework shown in Figure 1 also adds to the literature as it incorporates several elements that have never been captured before (e.g., information quality). It can also be used in future empirical research on the effect of business interoperability on the performance of other business networks such as value network and the network of systems within a company. Also, it can be used to design configurations of interoperable business network platforms—see the example in Cabral [92].

6.3. Managerial Implications. With regard to the practical contribution, the theoretical framework and the ABS model proposed in this research are intended to support SCN managers in decision-making processes regarding the business relationships their companies have with their business partners. In other words, it is intended to provide a model and a framework that can guide them on how to analyze

the effect of business interoperability on the performance of the networks in which their companies operate. In a more detailed way, the model seeks to help managers to

(1) better understand the complex nature of the business networks in which their companies operate and identify points where improvements in terms of business interoperability and operational performance can be achieved;

(2) better understand how the business relationships between their companies and their partners, and the whole network in which they operate, evolve over time;

(3) make informed decisions on the mechanisms of business interoperability that can be used by their companies and their partners;

(4) better analyze the impact of the implementation of a given BIDS;

(5) set the appropriate level of business interoperability for each BIDS, thereby avoiding unnecessary investments;

(6) predict the occurrence of business interoperability problems, not only between their companies and their partners but also between their partners and other elements of the network, and implement preventive actions rather than mitigation plans;

(7) better understand how internal events such as cooperation breakdown, entrance of new partners, and information system breakdown can impact the performance of their companies;

(8) better understand how external events, such as economic crisis, strikes, introduction of new technologies and/or legislations, and new competitors, can impact the performance of the network of companies in which they operate;

(9) identify the dyad(s) in which the levels of business interoperability are inappropriate and make informed decisions on behalf of the whole network.

6.4. Limitations and Future Research. This research is subject to a number of limitations. First, only one case study was conducted, which implies that conclusions cannot be generalized. Second, the data collected were not enough to fully explain the network effect, as in most cases the managers interviewed recognized that the network effect is a real "phenomenon" in the Valorpneu network but were unable to quantify its impact. Third, although the theoretical framework suggests that interoperability and performance are both multidimensional, the performance is reduced to two dimensions (economic and operational) and only some elements related to the dimensions "management of external relationships" and "cooperative business processes" have been considered in the demonstration of the ABS model.

Taking into account these limitations, there are many ways to extend this work in the future. First, more empirical data need to be collected in order to better explain the network effect and the link between the dimensions of business interoperability and performance. Second, the proposed ABS model must be applied to other business network contexts (e.g., automotive and aircraft industries) in order to compare the outcomes with those reported here. Also, more case studies need to be carried out in order to better decide on the appropriateness of ABS modeling to analyze the effect of business interoperability on the performance of companies, in a context of complex cooperative SCNs.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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References

[1] I. Cabral, A. Grilo, and V. Cruz-Machado, "A decision-making model for Lean, Agile, Resilient and Green supply chain management," *International Journal of Production Research*, vol. 50, no. 17, pp. 4830–4845, 2012.

[2] J. Mills, J. Schmitz, and G. Frizelle, "A strategic review of "supply networks"," *International Journal of Operations and Production Management*, vol. 24, no. 10, pp. 1012–1036, 2004.

[3] H. Håkansson and I. Snehota, "No business is an island: the network concept of business strategy," *Scandinavian Journal of Management*, vol. 22, no. 3, pp. 256–270, 2006.

[4] F. B. Vernadat, "Technical, semantic and organizational issues of enterprise interoperability and networking," *Annual Reviews in Control*, vol. 34, no. 1, pp. 139–144, 2010.

[5] H. Min and G. Zhou, "Supply chain modeling: past, present and future," *Computers & Industrial Engineering*, vol. 43, no. 1-2, pp. 231–249, 2002.

[6] D. M. Lambert and M. C. Cooper, "Issues in supply chain management," *Industrial Marketing Management*, vol. 29, no. 1, pp. 65–83, 2000.

