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FISOF: A formal industrial symbiosis opportunity filtering method

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ABSTRACT

Industrial Symbiotic Relations (ISRs), as bilaterally cooperative industrial practices, are emerging relations for exchanging reusable resources among production processes of originally distinct firms. In ISRs, firms can enjoy mutual environmental, social, and economic benefits. Due to similarities in aim and functionality of ISRs and the concept of Circular Economy (CE), it is expected that ISRs play a major role in implementing CE in the context of industrial production. However, industrial firms generally lack analytical tools tailored to support their decisions whether – and based on what priority – to negotiate a particular ISR opportunity, selected from a set of potential alternatives. This question is the main focus of the decision support method developed in this paper, that we call the "*industrial symbiosis opportunity filtering*" problem. The key economic factor that influences the decision of firms to reject or negotiate an ISR in real-life scenarios, is the total cost-reduction/benefit that they may enjoy in case the ISR would be implemented. In case they evaluate that a sufficient benefit is obtainable, they see the opportunity as a promising one and pursue to contract negotiations. Following this observation, we take an operations-oriented stance and provide a Formal Industrial Symbiosis Opportunity Filtering method (FISOFin short) that: (1) takes into account the key operational aspects of ISRs, (2) formalizes ISRs as industrial institutions using semantic structures adopted from multi-agent systems literature, and (3) enables evaluating ISR opportunities using implementable decision support algorithms. In practice, the FISOFmethod and its algorithms can be integrated into industrial symbiosis frameworks to support firms in the process of ISR evaluation. We also illustrate how information sharing enables the use of collective strategies to overcome epistemic limitations and provide a decision support algorithm that is able to capture all the mutually promising ISR implementations.

1. Introduction

The concept of Circular Economy (CE) and its application in the industrial context opposes the traditional linear production approaches that mainly take primary inputs, produce outputs, and dispose wastes. The circular economy is characterized by circulating reusable resources (e.g., waste material and energy) among production processes and maintaining them in the value chains (Pearce and Turner, 1990; Yuan et al., 2006). One step further, Industrial Symbiotic Relations (ISRs), as bilaterally cooperative industrial practices, are emerging relations for exchanging reusable resources among production processes of originally distinct industrial firms (Chertow, 2007; Yazan et al., 2016). So, due to similarities in aim and functionality of CE and ISR, it is reasonable to expect that ISRs play a major role in implementing CE in the context of industrial production (see Sertyesilisik and Sertyesilisik, 2016; Andersen, 2007). In ISRs, involved firms can enjoy mutual environmental, social, and economic benefits. Moreover, ISRs have a positive influence on both the resilience of firms (as they seek alternative resource suppliers) and the efficiency in exploitation of available resources (as they substitute traditional primary inputs with wastes) (Fraccascia et al., 2017).

As reviewed in van Capelleveen et al. (2018), there exist various information systems for identifying ISR opportunities. These platforms are mainly platforms that recommend to a firm that provides/requires a resource, the opportunity to negotiate ISRs with firms that require/provide the resource in question. However, industrial firms generally lack analytical tools tailored to support their decisions whether – and based on what priority – to negotiate a particular ISR opportunity. Roughly speaking, among the set of ISR opportunities, identified by a recommender system, which are sufficiently promising for a firm to pursue to the negotiation phase? This question is the main focus of the decision support method that we developed for addressing the "*industrial symbiosis opportunity filtering*" problem. Due to the multidimensional nature of ISRs, such a decision support method has to regard multiple operational aspects, e.g., the business-making model of industries, physical quantity matching, and possible presence of competitors/regulations. Although there exist methods for analyzing each of these dimensions in ISRs,[1] filtering ISR opportunities calls for methods that are able to take into account multiple operational aspects and can also deal with epistemic uncertainties inherited in such decisions. Then, the first step to support such decisions is to provide formal methods able to capture both the behavior of such relations and their potential economic outcomes.

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In real ISR scenarios, the key economic factor that influences the decision of firms to reject or negotiate an ISR is the obtainable cost-reduction (or benefit) that they may enjoy in case the ISR would be implemented (Albino et al., 2016). Accordingly, in case they evaluate that a sufficient amount of cost-reduction is obtainable, they see the opportunity as a promising one and pursue to contract negotiations.[2] Following this observation, we take an operations-oriented stance and provide a Formal Industrial Symbiosis Opportunity Filtering method (FISOFin short) that: (1) takes into account key operational aspects of ISRs, (2) formalizes ISRs as industrial institutions using semantic structures adopted from multi-agent systems literature, and (3) enables evaluating ISR opportunities using implementable decision support algorithms. In practice, the FISOFmethod and its algorithms can be integrated into industrial symbiosis decision-modeling frameworks to support firms in the process of ISR evaluation. We also illustrate how information sharing enables the use of collective strategies to overcome epistemic limitations (that each firm may suffer from) and provide a decision support algorithm that is able to capture all the mutually promising ISR implementations (as a basis for ISR negotiations).

