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# Business Models For Industrial Symbiosis: A Taxonomy Focused on the Form of Governance

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# A Taxonomy Focused on the Form of Governance

*Abstract*: The aim of this paper is to propose a taxonomy of industrial symbiosis (IS) business models. Rather than to adopt a firm perspective, we take a system perspective and focus on the governance of the system made up of the firms implementing IS, being the latter considered an important factor influencing firm's competitive advantage. Four extreme IS business models are identified, characterized on the basis of two governance features: (1) need for coordination and (2) centralization of control. For each model, the main characteristics are presented and the main factors influencing firm value creation and value capture discussed. In doing so, our study contributes to clarify how and why firms applying IS practice can gain competitive advantage, a major gap in the current literature. Consequently, we contribute to the practical development of IS, which appears to be still not fully exploited by firms, despite its relevance.

*Keywords: Industrial symbiosis, Sustainable business models, Taxonomy, Governance, Centralization, Circular Economy.*

## 1. INTRODUCTION

Facing the challenge to pursue sustainable development, firms are looking for new ways to do business delivering at the same time environmental and social benefits (e.g., Schaltegger et al., 2016). Sustainable business models are proposed to help firms in this regard (e.g., Boons and Lüdeke-Freund, 2013; Manninen et al., 2018).

A very promising sustainable business model derives from the firm's adoption of Industrial Symbiosis (IS) practice. This is a collaborative approach concerning the physical exchange of materials, energy, and services between partnering firms and utility sharing of related infrastructures (Chertow, 2000; Lombardi and Laybourn, 2012). In particular, wastes produced by a firm are used as inputs by other firms. There are many examples of successful adoptions of the IS practice (e.g., Jacobsen, 2006; Taddeo et al., 2017; Yang and Feng,

2008) as well as many studies in the literature investigating models and approaches of implementation (e.g., Albino and Fraccascia, 2015; Chertow and Ehrenfeld, 2012; Doménech and Davies, 2011).

However, an overall framework for classifying IS business models is currently lacking in the literature. Many classifications are proposed in the literature, but they refer to circular economy (CE) business models in general (Bocken et al., 2014; Boons and Lüdeke-Freund, 2013; Lewandowski, 2016; Lüdeke-Freund et al., 2018b, 2018a; Manninen et al., 2018) and do not explicitly focus on IS. However, IS differs from CE strategies. It involves complex and multiple relationships among firms producing and using wastes (forming the so-called IS network), rather than considering product-service systems or models of collaborative consumption, in which mainly customers play a central role. Such a difference aspect modifies the source of competitive advantage for firms, so that a specific analysis of business models is required for IS systems.

We also note a limitation of CE business models that needs to be overcome. Despite the diversity of the business model conceptualizations used, most of the CE business models proposed mainly adopt the firm perspective, with a notable exception (Tsvetkova and Gustafsson, 2012). This is problematic because integrating CE into business models requires a systemic view that considers different elements of the system and their interrelations (Evans et al., 2017; Zucchella and Previtali, 2018). This is especially true for an IS system, where firms are embedded in a complex and effective network of IS relationships, involving a variety of actors (i.e., stakeholders, government, social actors, facilitators, and firms). Neglecting this crucial aspect limits the understating of the source of value creation and value capture for firms implementing CE and, in particular, IS.

Therefore, the aim of this paper is providing a taxonomy specifically developed for IS business models, which adopts the system rather than the firm perspective. In doing so, we refer to business model literature and more recent conceptualizations including system dimensions. These conceptualizations extend the firm dimensions (e.g., strategy, structure, and revenue model), to include features referring to the whole system, such as supply chain, governance, and customers. They are applied to supply networks (e.g., Mason and Leek, 2008), industrial clusters (e.g., Arıkan and Schilling, 2011), and e-business models (e.g., Zott et al., 2011). In particular, these extended models recognize that value creation and value capture are affected by how the complex, interconnected set of exchange relationships and activities among multiple players (i.e., suppliers, partners, customers) is physically structured and managed (Zott et al., 2011; Zott and Amit, 2009). This accords well with the IS features above-mentioned.

Therefore, we focus on the governance of the IS system and argue that it influences how firms create and capture value by means of the adoption of IS. In particular, we propose a taxonomy of IS business models based on two IS governance dimensions, i.e., the need for coordination and the centralization of control (Arıkan and Schilling, 2011). Extreme values of these two dimensions give rise to four categories of IS business models that we characterize in terms of main value creation and value capture features.

The paper is organized as follows. First, we describe the theoretical background of this study by providing a literature review of IS, business models, and sustainable business models. Then, we discuss our taxonomy of IS business models highlighting for each class the main features and the main sources of value creation and capture. Finally, we present the implications of our study.

## 2. THEORETICAL BACKGROUND

### 2.1. Industrial Symbiosis

IS is recognized as an approach able to support the transition towards CE (e.g., Ghisellini et al., 2016; Korhonen et al., 2018). According to the symbiotic practice, materials, energy, and water generated as wastes by one production process can be used by other production processes instead of being discharged. Companies can use wastes to replace production inputs or exploit them to generate new products, which are sold on the market (Albino and Fraccascia, 2015). By adopting the IS practice, companies gain economic benefits thanks to reducing waste discharge costs and input purchase costs (Esty and Porter, 1998; Yuan and Shi, 2009) while creating environmental and social benefits for the collectivity. In particular, environmental benefits can be created in form of lower amounts of wastes disposed of in landfills, lower amounts of primary inputs, raw materials, and fossil fuels used by industry, and lower amounts of greenhouse gas (GHG) emissions generated (e.g., Hashimoto et al., 2010; Jacobsen, 2006; Martin and Eklund, 2011; Sokka et al., 2011). From the social perspective, the IS practice can create new jobs and help to preserve the current ones (Mirata and Emtairah, 2005; Sgarbossa and Russo, 2017). Accordingly, the European Commission has explicitly recommended the adoption of the IS approach (Domenech and Bahn-Walkowiak, 2017; European Commission, 2015) and policymakers in many countries have introduced IS into their economic agenda as a tool for reaching a sustainable economic development (e.g., Liu et al., 2017).

IS can be adopted at different geographic levels: within a facility, among co-located companies, and among companies not in close proximity (Chertow, 2000). Technical and economic issues dominate the choice of the spatial level. The close proximity among the involved companies is an essential requisite for the feasibility of the symbiotic exchange when physical infrastructures (e.g., pipelines) are required to operate the IS synergy (e.g., Han et al., 2017; Zhang et al., 2016). In the other cases, IS relationships may arise among firms very distant from each other as far as they are economically convenient (Jensen et al., 2011; Lyons, 2007; Sterr and Ott, 2004). Nevertheless, geographic proximity is considered as a potential facilitator for IS relationships because of economic (waste transportation costs are minimized when companies are in close proximity) and social issues (trust among companies might be enhanced) (Boons et al., 2017; Chertow, 2000; Tudor et al., 2007).

The network of entities among which IS relationships exist is referred to as IS network (ISN) (Fichtner et al., 2005). According to the 3–2 heuristic logic proposed by Chertow (2007), an ISN is defined as a network in which there are at least three different entities exchanging at least two different types of waste. The entities may belong to a single large organization such as an industrial group (e.g. the Guitang Group), may be separate industrial plants of a single company or, in general, may correspond to independent firms. This is consistent with the conceptualization of IS relationship given by Chertow et al. (2000) and Lombardi and Laybourn (2012).