[7] L. Li and R. Q. Zhang, "Cooperation through capacity sharing between competing forwarders," *Transportation Research Part E: Logistics and Transportation Review*, vol. 75, pp. 115–131, 2015.

[8] A. Grilo and R. J. Goncalves, "Value proposition on interoperability of BIM and collaborative working environments," *Automation in Construction*, vol. 19, no. 5, pp. 522–530, 2010.

[9] K. W. Green Jr., P. J. Zelbst, J. Meacham, and V. S. Bhadauria, "Green supply chain management practices: impact on performance," *Supply Chain Management Review*, vol. 17, no. 3, pp. 290–305, 2012.

[10] P. M. G. van Veen-Dirks and P. J. A. Verdaasdonk, "The dynamic relation between management control and governance structure in a supply chain context," *Supply Chain Management Review*, vol. 14, no. 6, pp. 466–478, 2009.

[11] J. C. P. Mesa and E. G. Galdeano-Gómez, "Collaborative firms managing perishable products in a complex supply network: an empirical analysis of performance," *Supply Chain Management Review*, vol. 20, no. 2, pp. 128–138, 2015.

[12] M. Finne and J. Holmström, "A manufacturer moving upstream: triadic collaboration for service delivery," *Supply Chain Management Review*, vol. 18, no. 1, pp. 21–33, 2013.

[13] F. Pomponi, L. Fratocchi, and S. R. Tafuri, "Trust development and horizontal collaboration in logistics: a theory based evolutionary framework," *Supply Chain Management Review*, vol. 20, no. 1, pp. 83–97, 2015.

[14] B. Schulze-Ehlers, N. Steffen, G. Busch, and A. Spiller, "Supply chain orientation in SMEs as an attitudinal construct: conceptual considerations and empirical application to the dairy sector," *Supply Chain Management Review*, vol. 19, no. 4, pp. 395–412, 2014.

[15] J.-H. Cheng, C.-H. Yeh, and C.-W. Tu, "Trust and knowledge sharing in green supply chains," *Supply Chain Management Review*, vol. 13, no. 4, pp. 283–295, 2008.

[16] C.-W. Chang, D. M. Chiang, and F.-Y. Pai, "Cooperative strategy in supply chain networks," *Industrial Marketing Management*, vol. 41, no. 7, pp. 1114–1124, 2012.

[17] C.-M. Chituc, C. Toscano, and A. Azevedo, "Interoperability in Collaborative Networks: independent and industry-specific initiatives—the case of the footwear industry," *Computers in Industry*, vol. 59, no. 7, pp. 741–757, 2008.

[18] L. E. Whitman and H. Panetto, "The missing link: culture and language barriers to interoperability," *Annual Reviews in Control*, vol. 30, no. 2, pp. 233–241, 2006.

[19] R. Jardim-Goncalves and A. Grilo, "Building information modeling and interoperability," *Automation in Construction*, vol. 19, no. 4, p. 387, 2010.

[20] A. Grilo, R. Jardim-Goncalves, and V. Cruz-Machado, "A framework for measuring value in business interoperability," in *Proceedings of the IEEE International Conference on Industrial Engineering and Engineering Management*, pp. 520–524, IEEE, Singapore, December 2007.

[21] R. Jardim-Goncalves, A. Grilo, C. Agostinho, F. Lampathaki, and Y. Charalabidis, "Systematisation of Interoperability Body of Knowledge: The foundation for Enterprise Interoperability as a science," *Enterprise Information Systems*, vol. 7, no. 1, pp. 7–32, 2013.

[22] W. Guédria, Y. Naudet, and D. Chen, "Maturity model for enterprise interoperability," *Enterprise Information Systems*, vol. 9, no. 1, pp. 1–28, 2015.