The structure of the paper is as follows. First we introduce an operational perspective on ISRs in Section 2. It includes the analysis of operational dimensions of ISRs, the role of epistemic aspects, and main ISR-related costs. The formal preliminaries required for modeling ISRs will be provided in Section 3. In Section 4, we sketch the FISOFmethod that includes a model of the behavior of ISRs as an industrial institution and the decision support algorithm. Section 5, presents an analysis on the occurrence of ISR negotiations in equilibrium, illustrates the fostering role of information sharing, and ends with an algorithmic method that enables ISR opportunity filtering under distributed knowledge. In Section 6, the applicability and performance of our methods are illustrated using a case study. Finally, concluding remarks are presented in Section 7.

2. Conceptual analysis and literature review

In this section, we present an operational perspective on Industrial Symbiosis Relations (ISRs from now on) and analyze various concepts that play a key role in the evaluation, establishment, and operation of such relations. Accordingly, we introduce operational dimensions of ISRs that in later sections frame a formal operations-oriented decision support method for ISRs.

We describe ISRs as two-member industrial institutions that correspond to two-sided matching markets (Roth and Sotomayor, 1992). In matching markets, the procedure of allocating resources involves a "match evaluation" stage. The class of *matching markets* and their associated economics opposes the traditional category of (merely) price-oriented markets. In the former the focus is on evaluation of potential matches while in the latter, price forms the market and explains its dynamics. Following Roth (2015), we distinguish the situation of standard commodities of which the price can be seen as the main parameter for decision-making from situations in which the transaction is based on non-standard commodities for which the price negotiation is not the first practical stage to operationalize the economic practice. In such cases, prior to the negotiation procedure, involved actors consider whether a given deal, relation, or in general a setting that describes the opportunity for implementing the economic practice, is a reasonable one. This approach, i.e. to model and evaluate specific classes of economic transitions as matching markets, resulted in successful scenarios in various contexts such as bilateral kidney exchange and educational student-institute matching (Roth et al., 2005; Abdulkadiroğlu et al., 2005). As discussed earlier, ISRs are transactions mainly based on reusable resources, e.g. waste energy and material, which typically do not operate in a commoditized price-driven market. For instance, when a firm manager learns about an ISR opportunity on a specific reusable waste, in most cases there is no standard market for that waste; hence no standard market price to rely on during the evaluation

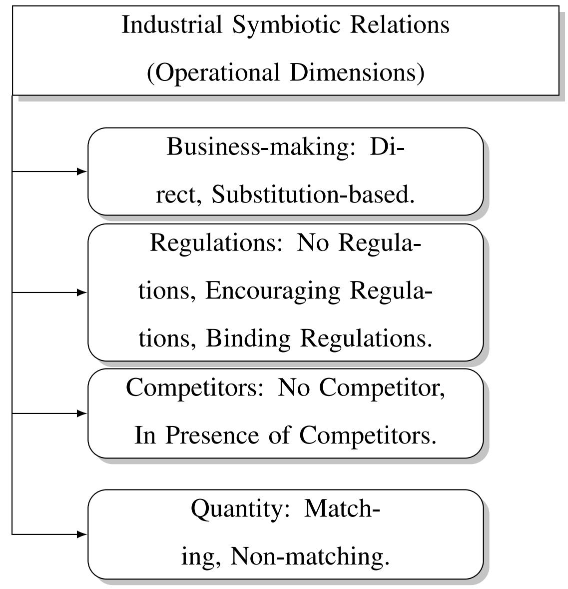

Fig. 1. ISR's operational dimensions.

phase. In such a situation, managers seek decision-support tools able to take into account various operational aspects of ISRs for evaluating and narrowing down the set of available ISR opportunities to a set of promising ones. Afterwards, firms may pursue negotiations with the most promising ISR opportunities and (potentially) implement some.