However, in ISNs, each company can be simultaneously involved in more symbiotic relationships with other companies. The IS practice allows firms to encompass the borders of traditional supply chains because symbiotic relationships are usually implemented among companies belonging to different industries that might not cooperate in traditional business models (Bansal and McNight, 2009; Geng and Côté, 2007; Herczeg et al., 2018; Jensen, 2016). In addition to waste producers and waste receivers, also companies carrying out waste treatment processes can take part in ISNs, when a waste treatment process is required to make the waste able to be used as input (e.g., Aviso, 2014; Hein et al., 2017b; Lèbre et al., 2017; Liwarska-Bizukojc et al., 2009; Shi and Chertow, 2017).

Two prominent formation mechanisms of ISNs have been recognized in the literature. ISNs can be designed by adopting a top-down approach or can spontaneously emerge from the bottom, as the result of a self-organized process carried out by different companies (Chertow and Ehrenfeld, 2012; Doménech and Davies, 2011; Park et al., 2008; Zhang et al., 2010).

## 2.2. Business models: definitions and conceptualizations

The business model is a popular concept spread in strategic and technology management literature. The term mainly refers to the conceptual logic of how the firm creates and appropriates economic value (Osterwalder, 2004). Many conceptualizations are available, each differing in scope and conceptual focus (e.g., Wirtz, 2011; Zott et al., 2011). Despite this, all of them recognize the strategic intent of the business model as a tool for designing business activities as well as for a comprehensive, cross-company description and analysis. The business model reflects the firm realized strategy, highlighting the combination of product and market factors needed to implement such a strategy, and the functions of all the involved actors. Furthermore, it defines: (1) the value proposition, i.e., what is the firm's basic approach to competitive advantage; (2) the value creation, i.e., what is the source of firm's competitive advantage; and (3) the value capture, i.e., how the firm generates revenue and profit (Richardson, 2008).

Zott and Amit (2009) conceptualize the firm's business model as a system of interdependent activities that transcends the focal firm and spans its boundaries. In fact, even though some researchers view the business model closer to the firm (e.g., Casadesus-Masanell and Ricart, 2010; Hurt, 2008), others place it closer to the network in which the firm is involved (e.g., Amit and Zott, 2001; Tapscott et al., 2000). In fact, a business model cannot be reduced to issues that concern the internal organization of firms. Many activities relevant to the focal firms for creating and capturing value will be not performed by the firm itself, but by its extended network, which includes suppliers, partners, and customers. These actors contribute to define the overall "size of the value pie", which is the upper limit of the firm's value capture potential. How this complex network of activities is organized is also critical for value creation and value capture. Therefore, some business model conceptualizations include value network, supply chain, and governance of the system as relevant dimensions. For example, Hamel (2000) introduces the customer interface and the value network beyond the classical elements concerning the core strategy and the strategic resources of the firm. Doganova and Eyquem-Renault

(2009) add the list of the partners and channels, through which firm's value is produced and delivered, among the three main building blocks of a business model along with the value proposition and the revenue model. Zott and Amit (2010) argue that the system governing relationships between the firms and its partners (suppliers and customers) together with the content and the structure are elements of a successful business model. Table 1 summarizes the main dimensions included in the firm- and system-level conceptualizations of business models. Referring to this study, in this paper, we consider the governance of the system made up of all the actors involved in the adoption the IS practice as a fundamental dimension of IS business model. We explain our argumentations in the next sections.

**Table 1. Firm vs. system dimensions in business model conceptualizations.**

| Firm-level dimensions | System-level dimensions |
|---|---|
| Content | Supply Chain |
| Structure | Value network |
| Revenue model | Customer interface |
| Activity | Governance |

### 2.3. Sustainable business models

Sustainable business models "*create competitive advantage through superior customer value and contribute to a sustainable development of the company and society*" (Lüdeke-Freund, 2010, p. 23). Therefore, compared to a classical business model, the value proposition of a sustainable business model includes value for society and natural environment in addition to the economic value for the firm (Boons and Lüdeke-Freund, 2013; Manninen et al., 2018; Schaltegger et al., 2016).

Different classifications of sustainable business models have been developed in the literature, based on several criteria. The earliest classification is provided by Bocken et al. (2014), who identify eight archetypes on the basis of the type of innovation, i.e. technological, social, or organizational oriented innovations. Similarly, Lüdeke-Freund et al. (2018a) identify 45 patterns of sustainable business models on the basis of ecological, social, and economic sustainability dimensions of sustainability. Other classifications focus on the strategies that contribute to make circular the economic system, for example by slowing, closing, or narrowing the resource loops (Bocken et al., 2016; Lüdeke-Freund et al. (2018b) or by using the actions proposed in the

ReSOLVE framework developed by the Ellen MacArthur Foundation (Lewandowski, 2016). A different approach is used by Urbinati et al. (2017). Rather than to focus on CE strategies, they refer to the degree of adoption of circularity, distinguishing among linear, downstream circular, upstream circular, and full circular business models. Each business model is defined along two dimensions: (1) the customer value proposition and interface, i.e., the implementation of the circularity concept in proposing value to customers; (2) the value network, i.e., the ways through which interacting with suppliers and reorganizing the own internal activities. This is a first attempt to introduce a system perspective in CE business models taxonomy.

In foregoing studies on sustainable business models, in fact, the system perspective is almost neglected. As said above, most of them focus on CE strategies that firms can independently implement, whereas just a limited number of CE business models include system-level dimensions such as supply chain and value network. A notable exception is provided by Urbinati et al. (2017) and Tsvetkova and Gustafsson (2012). In particular, the latter, rather than analyzing the single company, focus on industrial ecosystems, i.e., complex systems "*made up of a large number of parts that interact in a nonsimple way*" (Simon, 1962, p. 468), where companies need to interact amongst each other in the adoption of sustainable business models. In particular, the authors propose a modular approach to analyze business models of industrial ecosystems, which highlights the involved actors and their interaction patterns aimed at creating value. This is consistent with system-level conceptualization of business models.

To the best of our knowledge, no sustainable business model classification focuses on the governance dimension. We overcome this lack with reference to a specific class of sustainable business models, i.e. those implementing the IS practice.

## 3. FRAMEWORK FOR CLASSIFYING IS BUSINESS MODELS

To develop our framework, following Richardson (2008), we first consider that any business model is defined by three elements: (1) the value proposition, (2) the value creation, and (3) the value capture. However, we note that the value proposition is not critical to differ IS business models, because for all of them the value proposition relies on two main CE strategies: (1) "creating value from waste"; and (2) "maximize material and energy efficiency". The first strategy corresponds to using waste to produce new products to sell to the market or to other firms; the second strategy concerns reducing the amount of virgin materials used in the production processes (Bocken et al., 2014). Thus, we neglect this dimension in further analysis. It follows that IS business models differ only on the basis of value creation and value capture. Value creation refers to the ability of ISNs to develop value for final customers in terms of products and services exploiting the two CE strategies above-mentioned. Value captures resides in the ability of IS firms to capture customer value optimizing costs and revenues coming from the two CE strategies.