[23] H. Panetto and J. Cecil, "Information systems for enterprise integration, interoperability and networking: theory and applications," *Enterprise Information Systems*, vol. 7, no. 1, pp. 1–6, 2013.

[24] S. B. Brunnermeier and S. A. Martin, "Interoperability costs in the US automotive supply chain," *Supply Chain Management Review*, vol. 7, no. 2, pp. 71–82, 2002.

[25] F. Galasso, Y. Ducq, M. Lauras, D. Gourc, and M. Camara, "A method to select a successful interoperability solution through a simulation approach," *Journal of Intelligent Manufacturing*, vol. 27, no. 1, pp. 217–229, 2016.

[26] D. Chen, G. Doumeingts, and F. Vernadat, "Architectures for enterprise integration and interoperability: past, present and future," *Computers in Industry*, vol. 59, no. 7, pp. 647–659, 2008.

[27] Y. Gong and M. Janssen, "An interoperable architecture and principles for implementing strategy and policy in operational processes," *Computers in Industry*, vol. 64, no. 8, pp. 912–924, 2013.

[28] ATHENA, "Business Interoperability Framework—Work package B3.1-4 (Version 2.0)," 2007.

[29] A. Zutshi, A. Grilo, and R. Jardim-Goncalves, "The business interoperability quotient measurement model," *Computers in Industry*, vol. 63, no. 5, pp. 389–404, 2012.

[30] R. Jardim-Goncalves, C. Agostinho, J. Sarraipa, A. Griloc, and J. P. Mendonca, "Reference framework for enhanced interoperable collaborative networks in industrial organisations," *International Journal of Computer Integrated Manufacturing*, vol. 26, no. 1-2, pp. 166–182, 2013.

[31] C. Campos, R. Chalmeta, R. Grangel, and R. Poler, "Maturity model for interoperability potential measurement," *Information Systems Management*, vol. 30, no. 3, pp. 218–234, 2013.

[32] R. Chalmeta and V. Pazos, "A step-by-step methodology for enterprise interoperability projects," *Enterprise Information Systems*, vol. 9, no. 4, pp. 436–464, 2015.

[33] O. Noran, "Achieving a sustainable interoperability of standards," *Annual Reviews in Control*, vol. 36, no. 2, pp. 327–337, 2012.

[34] N. Daclin, D. Chen, and B. Vallespir, "Developing enterprise collaboration: a methodology to implement and improve interoperability," *Enterprise Information Systems*, vol. 10, no. 5, pp. 467–504, 2016.

[35] A. Boza, L. Cuenca, R. Poler, and Z. Michaelides, "The interoperability force in the ERP field," *Enterprise Information Systems*, vol. 9, no. 3, pp. 257–278, 2015.

[36] E. N. Loukis and Y. K. Charalabidis, "An empirical investigation of information systems interoperability business value in European firms," *Computers in Industry*, vol. 64, no. 4, pp. 412–420, 2013.

[37] M. P. Gallaher, A. C. O'Connor, and T. Phelps, *Economic Impact Assessment of the International Standard for the Exchange of Product Model Data (STEP) in Transportation Equipment Industries*, National Institute of Standards and Technology, Gaithersburg, Md, USA, 2002.

[38] M. P. Gallaher, A. C. O'Connor, J. L. Dettbarn Jr., and L. T. Gilday, *Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry*, National Institute of Standards and Technology, 2004.

[39] W. White, A. O'Connor, and B. Rowe, *Economic Impact of Inadequate Infrastructure for Supply Chain Integration*, National Institute of Standards and Technology, Gaithersburg, Md, USA, 2004.

[40] H. Håkansson and I. Snehota, *Developing Relationships in Business Networks*, Routledge, New York, NY, USA, 1995.

[41] DoD, *DoD, Levels of Information Systems Interoperability (LISI)*, Architecture Working Group of the US Department of Defence, 1998.

[42] W. J. Johnston, *Patterns in Industrial Buying Behavior*, Praeger, 1981.