In order to establish a basis for evaluating ISR opportunities,[3] in this section we present an operations-oriented analysis of parameters based on which firms can evaluate an ISR opportunity (Section 2.1). Moreover, we address epistemic aspects that have influence on a firm's evaluation (Section 2.2). Such a classification facilitates the process of formalizing ISRs and developing the Formal Industrial Symbiosis Opportunity Filtering (FISOF) method. In brief, FISOFsupports a firm's decision on whether a particular ISR opportunity is a promising one (to pursue to the negotiation phase) by taking into account the operational as well as epistemic aspects of the relation.

2.1. Operational dimensions of ISRs

In the following, we discuss operational dimensions of ISRs (illustrated in Fig. 1) and the structural subtleties that each brings into consideration.

2.1.1. Business-making perspective

First, we discuss ISRs from a business-making point of view. In particular, we distinguish whether the receiver side of an ISR is going to use the waste as a *substitution* for one of its traditional primary inputs or if it is going to build its business (e.g., establishing a new production line) *directly* based on the received resource. We call the latter cases *Direct ISRs* and the former cases *Substitution-based ISRs*.

Realizing whether an ISR is direct or based on substitution has both operational and technical consequences for the process of ISR evaluation and decision support. Firstly, concerning operational aspects, in substitution-based ISRs, the receiver firm will decide about the profitability of a potential ISR by considering the trade-off between implementing the ISR and rejecting it. This is basically because the firm is traditionally receiving a primary input from another source and should analyze whether *substituting* it with the reusable resource (from the ISR

[3] As this work is merely focused on the evaluation of ISR opportunities (and not on already implemented ISRs), we may simply say "ISRs" whenever it is clear from the context that we mean "ISR Opportunities".

in question) is profitable. Secondly, with respect to technical aspects of substitution-based ISRs, the benefits of substituting a traditional primary input with a reusable resource depends on the so-called *substitution rate*. Intuitively, the substitution rate is the ratio that must be taken into account while substituting two types of resources. For instance, in the cement production industry, one unit of an alternative fuel, e.g., Municipal Solid Waste (MSW), may substitute one or more units of coal—as the traditional energy source used in cement industries. We refer the reader to Albino et al. (0000) for details about the substitution rate and extensive investigations about the use of alternative resources for energy purposes in the cement industry. In further sections, we point out how distinguishing direct and substitution-based ISRs influences the procedure of ISR evaluation.

2.1.2. Presence of regulations

While we are dealing with reusable resources such as waste material/energy, various binding or encouraging regulations may be in place. Such regulations may exist for the provider/supplier in a potential ISR, the receiver, or both. Moreover, they can be either in the form of binding regulations, e.g., prohibition of discharge/transportation of a particular type of waste, or in the form of encouraging regulations, e.g. awarding tax-reductions or subsidies to the firms that use wastes of other firms as their input.

Some governmental regulations may consider prohibitions for specific resources and bind up discharge for a resource-provider or oblige the use of alternative inputs for a resource-receiver. There might be cases in which receivers are obliged to realize a certain amount of substitution which is driven by environmental regulations. For example, as discussed in Albino et al. (0000), a cement company might be obliged to reduce the CO_2 emissions caused by coal use, which may serve as a motivation to use alternative energy sources—causing less CO_2 emissions. Therefore, we need to consider the extra taxes paid for CO_2 emissions or any other sanctions introduced by the government. On the other hand, incentives may be present for waste reduction on the provider side or on the receiver side for reduced primary resource depletion. Additionally, incentives may exist to encourage circular economic business models (Murray et al., 2015; Pearce and Turner, 1990) as the umbrella concept for the practice of industrial symbiosis. For example, bioenergy producers may accept paying a high price for low energy-density biomass as they receive incentives from governments for producing renewable energy. Similarly, providers can be encouraged for supplying their reusable resources to a certain sector which is being promoted by governments for sustainability reasons.

As discussed in Zhu et al. (2007) and Desrochers (2004), encouraging incentives can foster the emergence of spontaneous industrial symbiotic relations as they compensate the involved costs (see further sections for a characterization of the main costs in ISRs). Hence, encouraging incentives can improve the profitability level so that involved firms are convinced that the ISR is a promising one, thus start the negotiations and potentially implement the ISR. Regulations in favor of ISR will generally lead to cost reductions whereas regulations against ISR may induce additional costs.