Referring to the recent conceptualizations of business models emphasizing the system perspective, we recognize that the governance of IS systems is important in affecting both value creation and value capture. This describes how the network of relationships resulting from the implementation of IS practice is organized and managed so influencing both the value creation and the value capture (Figure 1). This variable is shown to be very critical for the efficacy of IS systems (Li Sun et al., 2017)

In the following, we first define the governance dimensions of an IS system: (1) need for coordination and (2) centralization of control. Then, we discuss the four classes of IS business models so identified. In particular, for each class, we describe the main features by providing empirical examples and we elucidate the value creation and value capture features.

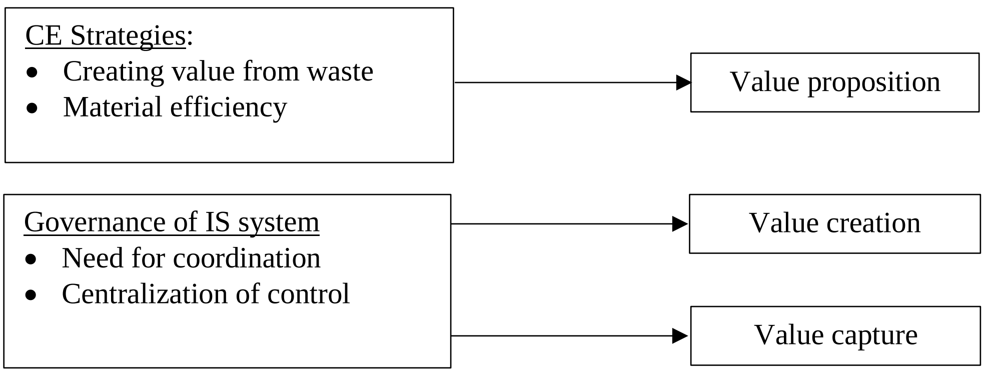


**Figure 1. Conceptualization of the IS business model.**

### 3.1. The IS governance dimensions

The *need for coordination* among firms occurs when the adoption of IS practice determines the existence of interdependencies between firms to manage. "*Management scholars use the term interdependence to suggest [that two or more parties] are dependent on each other to achieve their desired outcomes*" (Wicks et al., 1999, p. 104). There are different types of interdependencies: internal vs. external and workflow vs. resource

(Thompson, 1967). In particular, resource interdependence occurs when two or more parties are dependent on the resources they receive from each other (Pfeffer and Salancik, 2003). The symbiotic relationship is a type of resource interdependence, which mainly involves the physical exchange of materials, energy, water, and by-products (Chertow, 2000). Since the basic mechanism of IS is that one firm's waste becomes another firm's feedstock (Frosch and Gallopulos, 1989), firms involved in IS relationships become resource interdependent one from each other (Ehrenfeld and Gertler, 1997). This type of interdependence may also extend from the operational level to the strategic one when a company uses wastes from the other company to generate new products for the market (Albino and Fraccascia, 2015).

As firms become more and more embedded in the network of IS relationships, the degree of interdependence also rises and the need for coordination becomes high. In this regard, companies face inter-organizational challenges and several inter-firms activities need to be planned to carry out the IS relationship (Bansal and McNight, 2009; Herczeg et al., 2018). First, companies should agree on the quantity of waste that will be exchanged and the delivery time. Planning the right amount of waste that will be delivered to the right customer at the right time can be harder compared to similar activities in traditional businesses, since waste is not produced upon demand but emerges as a secondary output of main production activities (Densley Tingley et al., 2017; Yazan et al., 2016). Furthermore, some wastes might require a treatment process before being used as inputs, e.g., removing impurities or contaminants from the waste (e.g., Aviso, 2014; Hashimoto et al., 2010), which can be operated by a third firm. Such a practice increases the complexity of the IS relationship, which needs additional coordination. The need for coordination impacts on the amount of transaction costs for the involved companies. Accordingly, when inter-firm relationships require greater coordination, transaction costs increase, *ceteris paribus* (e.g., Gereffi et al., 2005). Rather than to exchange waste with another company, waste producers might use wastes within their boundaries (e.g., by using a waste produced by a given production process as input for other production processes or simply selling wastes on the market, when a waste market exists) (e.g., Shi and Chertow, 2017; Zhu et al., 2008). In such a case, there is no interdependence between firms within the system and the need for coordination is thus low, thus resulting in low transaction costs for the company. However, in order to use a given waste internally, companies need to operate production processes able to receive that waste as input.

The governance of the IS system is also characterized by *centralization of control*, i.e., the extent to which a central actor manages the entire system of relationships. A high centralization of control regards IS systems managed by a central actor who has disproportionate authority over which companies become part of the system, which symbiotic interactions take place, and how IS relationships are operated. This is the case of the top-down eco-industrial parks (Behera et al., 2012; Ubando et al., 2015; Yu et al., 2014) but also IS practices managed by local governments and recently IS experiences leaded by research centers (Geng et al., 2010; Park et al., 2016; Lu Sun et al., 2017). Conversely, centralization of control is low when symbiotic relationships are managed by adopting a decentralized approach. The IS relationships are regulated by contractual mechanisms negotiated by the involved companies, without the existence of a central authority (Albino et al., 2016; Desrochers, 2004). Low centralization of control is a feature characterizing self-organized ISNs (Chertow and Ehrenfeld, 2012).

As shown in Figure 2, the extreme values of need for coordination and centralization of control identify four types of IS business models.