[43] T. Ritter, I. F. Wilkinson, and W. J. Johnston, "Managing in complex business networks," *Industrial Marketing Management*, vol. 33, no. 3, pp. 175–183, 2004.

[44] W. Rand and R. T. Rust, "Agent-based modeling in marketing: Guidelines for rigor," *International Journal of Research in Marketing*, vol. 28, no. 3, pp. 181–193, 2011.

[45] Y. Naudet, T. Latour, W. Guedria, and D. Chen, "Towards a systemic formalisation of interoperability," *Computers in Industry*, vol. 61, no. 2, pp. 176–185, 2010.

[46] IEEE, Standard Computer Dictionary - A Compilation of IEEE Standard Computer Glossaries, IEEE Std 610.12-1990, The Institute of Electrical and Electronics Engineers, pp. 1, 1990.

[47] R. D. Ireland, M. A. Hitt, and D. Vaidyanath, "Alliance management as a source of competitive advantage," *Journal of Management*, vol. 28, no. 3, pp. 413–446, 2002.

[48] M. Gustavsson and C. Wänström, "Assessing information quality in manufacturing planning and control processes," *International Journal of Quality & Reliability Management*, vol. 26, no. 4, pp. 325–340, 2009.

[49] D. M. Lambert and M. G. Enz, "Issues in Supply Chain Management: Progress and potential," *Industrial Marketing Management*, vol. 62, pp. 1–16, 2017.

[50] R. A. Lancioni, "New Developments in Supply Chain Management for the Millennium," *Industrial Marketing Management*, vol. 29, no. 1, pp. 1–6, 2000.

[51] K. Kumar and H. G. van Dissel, "Sustainable collaboration: managing conflict and cooperation in interorganizational systems," *MIS Quarterly: Management Information Systems*, vol. 20, no. 3, pp. 279–299, 1996.

[52] P. H. Andersen and R. Kumar, "Emotions, trust and relationship development in business relationships: A conceptual model for buyer-seller dyads," *Industrial Marketing Management*, vol. 35, no. 4, pp. 522–535, 2006.

[53] R. Seppänen, K. Blomqvist, and S. Sundqvist, "Measuring interorganizational trust-a critical review of the empirical research in 1990-2003," *Industrial Marketing Management*, vol. 36, no. 2, pp. 249–265, 2007.

[54] T. Y. Choi, K. J. Dooley, and M. Rungtusanatham, "Supply networks and complex adaptive systems: control versus emergence," *Journal of Operations Management*, vol. 19, no. 3, pp. 351–366, 2001.

[55] M. Milgate, "Supply chain complexity and delivery performance: An international exploratory study," *Supply Chain Management Review*, vol. 6, no. 3, pp. 106–118, 2001.

[56] S. Serdarasan, "A review of supply chain complexity drivers," *Computers & Industrial Engineering*, vol. 66, no. 3, pp. 533–540, 2013.

[57] C. C. Bozarth, D. P. Warsing, B. B. Flynn, and E. J. Flynn, "The impact of supply chain complexity on manufacturing plant performance," *Journal of Operations Management*, vol. 27, no. 1, pp. 78–93, 2009.

[58] E. J. S. Hearnshaw and M. M. J. Wilson, "A complex network approach to supply chain network theory," *International Journal of Operations & Production Management*, vol. 33, no. 4, pp. 442–469, 2013.

[59] M. Barratt, "Understanding the meaning of collaboration in the supply chain," *Supply Chain Management Review*, vol. 9, no. 1, pp. 30–42, 2004.

[60] J. M. Whipple, D. F. Lynch, and G. N. Nyaga, "A buyer's perspective on collaborative versus transactional relationships," *Industrial Marketing Management*, vol. 39, no. 3, pp. 507–518, 2010.