2.1.3. Presence of competitors

The presence of competitors on either or both sides of an ISR affects the ISR evaluation and choice of involved firms (Kochan et al., 1984; Johanson and Mattsson, 2015). In basic cases, an ISR may be established with respect to a resource for which there exists only one provider and one receiver (in the region, country, or any geographical scope of analysis). On the other hand, for some resources there may exist more than one provider or receiver. Hence, in the ISR evaluation phase, firms mostly face a set of ISR opportunities – and not a single opportunity – to be evaluated. As presented in Yazan et al. (2012), the dynamics of *bargaining power* in industrial symbiotic relations is highly dependent on the number of potential relations. In general, the higher the number of potentials, the higher a firm's bargaining power—hence its risk tolerance. One step further, in established relations, ensuring the resilience and stability of the relation against the entrance of a competitor may even require external monetary incentives (Yazdanpanah et al., 2018).

Moreover, in some cases an ISR opportunity might be evaluated as "promising" while competitors are dismissed but as "non-promising" while we take them into account. For instance, when the quantity of a resource, provided by a firm A, does not match the amount that firm B requires, B may reject to negotiate the ISR with A (only) if it observes the possibility to establish another relation with a competitor resource-provider firm C—that is able to provide the quantity that B requires.

In principle, the presence of competitors leads to more ISR opportunities for firms to evaluate, potentially negotiate, and implement. Formal representations of these concepts and methods to rank such a set will be presented in further sections.

2.1.4. Quantity matching

The other operational dimension that characterizes an ISR opportunity is the relation between the physical quantity of the reusable resources: produced by the provider and required for the receiver.[4] If the quantity of a produced resource matches the need of another firm, supply meets demand and the ISR (in case of operationalization) experiences a higher level of stability in comparison to non-matching quantities. Several ISR research contributions highlight the importance of *quantity matching* and aim for reducing the resource disposal by means of finding perfect symbiotic relations in which the produced amount matches the required amount (e.g., Yazan et al., 2016; Standing et al., 2008). In Yazan et al. (2016), matching physical quantities in an Industrial symbiotic Network (ISN) is one of the main conditions for realizing a so called *perfect ISN* and in Standing et al. (2008), the authors argue that the unavailability of reliable and consistent quantity data is one of the barriers against the establishment of sustainable production chains as a step towards the circular economy (Pearce and Turner, 1990).

In general, when two quantities match, the resource provider firm can enjoy paying no discharge cost while the receiver firm has no purchase cost for obtaining its traditional input. On the other hand – in non-matching quantities – even after implementing the ISR, provider/receiver firms have to deal with the remaining discharge/purchase costs to compensate the mismatching quantities.

2.2. Epistemic dimensions of ISRs

In this section, we focus on the availability of information for decision makers faced with an ISR opportunity.[5] Information is crucial in the process of decision-making to get engaged in an industrial relation. In principle, the more information available for the decision-maker, the more accurate the decision is. It is also suggested by Chertow (2000) that in successful industrial symbiosis cases in Denmark (Christensen, 1992), information availability played a key role. However, in industrial practices, the availability of perfect information is not a reasonable assumption. Considering possibly distant firms and also taking into account the diversity of suppliers/receivers may result in cases where firms are not perfectly informed about the presence of competitors. With respect to the availability of information about the business-making models and the quantities, assuming perfect information is not reasonable as the firms involved in a potential ISR are independent and autonomous companies that may opt not to fully share information. Accordingly, in our modeling we consider ISR opportunity evaluation under imperfect information with respect to (1) business observability,

[4] Note that wastes are a form of secondary product—not produced upon demand.

[5] In this work, we see each firm as a single industrial agent, autonomous in its decision-making. Moreover, we abstract from intra-organizational decision processes and also cognitive/mental aspects of decision-making.

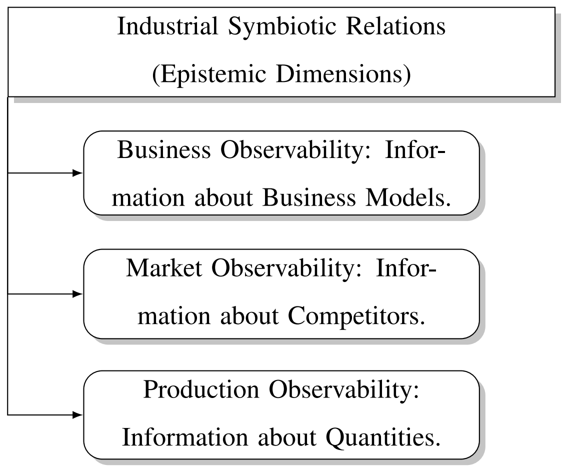

Fig. 2. ISR's epistemic dimensions.