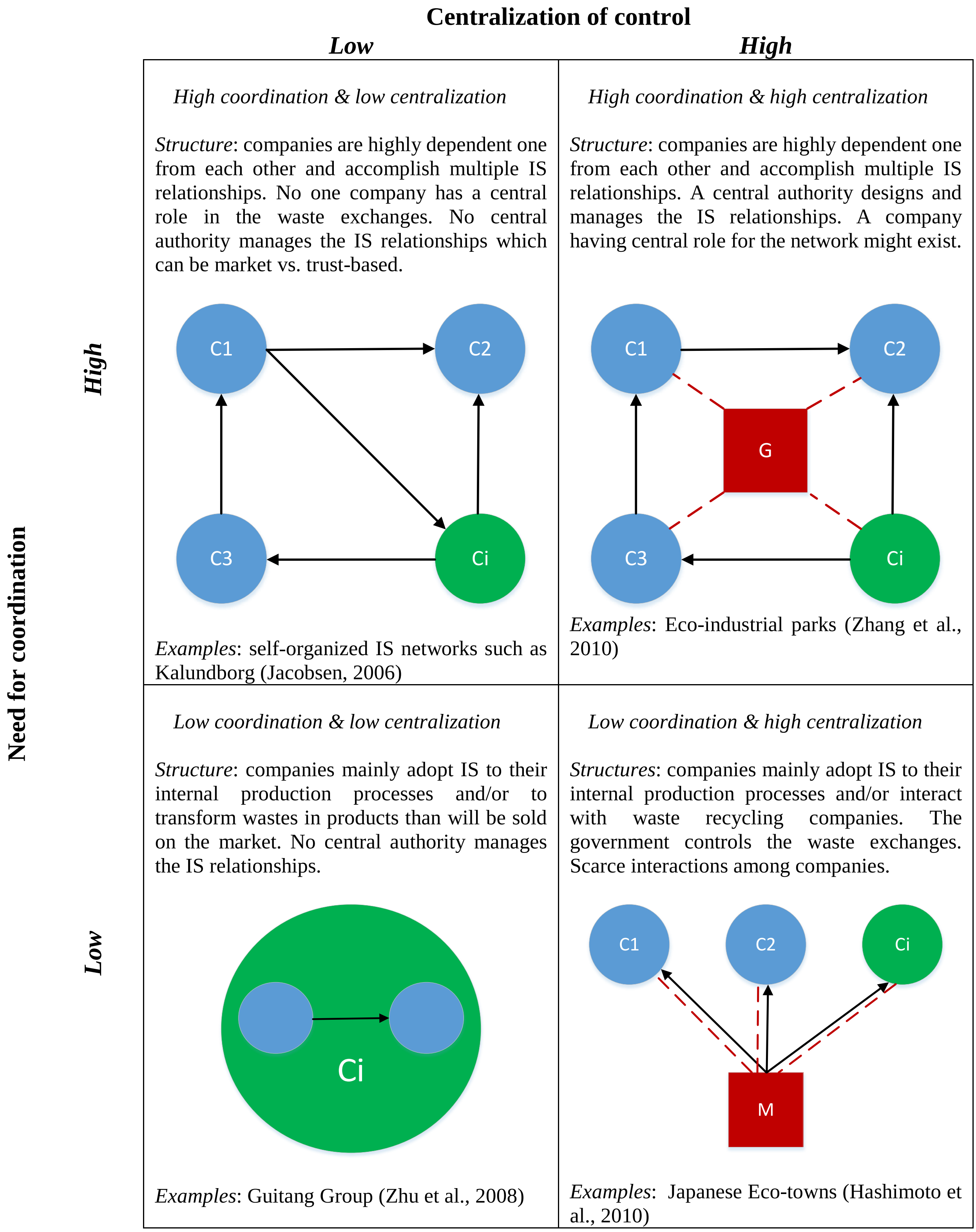


**Figure 2. Taxonomic dimensions of IS business models.**

## 3.2. Framework Description

### 3.2.1. Low Coordination and Low Centralization

This IS business model characterizes firms implementing the IS practice within their organizational boundaries. Firms can follow two models: (1) using wastes as inputs for their production processes; and (2) exploiting wastes to produce new products, which are sold on the market. By adopting such a model, firms are not required to interact with other companies.

Because firm internalizes the IS relationship within its boundary, both the need for coordination and the centralization of control are low. Hence, rather than to be a complex network of IS relationships, this model is made up of symbiotic synergies adopted within boundaries of one company or at most of an industrial group.

A real case of a company implementing such a model is offered by the Guitang Group, one of the biggest Chinese sugar producers, established by the Chinese government in 1956 (Shi and Chertow, 2017; Yang and Feng, 2008; Zhu et al., 2008). At the time of establishment, the Guitang Group produced sugar and molasses as main products and exploited waste molasses to produce alcohol. In the 1970–80s, Guitang Group started to exploit the fibrous by-product of sugarcane to produce toilet paper, which was sold on the market. During this time, further symbiotic exchanges were implemented among the sugar, alcohol, and paper production processes. In the 1990s, Guitang Group started to produce and sell on the market other products (e.g., alkali, cement, fertilizer) to capture more value from the wastes. A similar case in the UK is described by Short et al. (2014).

Companies producing energy and alternative fuels from the wastes they produce are further real cases of this model. Several examples are discussed in the literature. For instance: (1) the animal manure produced by a smallholder farm can be used to produce methane and the digestate resulting from anaerobic digestion can be used as fertilizer (Alfaro and Miller, 2014); (2) liquid fuel, biochar, and gas fuel can be achieved from solid and semi-solid wastes produced in an olive farm (Zabaniotou et al., 2015); (3) spent grain from beer production can be converted into pellet that will be used for heat generation in beer production or into biochar through thermochemical process of pyro-gasification (Sperandio et al., 2017). These products generated by exploiting wastes can be used either within the company or sold on the market.

In creating value, companies do not need to cooperate with other ones, so that they need to pay neither waste transportation costs nor transaction costs. The value creation process depends on their technical and organizational abilities to exploit the wastes they produce to replace primary inputs or to generate new products. In this regard, companies should have knowledge about the relevant technology to use and should possess the ability to design and implement new production processes (e.g., processes for waste treatment of new product generation) and to upgrade existing processes (e.g., make processes able to use wastes as production inputs). They should be able to face this internal change and properly manage the traditional and new production processes together.

Companies can capture value through the following possibilities: (1) reduction in waste disposal costs (WDC); (2) reduction in input purchase costs (IPC); (3) additional gains from selling the new products generated from wastes (AGP); (4) additional gains thanks to the better environmental reputation of the company (AGR), in form of premium price for their products and higher amount sold on the market. However, the value created can be eroded by additional costs required for making wastes able to be used as inputs (ACR). The value captured (CV) by the generic company *i* is given by the following equation:

$$CV_i = WDC_i + IPC_i + AGP_i + AGR_i - ACR_i \qquad (1)$$

We provide details about how to quantify each term of this equation in the Appendix. In particular, the variables, contributing to the value captured by firms in all the four business models proposed, are given in Table 3. The aim is to assist companies in quantifying the portion of value created they can capture in each business model, but also to suggest them which factors are critical to improve it.

#### 3.2.2. Low Coordination and High Centralization

This IS business model characterizes companies that replace production inputs with urban wastes or use them to produce new products. These companies adopt the IS practice internally with minimal interactions with other firms, similarly to the model above, but are usually co-located in a geographical area. Companies maintain their independence and do not exchange resources amongst each other. Therefore, the system is characterized by a low need for coordination. However, differently from the case above, this system is characterized by high-centralized control, because the re-use of urban waste is strongly supported by the territorial government of the area. A municipal committee usually exists that identify companies that can locate into the area, provides them with support for the project investigation, and elaborate future plans. The committee can attract companies by providing economic incentives or financing the construction of new plants. The governmental intervention is mainly aimed at diverting wastes from landfills, according to the concept of "zero waste city" (Zaman and Lehmann, 2013, 2011).

Such a model was adopted for example by the Japanese government when implementing the Eco-town programme (Hashimoto et al., 2010; Ohnishi et al., 2012; Van Berkel et al., 2009b, 2009a). The Eco-town programme was mainly aimed at reducing the amounts of urban wastes incinerated, because of the lack of adequate space in landfills to dispose of the ash resulting from the incineration process. Companies able to use urban wastes in production processes were subsidized by the government to locate their factories in industrial areas close to Japanese cities. Apart from receiving subsidies, companies might also be paid to manage urban wastes. The Eco-town programme was adopted in 26 Japanese cities. The most famous case in the literature is Kawasaki (Hashimoto et al., 2010), where four main IS synergies have been implemented thanks to the governmental intervention; (1) plastic wastes (127,800 t/y) are used as alternative fuel replacing coal; (2) wastes from construction sites (70,700 t/y) are used in cement production; (3) organic sludge and sewage sludge from wastewater treatment plant are used in cement production; and (4) paper wastes (84,000 t/y) are used to produce toilet paper. Apart from waste diversion from incinerators, additional environmental benefits were created in form of lower $CO_2$ emissions. Compared to other IS projects, this model does not suffer from fluctuations in the amount of produced wastes in the long period, which is recognized as an important issue limiting the feasibility of IS projects (Herczeg et al., 2018). This occurs because of the stable production of urban wastes compared to industrial waste. However, it is highly dependent on the policy instruments.