[61] C. Scandelius and G. Cohen, "Sustainability program brands: Platforms for collaboration and co-creation," *Industrial Marketing Management*, vol. 57, pp. 166–176, 2016.

[62] P. J. Batt and S. Purchase, "Managing collaboration within networks and relationships," *Industrial Marketing Management*, vol. 33, no. 3, pp. 169–174, 2004.

[63] R. Rezaei, T. K. Chiew, and S. P. Lee, "A review on E-business Interoperability Frameworks," *The Journal of Systems and Software*, vol. 93, pp. 199–216, 2014.

[64] R. Rezaei, T. K. Chiew, and S. P. Lee, "An interoperability model for ultra large scale systems," *Advances in Engineering Software*, vol. 67, pp. 22–46, 2014.

[65] R. Rezaei, T. K. Chiew, S. P. Lee, and Z. Shams Aliee, "Interoperability evaluation models: A systematic review," *Computers in Industry*, vol. 65, no. 1, pp. 1–23, 2014.

[66] IDEAS, Deliverables D 3.4, D 3.5, D 3.6: A Gap Analysis Required Activities in Research, Technology and Standardisation to close the RTS Gap Roadmaps and Recommendations on RTS activities, 2003.

[67] iDABC, European Interoperability Framework for Pan-European eGovernment Services, Luxembourg: Office for Official Publications of the European Communities, 2004.

[68] ATHENA, Overview of the ATHENA Interoperability Framework 2004.

[69] NEHTA, Towards an Interoperability Framework (Version 1.8) National E-Health Transition Authority, Australia, 2005.

[70] D. Chen, Enterprise Interoperability Framework, Proceedings of the Open Interop Workshop on Enterprise Modelling and Ontologies for Interoperability, Co-located with CAiSE'06 Conference, Luxembourg, 2006.

[71] V. P. Corella, R. C. Rosalena, and D. M. Simarro, "SCIF-IRIS framework: A framework to facilitate interoperability in supply chains," *International Journal of Computer Integrated Manufacturing*, vol. 26, no. 1-2, pp. 67–86, 2013.

[72] W. H. DeLone and E. R. McLean, "Information systems success: the quest for the dependent variable," *Information Systems Research*, vol. 3, no. 1, pp. 60–95, 1992.

[73] R. Wilding, "The supply chain complexity triangle: Uncertainty generation in the supply chain," *International Journal of Physical Distribution & Logistics Management*, vol. 28, no. 8, pp. 599–616, 1998.

[74] M. Gerschberger, C. Engelhardt-Nowitzki, S. Kummer, and F. Staberhofer, "A model to determine complexity in supply networks," *Journal of Manufacturing Technology Management*, vol. 23, no. 8, pp. 1015–1037, 2012.

[75] C. Shahabi and F. Banaei-Kashani, "Modelling P2P data networks under complex system theory," *International Journal of Computational Sciences and Engineering*, vol. 3, no. 2, pp. 103–111, 2007.

[76] Y. Kim, T. Y. Choi, T. Yan, and K. Dooley, "Structural investigation of supply networks: A social network analysis approach," *Journal of Operations Management*, vol. 29, no. 3, pp. 194–211, 2011.

[77] R. Hoole, "Five ways to simplify your supply chain," *Supply Chain Management: An International Journal*, vol. 10, no. 1, pp. 3–6, 2005.

[78] T. Y. Choi and D. R. Krause, "The supply base and its complexity: implications for transaction costs, risks, responsiveness, and innovation," *Journal of Operations Management*, vol. 24, no. 5, pp. 637–652, 2006.

[79] S. D. Pathak, J. M. Day, A. Nair, W. J. Sawaya, and M. M. Kristal, "Complexity and adaptivity in supply networks: building supply network theory using a complex adaptive systems perspective," *Decision Sciences*, vol. 38, no. 4, pp. 547–580, 2007.