(2) market observability, and (3) production observability (Fig. 2). Under imperfect information some potential implementations of an ISR opportunity may be indistinguishable for a firm. For instance, when a resource-provider firm A is not informed about the business model of a resource-receiver B, firm A cannot distinguish between a direct implementation of its ISR opportunity with B and the substitution-based ones. Similar indistinguishable situations occur when firms lack information about other epistemic dimensions of an ISR opportunity.

Regarding regulations, we assume that all industrial firms are perfectly informed about the presence of regulations. This is reasonable since regulations are publicly available and are introduced by governments.[6] Such regulations involve encouraging incentives or binding rules in favor of, or against a particular ISR opportunity. We later show how firms can reason under imperfect information and also illustrate the advantages of information sharing.

2.3. ISR costs and cost allocation mechanisms

Implementing ISRs have economic, environmental, and social benefits. Following Albino et al. (2016), we believe that economic benefits can be seen as the main parameter that affects the decision-making process of industries to get involved in a potential ISR (see also contributions that aim for minimizing ISR operational costs, e.g., Montastruc et al., 2013; Rubio-Castro et al., 2011). In other words, when a firm evaluates whether an ISR opportunity is sufficiently promising to start the negotiation procedure, it mainly compares the potential case with its current situation. In such an evaluation, firms compute the amount of cost reduction (or benefits) they can enjoy thanks to the implementation of the relation. Roughly speaking, the total cost to operationalize an ISR should be compared with the total cost reductions (or potential benefits) that it brings about—due to its potential to reduce waste discharge cost and traditional-input purchase cost. In the following, we firstly present the two classes of ISR operational costs: *3T operational* costs and *profile-specific* costs. Secondly, a Shapley-based (Shapley, 1953) method for sharing operational costs among the involved firms will be presented.

2.3.1. 3T operational costs

According to Esty and Porter (1998) and Sinding (2000), the three main operational costs that are involved in an ISR are *transportation*, *treatment*, and *transaction* costs (*3T costs* in short).

[6] Such an assumption can be relaxed in future work by considering multiple epistemic levels for industrial agents.

Transportation cost. The role of transportation costs in the establishment of ISRs and potential cost reductions thanks to implementing one is well-studied in the literature (see Carpenter and Gardner, 2008; Chen et al., 2012; Zhang et al., 0000). For instance, in a case study in Carpenter and Gardner (2008), the transportation costs reduced with 25% due to closer proximity of the substituted resource. In general, transporting reusable resources can be done via land vehicles, ships, trains, or even combined transportation modes (Zijm et al., 2015) with respect to the resource type, geographical boundaries, and whether the resource is categorized as a hazardous one. Moreover, potential partners might decide to invest in implementing new infrastructures, e.g., a pipeline system, and paying the investment cost together. In this work, we abstract from subtleties in the mode of transportation (as discussed by Guenther and Farkavcová (2010)) and assume a standard total cost for resource transportation.

Treatment cost. In principle, most reusable resources (e.g., waste material and energy) as secondary outputs of a production process first need to be treated. Treatment processes might be sorting, drying, dismantling, liquefaction, gasification, etc., depending on the resource type (Magram, 2011; Lovelady and El-Halwagi, 2009; Costa et al., 2010). Accordingly, the implementation of the treatment facility may change. Moreover, the location of a treatment facility may differ due to the dynamics of treatment costs. For instance, as studied in Yazan (2016), there are various options to locate the treatment facility: at the provider firm, at the receiver firm, at a third party specialized on recycling, or even at the traditional primary resource provider (that stays in the loop and attempts not to get influenced by the resource substitution procedure). Accordingly, the treatment process results in a total cost for any given ISR.

Transaction cost. In general, transaction costs include the costs of: market research, contract negotiations, coordination, and adaptation to the use of the substituted resource (Dahlman, 1979; Williamson, 1981). According to Andrews (2000) and Sharfman et al. (1997), industrial symbiotic practices can lead to reduction in the total transaction cost. As in this work we are focusing on industrial symbiotic relations and not networks with (potentially) diverse sets of transaction costs, we take into account a single value for the total transaction cost per symbiotic relation.