In this business model, companies create value by strongly cooperating with the local government and localizing their plants in close proximity to the municipality. Furthermore, companies are required to adapt their production processes, from both the technical and organizational perspective, in order to make them able to use urban wastes in place of primary inputs. This may also require that companies implement additional processes, for instance sorting wastes aimed at removing impurities (Hashimoto et al., 2010). In some cases, companies might be also required to manage the collection process for urban wastes.

Similarly to the model above, companies can capture value through: (1) reduction in input purchase costs (IPC); (2) additional gains from selling the new products generated from wastes (AGP); (3) additional gains thanks to the better environmental reputation of the company, in form of premium price for their products and higher amount sold on the market (AGR). In addition, this model allows value to be captured by means of economic subsidies from the government (S), in form of additional revenues or tax discounts (4). However, the value created can be eroded by: (1) additional waste treatment costs (ACR); and (2) waste collection and transportation costs (ACT). The value captured by the generic company *i* ($CV_i$) can be computed by the following equation, whose elements are presented in Table 3:

$$CV_i = IPC_i + AGP_i + AGR_i + S_i - (ACR_i + ACT_i) \quad (2)$$

### 3.2.3. High Coordination and Low Centralization

This IS business model corresponds to the case of firms forming a self-organized ISN. Here, firms selling waste produced in their production process and firms buying waste to replace their production input can be distinguished. They spontaneously decide to carry out a symbiotic exchange so as forming a complex network of IS relationships, mainly for gaining economic and environmental benefits (Ashton, 2011; Lyons, 2007). Economic and environmental benefits created by these relationships become visible even outside the ISN, improving the market image of the companies involved. Each firm can be simultaneously involved in multiple IS relationships with more than one company, so that the network of relationships proves to be complex (Chopra and Khanna, 2014; Fraccascia et al., 2017). Thus, the need for coordination is high. The dynamics underlying the creation of self-organized ISNs have been extensively described by the literature (e.g., Boons et al., 2017) and several theoretical models have been proposed (Baas and Boons, 2004; Chertow and Ehrenfeld, 2012; Doménech and Davies, 2011).

This model is characterized by a low centralization of control. No single firm usually holds significant power in the network letting it controlling and guiding the system towards a desired direction. In fact, it might happen that companies in one part of the ISNs have partial or even no knowledge about companies in other parts of the ISN (e.g., Boons et al., 2017). The system is also characterized by high adaptiveness. It is very common that over time new IS relationships are created and some existing ones are interrupted, because of the exploitation of current economic benefits. Similarly, new companies often enter into the network and existing ones leave the system (Ashton et al., 2017; Zhu and Ruth, 2014). This assures high flexibility to the network.

However, the perfect match between demand and supply of wastes cannot always be ensured by this spontaneous mechanism (Fraccascia and Yazan, 2018). Mismatch between demand and supply can occur because of: (1) the lack of firms producing (requiring) a given waste for which demand (supply) exists (Alfaro and Miller, 2014; Eilering and Vermeulen, 2004; Fichtner et al., 2005); (2) the lack of information, i.e., demand (supply) for a given waste exists but firms producing (requiring) that waste are not aware of such a demand (supply) (Aid et al., 2017; Chertow, 2007; Golev et al., 2015; Sakr et al., 2011; Zhu and Cote, 2004).

Contractual clauses negotiated by the involved parties rule the IS relationships. These prescribe the operations for carrying out the waste exchange, specify how the parties share the costs stemming from the IS relationship (e.g., waste treatment and waste transportation costs, costs to build new infrastructures), and fix the waste exchange price. In this regard, it may happen that: (1) the waste user pays the waste producer to purchase the waste; (2) the waste producer pays the waste user to dispose of its waste; (3) the waste exchange is operated free of charges (Albino et al., 2016). The bargaining power of companies plays a key role on the negotiation process. Bargaining power mainly depends on the economic benefits that the partnering firms gain from the IS relationship (Yazan et al., 2012). For instance, if the waste discharge cost (input purchase cost) is much higher than the input purchase cost (waste discharge cost), the waste user (waste producer) has a higher bargaining power than the waste producer (user). Obviously, bargaining power affects how the additional costs are shared among parties as well as the definition of the waste exchange price. It is noteworthy that during this negotiation phase firms sustain transaction costs, which can substantially erode the economic benefits created by the IS approach (Chertow and Ehrenfeld, 2012). To reduce them, firms resort to collaborative and long-term relationships. Trust-based governance mechanisms have been also introduced for sustaining and nurturing the cooperative exchange (Gibbs, 2003; Gibbs and Deutz, 2007; Hewes and Lyons, 2008; Lambert and Boons, 2002). Trust is favored by the geographical proximity among firms, enhance the transparency of actions and information sharing, and foster cooperation among firms (Hewes and Lyons, 2008). The existence of strong social ties, familiarity, and shared norms among firms effectively limit opportunistic behavior by firms. Therefore, even though the likelihood of achieving a unilateral and opportunistic gain in interrupting the symbiotic relationships is high, firms do not exploit this, because of the high level of trust (Jensen et al., 2011). In this regard, recent studies confirm that many IS exchanges rely upon social relationships (e.g., Ashton, 2008; Jacobsen, 2006; Krones, 2017).

The most famous real case of this type of model is the ISN in Kalundborg, Denmark (Jacobsen, 2006; Valero et al., 2013). Such a network has been created through an evolutionary process in which independent by-product exchanges have gradually evolved into a complex web of IS interactions among co-located companies and the local municipality. The first symbiotic exchange between two companies was implemented in 1961; the ISN accounts now for twenty-three IS exchanges among eight plants and the local municipality, which does not give any financial support to firms. The involved companies belong to different sectors: energy plant, plasterboard producer, refinery, second-generation biofuel producer, wastewater plant, enzymes producer, insulin producer, and waste management company. These companies exchange among them thirteen waste materials, water, and energy.

In this business model, each company creates value by cooperating and collaborating with other companies, playing the role of waste supplier or customer. Hence, the value creation process depends on the company's ability to find partnering company requiring wastes it produces and producing wastes it requires at low cost, as well as to negotiate contractual clauses related to economic and operative issues (i.e., the waste exchange price, how to share additional costs, waste delivery time and frequency, etc.) so that each IS relationship is convenient enough for all the involved companies. It is also important the ability to develop and nurturing trust-based relationships with partnering firms, which can favor the creation of IS relationships.