[80] G. Li, H. Yang, L. Sun, P. Ji, and L. Feng, "The evolutionary complexity of complex adaptive supply networks: A simulation and case study," *International Journal of Production Economics*, vol. 124, no. 2, pp. 310–330, 2010.

[81] C. Agostinho and R. Jardim-Goncalves, "Sustaining interoperability of networked liquid-sensing enterprises: a complex systems perspective," *Annual Reviews in Control*, vol. 39, pp. 128–143, 2015.

[82] A. Surana, S. Kumara, M. Greaves, and U. N. Raghavan, "Supply-chain networks: a complex adaptive systems perspective," *International Journal of Production Research*, vol. 43, no. 20, pp. 4235–4265, 2005.

[83] M. Mitchell and M. Newman, "Complex systems theory and evolution," in *Encyclopedia of Evolution*, M. Pagel, Ed., Oxford, New York, NY, USA, 2002.

[84] A. Laszlo and S. Krippner, "Chapter 3 Systems theories: Their origins, foundations, and development," *Advances in Psychology*, vol. 126, no. C, pp. 47–74, 1998.

[85] N. Gilbert, *Agent-Based Models*, Sage Publications, Guildford, UK, 2008.

[86] C. M. MacAl and M. J. North, "Tutorial on agent-based modelling and simulation," *Journal of Simulation*, vol. 4, no. 3, pp. 151–162, 2010.

[87] M. Barbati, G. Bruno, and A. Genovese, "Applications of agent-based models for optimization problems: a literature review," *Expert Systems with Applications*, vol. 39, no. 5, pp. 6020–6028, 2012.

[88] L. Monostori, J. Váncza, and S. R. T. Kumara, "Agent-based systems for manufacturing," *CIRP Annals - Manufacturing Technology*, vol. 55, no. 2, pp. 697–720, 2006.

[89] C. M. Macal and M. J. North, "Agent-based modeling and simulation," in *Proceedings of the 2009 Winter Simulation Conference, WSC 2009*, pp. 86–98, USA, December 2009.

[90] M. Giannakis and M. Louis, "A multi-agent based framework for supply chain risk management," *Journal of Purchasing and Supply Management*, vol. 17, no. 1, pp. 23–31, 2011.

[91] W. Michael and N. R. Jennings, "Intelligent agents: theory and practice," *The Knowledge Engineering Review*, vol. 10, pp. 115–152, 1995.

[92] I. Cabral, A Systematic Methodology to Analyse the Performance and Design Configurations of Business Interoperability in Cooperative Industrial Networks, Departamento de Engenharia Mecânica e Industrial, Universidade Nova de Lisboa, Caparica, Portugal, 2015.

[93] N. P. Suh, *The Principles of Design*, Oxford Press, New York, NY, USA, 1990.

[94] N. P. Suh, *Axiomatic Design: Advances and Applications*, Oxford University Press, New York, NY, USA, 2001.

[95] H. Panetto, R. Jardim-Goncalves, and A. Molina, "Enterprise integration and networking: Theory and practice," *Annual Reviews in Control*, vol. 36, no. 2, pp. 284–290, 2012.

[96] R. Jardim-Goncalves, K. Popplewell, and A. Grilo, "Sustainable interoperability: The future of Internet based industrial enterprises," *Computers in Industry*, vol. 63, no. 8, pp. 731–738, 2012.

[97] B. Fahimnia, J. Sarkis, and H. Davarzani, "Green supply chain management: a review and bibliometric analysis," *International Journal of Production Economics*, vol. 162, pp. 101–114, 2015.

[98] J. Brower and K. Rowe, "Where the eyes go, the body follows?: Understanding the impact of strategic orientation on corporate social performance," *Journal of Business Research*, vol. 79, pp. 134–142, 2017.

[99] P. Esteban-Sanchez, M. de la Cuesta-Gonzalez, and J. D. Paredes-Gazquez, "Corporate social performance and its relation with corporate financial performance: International evidence in the banking industry," *Journal of Cleaner Production*, vol. 162, pp. 1102–1110, 2017.