2.3.2. Profile-specific costs

The above mentioned 3T costs are general operational costs that are common for different forms of ISR (e.g., direct or substitution-based ISRs). In the process of ISR evaluation, in addition to the general 3T operational costs, a profile-specific cost that should be taken into account for direct ISRs is the *total production setup cost* that includes the set of costs related to the initiation of a new production line. These costs involve the monetary investments, related costs for production licenses, facilitation costs, and all the costs necessary for initiation of a new production line on the receiver side of a direct ISR.

Moreover, one specific design choice is to formulate the effects of regulations and mismatching quantities in terms of costs. In other words, whenever there exists a regulation that binds a particular ISR, we add a positive cost to our ISR evaluation equations. Analogously, we add a negative cost if an ISR takes place in the presence of incentives in its favor. Finally, the costs due to quantity mismatch will be considered as extra costs for firms. This representation enables a utility-based approach that fosters quantitative analysis of dynamic decisions in ISRs using the rich literature on game-theory (Kreps, 1990; Osborne, 2004).

2.3.3. ISR cost allocation mechanisms

As discussed earlier, various industrial symbiosis and case-specific studies see economic benefit (or cost reduction) as the main driver behind industrial symbiotic relations (Jacobsen, 2006; Van Berkel et al., 2009; Park and Behera, 2014). In an ISR, the provider firm may enjoy cost reductions by shifting from disposing the resource to a novel symbiotic practice while the receiver firm may enjoy cost reduction in its purchasing cost. The main point is that for an ISR to be implementable, the total ISR operational costs (after integrating monetary incentives and other extra costs) must be less than the firms' costs in case they do not implement the ISR. Thus, methods for allocating the operational costs among firms play a key role in feasibility and long-term stability of such relations.

Reviewing the mature literature on game-theoretic cost-allocation solution concepts (Lozano et al., 2013; Lindroos, 2004; Lemaire, 1984; Young, 1985; Littlechild and Owen, 1973), the efficiency and rationality of such mechanisms result in cost-allocation methods able to guarantee that players have an incentive to collaborate and remain collaborating. In this work, we employ the tailored Shapley-based cost-allocation method in Yazdanpanah and Yazan (2017) which guarantees both fairness and stability of ISRs over time.

3. Preliminaries: Formal definitions and semantic machinery

In this section, we first present the formal semantic structure based on which we build the FISOFmethod, then define the set of variables that represent an ISR setting, and finally illustrate the cost-sharing mechanism that will be employed for allocating costs in our decision support algorithm.

3.1. Concurrent epistemic game structures

To model Industrial Symbiotic Relations (ISRs) and enable systematic reasoning about their behavior, we use *Concurrent Epistemic Game Structures (CEGS)* (Ågotnes et al., 2015) as an epistemic extension of *Concurrent Game Structures* (CGS) (Alur et al., 2002). In general, CEGS allows modeling any system in which multiple actors/agents are involved and act under imperfect information. Formally, CEGS is a tuple $\mathcal{M} = \langle N, Q, Act, \sim_1, \dots, \sim_n, d, o\rangle$ where:

- $N = \{a_1, \dots, a_n\}$ is a finite, non-empty set of *agents*;
- Q is a finite, non-empty set of *states*;
- Act is a finite set of atomic *actions*;
- $\sim_a \subseteq Q \times Q$ is an *epistemic indistinguishability relation* for each agent $a \in N$ assuming that $\sim_a$ is an equivalence relation (i.e., $q \sim_a q'$ means that states q and q' are indistinguishable to a);
- function $d : N \times Q \mapsto \mathcal{P}(Act)$ defines the set of actions available for each agent in each state (we require that the same actions be available to an agent in indistinguishable states, i.e., $d(a, q) = d(a, q')$ whenever $q \sim_a q'$);
- and o is a deterministic transition function that assigns the outcome state $q' = o(q, \alpha_1, \dots, \alpha_n)$ to state q and a tuple of actions $\alpha_i \in d(i, q)$ that can be executed by N in q.

Having an ISR modeled in a CEGS-based multi-agent system, one can reason about states that involved firms can bring about in case they follow specific forms of decision-making strategies. The following notions enable representing and reasoning about such *strategies* and their *outcomes* under imperfect information.[7]

Group epistemic relations. When agents form groups, their epistemic limitations (in the collective level) will be represented as follows. Let $G \subseteq N$ be a group of agents. Following Fagin et al. (1995), we model the notions of *distributed* knowledge by means of derived relation $\sim^D_G = \bigcap_{a\in G} \sim_a$. Intuitively, this notion circumscribes the epistemic limitations of a group to the set of state tuples that are indistinguishable for all the group members—represented by the intersection of indistinguishability relations.