In these model the generic company (waste selling or buying firm) can capture value through: (1) reduction in waste disposal cost (WDC); (2) reduction in input purchase costs (IPC); (3) additional gains thanks to the better environmental reputation of the company (AGR); (4) additional gains from selling wastes (AGW); and (5) additional gains from selling waste disposal service (i.e., the waste producer company pays the waste user company to dispose of its waste) (AGD). However, there are additional costs that can erode value: (1) waste treatment costs (ACR); (2) waste transportation costs (ACT); (3) waste purchase costs (i.e., the waste user company pays the waste producer company to purchase its waste) (ACW); (4) waste disposal service costs (i.e., the waste producer company pays the waste user company to dispose of its waste) (ACD); and (5) transaction costs (CC). The value captured by the generic company *i* ($CV_i$) is given by equation (3), whose variables are defined in Table 3 given in Appendix.

$$CV_i = WDC_i + IPC_i + AGR_i + AGW_i + AGD_i - (ACR_i + ACT_i + ACW_i + AGD_i + CC_i) \quad (3)$$

#### 3.2.4. High Coordination and High Centralization

This business model characterizes firms (selling wastes and buying waste) involved in complex and multiple IS relationships, which are designed and planned by a central authority. This business model usually corresponds to the case of industrial symbiotic parks created by means of governmental initiatives, mainly driven by environmental concerns. In fact, governments support eco-industrial parks when tackling the challenge to reduce the environmental impact of industrial activities by limiting the amounts of primary inputs used, wastes disposed of in the landfill, and GHG emissions generated (Farel et al., 2016; Liu et al., 2018). Readers who are interested to examine in depth these dynamics are referred to Boons et al. (2017). In addition, since companies are localized in close geographic proximity, they can exploit the shared use of utility infrastructure, for example for energy production, water, and wastewater treatment (e.g., Eilering and Vermeulen, 2004; Van Beers et al., 2007). The geographic proximity offers two further advantages. First, waste transportation costs are minimized, because of the co-localization of companies. Second, since it is likely that personal social relationships exist among managers of different companies, transaction costs tend to be low (e.g., Hewes and Lyons, 2008). From the financial perspective, the government supports companies by offering preferential policies on land lease and tax reduction (e.g., Dong et al., 2017; Shi et al., 2012; Yu et al., 2015) and it might finance (partially or totally) infrastructures for waste exchanges and utility sharing (Hein et al., 2017a).

In these parks, a central authority is in charge of the park management, being responsible for: (1) identifying the companies that will establish their factories into the park, based on their potential contributions to IS exchanges (e.g., companies able to be involved in existing materials or energy flows, in order to favor a full match between demand and supply of waste materials); (2) designing the IS relationships to be implemented among companies; (3) managing directly operational and economic issues related to IS relationships or assisting companies in carrying out these relationships; (4) designing infrastructures for supporting waste exchanges; (5) picking up other activities such as infrastructure maintenance, provision of common services, as well as designing and managing the shared utilities; (6) assessing the environmental and economic performance of the park; and (7) driving the evolution of the park (e.g., Eilering and Vermeulen, 2004; Lowe, 1997). Furthermore, such a central authority can be engaged to optimize the IS operations, by minimizing the operational costs or enhancing the environmental performance of the park (e.g., Afshari et al., 2018; Aviso et al., 2010; Boix et al., 2015). Therefore, in this type of system all the IS relationships are centrally managed. The central authority can also be a public agency, a private company, or a public-private institution (e.g., Farel et al., 2016). Research institutes and companies located in the park can be involved in the park management authority (e.g., Behera et al., 2012; Lowe, 1997).

The eco-industrial park created in the Tianjin Economic-technological Development Area (TEDA) is an example of this model (Shi et al., 2010; Yu et al., 2014). TEDA extends for 98 $km^2$ in the Northeast of China and includes 46 $km^2$ of industrial area. The area is characterized by water and natural resource scarcity and the existing companies are forced to rely on external resources and energy. In 1984, the Tianjin municipal government created TEDA's Administrative Committee (AC), which is in charge to promote the eco-development of the area. To solve the waste scarcity problem, the AC promoted the building of wastewater treatment plants and financed pipelines so that companies could have used treated water instead of groundwater. Furthermore, it supported cogeneration plants to produce *in loco* energy from wastes, financed infrastructures to provide companies with steam resulting from the cogeneration process, and promoted the use of ashes as production input. In addition, other waste treatment facilities have been subsidized. The AC was also engaged in several activities aimed at supporting companies in implementing IS exchanges. For instance, experts organized by TEDA selected one company each month and investigated the efficiency of its energy and water usage, aimed at providing the company management with potential solutions to minimize waste. In addition, a solid waste management information system was developed to highlight possible IS synergies to be implemented, based on data provided by companies in workshops organized *ad hoc*. Companies belonging to the park are required to monitor their environmental impact. The AC has the power to punish companies failing in do this by depriving them of preferential policies and to give financial rewards to companies that continued publishing their environmental information.

In this model, companies create value through localizing their facilities into the area of the park and accepting that a central authority manages their IS relationships. Therefore, it is important that firms are available to outsource the management of IS relationships to the central authority and is able to effectively manage the relationship with it. This implies that companies need to disclose sensitive information with the central authority, so that it can manage IS relationships with an integrated approach and monitor the environmental performance. Companies can create additional values by sharing infrastructures and services amongst them, thanks to their close proximity.

Companies can capture value through: (1) reduction in waste disposal cost (WDC); (2) reduction in input purchase costs (IPC); (3) reduction in infrastructures, service, and utility costs (ISC); (4) additional gains thanks to the better environmental reputation of the company (AGR); (5) additional gains from selling wastes (AGW); (6) additional gains from selling waste disposal service (i.e., the waste producer company pays the waste user company to dispose of its waste) (AGD); and (7) economic subsidies from the government (S), in form of additional revenues or tax discounts. However, the following additional costs can erode such a value: (1) waste treatment costs (ACR); (2) waste transportation costs (ACT); (3) waste purchase costs (i.e., the waste user company pays the waste producer company to purchase its waste) (ACW); and (4) waste disposal service costs (i.e., the waste producer company pays the waste user company to dispose of its waste) (ACD). The value captured by the generic company $i$ ($CV_i$) is shown by the following equation, whose variables are defined in Table 3.

$$CV_i = WDC_i + IPC_i + ISC_i + AGR_i + AGW_i + AGD_i + S_i - (ACR_i + ACT_i + ACW_i + ACD_i) \qquad (4)$$

**Table 2. Summary of IS business models features for value creation and capture.**

| | **Low Coordination Low Centralization** | **Low Coordination High Centralization** | **High Coordination Low Centralization** | **High Coordination High Centralization** |
|---|---|---|---|---|
| **Models** | • Companies use wastes as inputs for their production processes<br>• Companies exploit wastes to produce new products sold on the market | • Companies replace production inputs with urban wastes<br>• Companies use urban wastes to produce new products | • Complex network of companies involved in multiple and independent resource exchanges | • Complex network of companies involved in multiple exchanges managed by a central authority |
| **Value Creation** | • Technical ability<br>• Organizational ability | • Cooperation with local government<br>• Localization close to municipality<br>• Ability to reconfigure production processes | • Ability to search for new partner<br>• Ability to design proper contractual mechanisms ruling relationships<br>• Ability to design trust-based relationship | • Ability to outsource the management of IS relationships<br>• Visibility and information sharing |
| **Value Capture** | • Lower waste disposal | • Lower input purchase | • Lower waste disposal | • Lower waste disposal |

| | | | | |
|---|---|---|---|---|
| | costs<br>• Lower input purchase costs<br>• Additional gains from selling new products<br>• Additional gains from better company reputation | costs<br>• Additional gains from selling new products<br>• Economic subsidies from the government | costs<br>• Lower input purchase costs<br>• Additional gains from better company reputation<br>• Additional gains from selling wastes<br>• Additional gains from selling waste disposal | costs<br>• Lower input purchase costs<br>• Reduction in infrastructures costs<br>• Additional gains from better company reputation<br>• Additional gains from selling wastes<br>• Additional gains from selling waste disposal<br>• Economic subsidies from the government |

## 5. CONCLUSIONS

IS business models are a specific class of sustainable business models arising from the implementation of the IS practice. We proposed a taxonomy of IS business models which adopts a system perspective, whilst previous classifications are firm-based and concerning CE in general. Rather than to focus on the single-firm dimensions influencing value creation and value capture, borrowing from recent conceptualizations of business models extended to the system and including suppliers and customers, we argued that it is the governance of the system adopting IS to affect firm value creation and value capture. Therefore, we characterized the IS business model on the basis of two governance features: (1) need for coordination and (2) centralization of control. So doing, we identified four extreme cases of IS business models. Each of them was characterized in terms of value creation and value capture and the main factors affecting both of them are identified.