[100] S. Lambert, D. Riopel, and W. Abdul-Kader, "A reverse logistics decisions conceptual framework," *Computers & Industrial Engineering*, vol. 61, no. 3, pp. 561–581, 2011.

[101] R. Geng, S. A. Mansouri, E. Aktas, and D. A. Yen, "The role of Guanxi in green supply chain management in Asia's emerging economies: A conceptual framework," *Industrial Marketing Management*, vol. 63, pp. 1–17, 2017.

[102] S. Luthra, D. Garg, and A. Haleem, "The impacts of critical success factors for implementing green supply chain management towards sustainability: An empirical investigation of Indian automobile industry," *Journal of Cleaner Production*, vol. 121, pp. 142–158, 2016.

[103] C. W. Autry, "Formalization of reverse logistics programs: A strategy for managing liberalized returns," *Industrial Marketing Management*, vol. 34, no. 7, pp. 749–757, 2005.

[104] R. G. Richey, H. Chen, S. E. Genchev, and P. J. Daugherty, "Developing effective reverse logistics programs," *Industrial Marketing Management*, vol. 34, no. 8, pp. 830–840, 2005.

[105] T. Y. Chiou, H. K. Chan, F. Lettice, and S. H. Chung, "The influence of greening the suppliers and green innovation on environmental performance and competitive advantage in Taiwan," *Transportation Research Part E: Logistics and Transportation Review*, vol. 47, no. 6, pp. 822–836, 2011.

[106] L. G. Mattsson, "An application of a network approach to marketing: defending and changing market positions," in *Changing the Course of Marketing: Alternative Paradigms for Widening Marketing Theory*, N. D. A. J. Arndt, Ed., pp. 263–288, JAI Press, Greenwich, 1985.

[107] H. Håkansson, "Product development in networks," in *Technological Development: A Network Approach Helm*, H. Håkansson, Ed., pp. 84–128, 1987.

[108] B. Cova, F. Prévot, and R. Spencer, "Navigating between dyads and networks," *Industrial Marketing Management*, vol. 39, no. 6, pp. 879–886, 2010.

[109] H. Håkansson, *International Marketing and Purchasing of Industrial Goods: An Interaction Approach*, John Wiley and Sons, Chichester, UK, 1982.

[110] W. D. Kelton, R. P. Sadowski, and D. T. Sturrock, *Simulation with Arena*, McGraw-Hill, New York, NY, USA, 2004.

[111] D. R. Towill, "Industrial dynamics modelling of supply chains," *International Journal of Physical Distribution & Logistics Management*, vol. 26, no. 2, pp. 23–42, 1996.

[112] I. Cabral and A. Grilo, "Analyzing the impact of business interoperability on the performance of cooperative supply chain networks," in *Proceedings of the 5th International Conference on Industrial Engineering and Operations Management, IEOM 2015*, UAE, March 2015.

[113] T. Homer-Dixon, The Ingenuity Gap, Random House, 2001.

[114] T. M. Froese, "The impact of emerging information technology on project management for construction," *Automation in Construction*, vol. 19, no. 5, pp. 531–538, 2010.

[115] R. K. Yin, *Case Study Research: Design and Methods*, Sage Publications, Thousand Oaks, Calif, USA, 2003.

[116] M. J. North and C. M. Macal, *Managing Business Complexity: Discovering Strategic Solutions with Agent-Based Modeling and Simulation*, Oxford University Press, New York, NY, USA, 2007.

[117] U. Wilensky, NetLogo. http://ccl.northwestern.edu/netlogo/, Center for Connected Learning and Computer-Based Modeling, Northwestern University. Evanston, IL., 1999.

[118] C. Chung and A. C. Chung, *Simulation Modeling Handbook: A Practical Approach*, CRC PRESS, Florida, Fla, USA, 2004.