Successors and computations. To represent the relation among possible states, potential chains of states, and their dynamics, we have the following. For two states q and q', we say q' is a *successor* of q if there exist actions $\alpha_i \in d(i, q)$ for $i \in \{1, \dots, n\}$ such that $q' = o(q, \alpha_1, \dots, \alpha_n)$, i.e., in q, agents in N can collectively guarantee that q' will be the next system state. A *computation* of a given CEGS $\mathcal{M}$ is an infinite sequence of states $\lambda = q_0, q_1, \dots$ such that for all $i > 0$ we have that q_i is a successor of q_{i-1}. We refer to a computation that starts in q by a q-*computation*. Moreover, for $i \in \{0, 1, \dots\}$, we denote the i'th state in λ by $\lambda[i]$. Finally, $\lambda[0, i]$ and $\lambda[i, \infty]$ respectively denote the finite prefix $q_0, \dots, q_i$ and infinite suffix $q_i, q_{i+1}, \dots$ of λ.

Strategies and outcomes. Strategies can be seen as a form of decision-making agenda for agents. Formally, an *imperfect information strategy* for an agent $a \in N$ is a function $\zeta_a : Q \mapsto Act$ such that, for all $q \in Q$: (1) $\zeta_a(q) \in d(q, a)$ and (2) $q \sim_a q'$ implies $\zeta_a(q) = \zeta_a(q')$. For a group of agents $G \subseteq N$, a *collective strategy* $Z_G = \{\zeta_a \mid a \in G\}$ is an indexed set of strategies, one for every $a \in G$. Then, $out(q, Z_G)$ is defined as the set of potential q-computations that agents in G can enforce by following their corresponding strategies in Z_G.

3.2. Industrial symbiosis setting

We discussed in Section 2 that firms face costs either in case they opt to implement an ISR (including 3T operational costs) or if they continue their traditional practice (i.e., discharge/purchase costs for the resource-provider/-receiver firms). Moreover, they may enjoy monetary incentives (in form of subsidies or taxes) in either cases. This results in a trade of for each firm when they are reasoning about an ISR opportunity. Accordingly, a firm considers an ISR promising if it has the potential to bring about a *sufficient* benefit (or cost reduction). That means, if an ISR can lead to cost reductions more than a specific (subjective) value, then the firm opts to pursue to the negotiation phase. To represent the set of above mentioned cost parameters that reflect the so called *industrial symbiosis setting*, we employ a value profile structure. Formally, we model an industrial symbiosis setting between resource provider firm A and resource receiver firm B as a tuple $\mathcal{S} = \langle O, T_A, T_B, R_A, R_B, \epsilon_A, \epsilon_B, E_A, E_B\rangle$ where:

- O is the total 3T operational cost for implementing the ISR;
- T_A is the traditional resource discharge cost for firm A;
- T_B is the traditional input purchase cost for firm B;
- for $i \in \{A, B\}$, R_i is the amount of monetary incentive that i receives for implementing the ISR;
- for $i \in \{A, B\}$, ϵ_i is the minimum amount of obtainable cost reduction that i considers sufficient to pursue to ISR negotiations;
- for $i \in \{A, B\}$, E_i is the summation of i's extra costs due to mismatching resource quantities and individual investments.

We highlight that in case an ISR is considered as an "undesired" relation from the legislative point of view (e.g., when an ISR is against environmental standards), the applicable amount of tax/penalty can be represented as a negative value for R_i.

3.3. Shapley-based cost sharing

As discussed in Section 2.3, the implementation of ISRs includes various forms of costs that are ought to be shared among the involved firms. Then, one main factor to ensure the long term stability of the relation is the fairness of the employed cost sharing method.[8] In the following, we recall a cost sharing mechanism, developed in Yazdanpanah and Yazan (2017), that guarantees the Shapley-based notion of fairness

[7] References to elements of $\mathcal{M}$ should be seen as elements of a CEGS $\mathcal{M}$ that is modeling a particular multi-agent system, e.g., we write Q instead of Q in $\mathcal{M}$.

[8] See Yazdanpanah and Yazan (2017) and Yazdanpanah et al. (2018) for game-theoretic evaluations of this claim and Yazan et al. (2017) for agent-based simulation results on this account.

and preserves its desirable properties, i.e., efficiency, symmetry, dummy player, and additivity (Shapley, 1953).