Following the business model perspective, our study contributes to clarify how and why firms applying IS practice can gain competitive advantage. In doing so, we overcome a major gap in the IS literature, which is recognized to remain quite disconnected from business studies. This would foster firms to adopt IS favoring the development of its implementation in practice. In fact, thanks to the improved knowledge about the factors affecting value creation and value capture, proper strategies can be suggested to firms for the successful implementation of IS. In particular, we showed for each IS business model which specific technical and organizational capabilities should be possessed or enhanced by firms would like to implement it. Furthermore, we identified the main sources of value capture.

In the model characterized by low need for coordination and low centralization of control, it is fundamental to improve the efficiency in waste exploitation resorting to recent advances in technology for maximizing the amount of inputs replaced by waste and the amount of products generated by waste. Marketing capabilities are also important for increasing firm reputation on sustainability so as to gain higher premium prices.

In the model characterized by low need for coordination and high centralization of control, it is important the role of government to fully exploit the amount of economic subsidies and thus relational capabilities.

In the model characterized by high need for coordination and low centralization of control, the ability of companies to create value mainly depends on the capability to negotiate advantageous contractual clauses and to minimize transaction costs, for instance by using online platforms for finding symbiotic partners (Fraccascia and Yazan, 2018) or by implementing long-time and trust-based relationships with partners (Doménech and Davies, 2011; Hewes and Lyons, 2008).

In the model characterized by high need for coordination and high centralization of control, the ability of companies to create value stands in maximizing the amount of economic subsidies received from the government and exploiting services and infrastructures provided by the park.

The findings of this paper also contribute to the development of IS literature. To the best of our knowledge, no study recognizes the importance of the two governance dimensions proposed in this paper simultaneously. A common way to classify ISNs is in fact to distinguish between top-down vs bottom-up approach (Chertow and Ehrenfeld, 2012; Doménech and Davies, 2011; Park et al., 2008; Zhang et al., 2010). This however limits the analysis to the process by which the ISNs emerge, which is led by the government in one case (top-down) or is spontaneous and self-organized in the other one (bottom-up). From the strategic point of view, however, it is critical to characterize how relationships are structured and managed rather than how they emerged. For this reason, our study differs from Boons et al. (2017), who provide a more nuanced classification of IS models focusing on IS dynamics, conceptualized as "*the typical path ways through which the process of IS unfolds*" (p. 941). Their focus is thus on how the IS relationships form and evolve, while we characterize the ISN forms of governance. In particular, we argued that the "need for coordination" is an important feature to consider. We distinguished interdependence in internal (occurring inside the firm organizational boundaries) but also external (between independent firms), associated with a low vs. high need for coordination. In particular, external interdependences cause conflicting aims among firms, which result in trade-offs that can be resolved only by coordinating and synchronizing decisions (Nair et al., 2009; Simchi-Levi et al., 2000). In this case, complexity is high and should be properly handled. To the best of our knowledge, this is the first examination of this issue in IS research.

Our study provides also interesting implications for what concerns future research directions. For each business model, we defined specific factors affecting value capture and value creation. However, the influence of these variables should be empirically tested in further studies via case study analysis (e.g., Eisenhardt and Graebner, 2007). In addition, we note that some factors we identified are not enough investigated in the IS literature from the theoretical point of view. For example, we believe that the design of proper incentives regulating IS should be fostered. Developing models based on the game theory approach (e.g., Yazdanpanah and Yazan, 2017) can be useful at this end. The effectiveness of these models can be further investigated via agent-based simulation in multiple contexts (e.g., Albino et al., 2016). This research effort may contribute to the development of low coordination and high centralization IS type. For the high coordination and low centralization business we suggest more investigation on the effect of trust in IS relationship. Accordingly, a recent paper by Herczeg et al. (2018) recognizes this need and addresses it. We also argue that the high coordination and high centralization IS type would benefit from research investigating public-private partnership as well as the role of new actors such as research centers.

Our study presents some limitations. As any paper proposing a taxonomy, it cannot be exhaustive. Furthermore, we simply consider both governance dimensions as binary variables, distinguishing between low vs. high, while more nuanced values could be possible. Despite we adopted a system perspective, we just focused on two types of actors, i.e., companies and government, involved in IS relationships. These systems however could also include different actors, such as social communities and IS facilitators. They could be integrated and new classifications proposed.

## APPENDIX

The following table describes in detail how to compute each of the terms in Equations (1)-(4). These terms are divided into three categories: (1) cost reduction; (2) additional gains; and (3) additional costs.

**Table 3. Variables in equations (1)-(4).**

| **Cost reduction** |
| --- |

| | | |
|---|---|---|
| Reduction in waste disposal costs (WDC) | $WDC_i = \sum_{k=1}^{w(i)} dc_{ki} \sum_{l=1}^{r(i)} \sum_{j=1}^{n(i)} e_{ki}^{lj}$ | *w(i)* = number of wastes produced by company *i*<br>$dc_{ki}$ = cost for company *i* to dispose of one unit of waste *k*<br>*r(i)* = number of inputs required by company *i*<br>*n(i)* = number of companies cooperating with company *i*<br>$e_{kj}^{li}$ = units of waste *k* produced by company *k* used by company *i* to replace input *l* |
| Reduction in input purchase costs (IPC) | $IPC_i = \sum_{l=1}^{r(i)} pc_{li} \sum_{k=1}^{w(i)} \sum_{j=1}^{n(i)} s_{kj}^{li} \cdot e_{kj}^{li}$ | *r(i)* = number of inputs required by company *i*<br>$pc_{li}$ = cost for company *i* to purchase one unit of input *l*<br>*w(i)* = number of wastes produced by company *i*<br>*n(i)* = number of companies cooperating with company *i*<br>$s_{kj}^{li}$ = units of input *l* required by company *i* that can be replaced by one unit of waste *k* produced by company *j*<br>$e_{kj}^{li}$ = units of waste *k* produced by company *j* used by company *i* to replace input *l* |
| Reduced costs because sharing infrastructures and services | $ISC_i$ | |
| **Additional gains** | | |
| Gains thanks to selling new products (AGP) | $AGP_i = \sum_{v=1}^{m(i)} (p_{vi} - mc_{vi}) \left( \sum_{j=1}^{n(i)} \sum_{k=1}^{w(i)} q_{kj}^{vi} \cdot e_{kj}^{vi} \right)$ | *m(i)* = number of new products generated from wastes by company *i*<br>$p_{vi}$ = market price of product *v* sold by company *i*<br>$mc_{vi}$ = production cost per unit of product *v* for company *i*<br>*n(i)* = number of companies cooperating with company *i*<br>*w(i)* = number of wastes produced by company *i*<br>$q_{kj}^{vi}$ = units of product *v* that company *i* can produce from one unit of waste *k* produced by company *j*<br>$e_{kj}^{li}$ = units of waste *k* produced by company *j* used by company *i* to replace input *l* |
| Gains thanks to the better reputation (AGR) | $AGR_i = \sum_{u=1}^{z(i)} [\Delta p_{ui} \cdot x_{ui} + (p_{ui} + \Delta p_{ui} - mc_{ui}) \cdot \Delta x_{ui}]$ | *z(i)* = number of products sold on the market by company *i*<br>$\Delta p_{ui}$ = premium price for product *u* sold by company *i* thanks to better reputation<br>$x_{ui}$ = amount of product *u* sold on the market by company *i*<br>$p_{ui}$ = market price of product *u* sold by company *i*<br>$\Delta x_{ui}$ = additional amount of product *u* sold on the market by company *i* thanks to better reputation<br>$mc_{vi}$ = production cost per unit of product *v* for company *i* |
| Gains from selling wastes (AGW) | $AGW_i = \sum_{j=1}^{n(i)} \sum_{k=1}^{w(i)} \sum_{l=1}^{r(j)} wsp_{ki}^{j} \cdot e_{ki}^{lj}$ | *n(i)* = number of companies cooperating with company *i*<br>*w(i)* = number of wastes produced by company *i*<br>*r(j)* = number of inputs required by company *j*<br>$wsp_{ki}^{j}$ = unitary selling price for waste *k* paid by company *j* to company *i*<br>$e_{ki}^{lj}$ = units of waste *k* produced by company *i* used by company *j* to replace input *l* |
| Gains from selling waste disposal service (AGD) | $AGD_i = \sum_{j=1}^{n(i)} \sum_{k=1}^{w(j)} \sum_{l=1}^{r(i)} dsp_{kj}^{i} \cdot e_{kj}^{li}$ | *n(i)* = number of companies cooperating with company *i*<br>*w(j)* = number of wastes produced by company *j*<br>*r(i)* = number of inputs required by company *i*<br>$dsp_{kj}^{i}$ = unitary disposal service price for waste *k* paid by company *j* to company *i*<br>$e_{kj}^{li}$ = units of waste *k* produced by company *j* used by company *i* to replace input *l* |
| Subsidies from the government | $S_i$ | |
| **Additional costs** | | |

| | | |
|---|---|---|
| Waste treatment costs (ACR) | $ACR_i = \sum_{j=1}^{n(i)} \left[ \sum_{k=1}^{w(i)} \sum_{l=1}^{r(j)} \alpha_{ki}^{lj} \cdot rc_{ki}^{lj} \cdot e_{ki}^{lj} + \sum_{l=1}^{r(i)} \sum_{k=1}^{w(j)} \alpha_{kj}^{ll} \cdot rc_{kj}^{li} \cdot e_{kj}^{li} \right]$ | *n(i)* = number of companies cooperating with company *i*<br>*w(i)* = number of wastes produced by company *i*<br>*r(j)* = number of inputs required by company *j*<br>$\alpha_{ki}^{lj}$ = percentage of waste treatment cost (to make waste *k* produced by company *i* able to replace input *l* by company *j*) which is paid by company *i*<br>$rc_{ki}^{lj}$ = waste treatment cost required to make one unit of waste *k* produced by company *i* able to replace input *l* required by company *j*<br>$e_{ki}^{lj}$ = units of waste *k* produced by company *i* used by company *j* to replace input *l*<br>*r(i)* = number of inputs required by company *i*<br>*w(j)* = number of wastes produced by company *j*<br>$\alpha_{kj}^{li}$ = percentage of waste treatment cost (to make waste *k* produced by company *j* able to replace input *l* by company *i*) which is paid by company *i*<br>$rc_{kj}^{li}$ = waste treatment cost required to make one unit of waste *k* produced by company *j* able to replace input *l* required by company *i*<br>$e_{kj}^{li}$ = units of waste *k* produced by company *j* used by company *i* to replace input *l* |
| Waste transportation costs (ATC) | $ATC_i = \sum_{j=1}^{n(i)} \left[ \sum_{k=1}^{w(i)} \sum_{l=1}^{r(j)} \beta_{ki}^{i\to j} \cdot tc_k^{i\to j} \cdot e_{ki}^{lj} + \sum_{l=1}^{r(i)} \sum_{k=1}^{w(j)} \beta_{ki}^{j\to i} \cdot tc_k^{j\to i} \cdot e_{kj}^{li} \right]$ | *n(i)* = number of companies cooperating with company *i*<br>*w(i)* = number of wastes produced by company *i*<br>*r(j)* = number of inputs required by company *j*<br>$\beta_{ki}^{i\to j}$ = percentage of waste transportation costs (required to transport waste *k* from company *i* to company *j*) which is paid by company *i*<br>$tc_k^{i\to j}$ = cost to transport one unit of waste *k* from company *i* to company *j*<br>$e_{ki}^{lj}$ = units of waste *k* produced by company *i* used by company *j* to replace input *l*<br>*r(i)* = number of inputs required by company *i*<br>*w(j)* = number of wastes produced by company *j*<br>$\beta_{ki}^{j\to t}$ = percentage of waste transportation costs (required to transport waste *k* from company *j* to company *i*) which is paid by company *i*<br>$tc_k^{j\to i}$ = cost to transport one unit of waste *k* from company *j* to company *i*<br>$e_{kj}^{li}$ = units of waste *k* produced by company *j* used by company *i* to replace input *l* |
| Waste purchase costs | $ACW_i = \sum_{j=1}^{n(i)} \sum_{k=1}^{w(j)} \sum_{l=1}^{r(i)} wpc_{kj}^{i} \cdot e_{kj}^{li}$ | *n(i)* = number of companies cooperating with company *i*<br>*w(j)* = number of wastes produced by company *j*<br>*r(i)* = number of inputs required by company *i*<br>$wpc_{kj}^{i}$ = cost paid by company *i* to buy one unit of waste *k* from company *j*<br>$e_{kj}^{li}$ = units of waste *k* produced by company *j* used by company *i* to replace input *l* |
| Waste disposal service cost | $ACD_i = \sum_{j=1}^{n(i)} \sum_{k=1}^{w(i)} \sum_{l=1}^{r(j)} dsc_{ki}^{j} \cdot e_{ki}^{lj}$ | *n(i)* = number of companies cooperating with company *i*<br>*w(i)* = number of wastes produced by company *i*<br>*r(j)* = number of inputs required by company *j*<br>$dsc_{ki}^{j}$ = disposal service cost for waste *k* paid by company *i* to company *j*<br>$e_{ki}^{lj}$ = units of waste *k* produced by company *i* used by company *j* to replace input *l* |
| Transaction costs | $CC_i = \sum_{j=1}^{n(i)} cc_i^j$ | *n(i)* = number of companies cooperating with company *i*<br>$cc_i^j$ = transaction costs for company *i* stemming from the symbiotic cooperation with company *j* |

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