According to Yazdanpanah and Yazan (2017), the allocation of the total 3T operational cost for implementing an ISR between firms A and B is *fair* and *stable* only if it takes into account the dynamics of their traditional costs (i.e., what are the costs if they opt not to implement the ISR).[9] Then, formally, the fair cost share for firm $i \in N = \{A, B\}$ is equal to $\frac{1}{2}[O + T_i - T_{N\setminus\{i\}}]$ where:

- O is the total 3T operational cost for implementing the ISR;
- and T_i is the *traditional* cost for firm i.

Note that cost sharing only applies to 3T operational costs (and not to firms' extra costs E_i). This is based on the assumption that firms only share the costs related to resources that are contributing to an ISR and not for the excess resource that should be discharged/purchased due to mismatching quantities or for a firm's individual investment (e.g., to purchase a required facility that will become a firm's property regardless of the ISR).

In the next section, we present the FISOFmethod and illustrate how the Shapley-based cost sharing mechanism, values that represent firms' costs or preferences, and the epistemic game structure that models the ISR's behavior can be integrated.

4. The FISOFmethod

The Formal Industrial Symbiosis Opportunity Filtering method (FISOF) consists of the following components:

- Institutional Behavior Modeling
- Industrial Symbiosis Settings
- Cost Sharing Mechanism
- Decision Support Algorithm

While the first three components contribute to modeling the ISR as an industrial institution (in Section 4.1), the fourth component focuses on practicality by providing a decision support algorithm (in Section 4.2) that generates the ranked list of promising ISR opportunities for a firm.

4.1. ISR modeling

In order to have a realistic representation of a potential ISR, we use (1) Concurrent Epistemic Game Structures (CEGS) to model its institutional behavior, (2) a set of values that represent all the potential industrial symbiosis settings, and (3) a cost sharing mechanism that allocates the operational costs to involved firms. In the following, we first discuss these three elements in detail and then introduce the ISR model as an industrial institution.

Institutional behavior modeling. As discussed in Yazdanpanah and Yazan (2017), industrial symbiotic relations can be seen as games in which involved agents (i.e., industrial firms) cooperate to materialize benefits *collectively* but also compete to obtain a larger share in the total benefit *individually*. This results in a form of *coopetition* (Bengtsson and Kock, 2000). For such a form of industrial institution, we require mechanisms to ensure the fairness of the value-sharing. Otherwise, the stability of the institution will be questionable. While (Yazdanpanah and Yazan, 2017) addresses this problem under the perfect information assumption – using solution concepts from cooperative game theory – we relax this assumption, model ISRs' behavior under imperfect information, and combine solution concepts from cooperative game theory with concurrent game structures.

[9] In the game-theoretic language, a fair cost sharing considers the *marginal contributions* of involved agents to the cost game (Shapley, 1953).

Industrial symbiosis settings. Dynamics of costs, regulations, quantities, and type of business model play a key role in a firm's decision to consider an ISR as a promising one (to pursue the negotiation). E.g., when a resource-receiver firm aims to start a new production line based on a waste material, it may have higher expectations than when it simply aims to substitute a traditional input (of its established production line). Therefore, it is reasonable to allow different ISR settings (as discussed in Section 3.2) in different ISR implementations. We further elaborate how such a dynamicity can be formulated in the FISOFmethod by taking into account ISR settings (instead of a unique ISR setting).

Cost sharing mechanism. We discussed above that cost values may change with respect to operational dimensions of an ISR. This directly affects the total operational cost of an ISR and accordingly each firm's share. Thus, we localize the Shapley-based cost sharing mechanism with respect to the outcome of agents' actions and employ our Shapley-based allocation as the principle solution concept to ensure fairness and stability in ISRs.

Accordingly, we define the ISR model as an industrial institution.

Definition 1 (*ISR Model*)**.** We say an ISR institution is a tuple $\mathcal{I} = \langle \mathcal{M}, q_0, \mathcal{S}_Q, \Phi \rangle$ where:

- $\mathcal{M} = \langle N, Q, Act, \sim_1, \sim_2, d, o \rangle$ is a two-person concurrent epistemic game structure;
- $q_0 \in Q$ is a uniquely marked state that represents the initial situation of the institution;
- $\mathcal{S}_Q = \{\mathcal{S}_q \mid q \in Q \setminus \{q_0\}\}$ is the indexed set of industrial symbiosis settings, one for every $q \in Q \setminus \{q_0\}$;
- and function $\Phi : N \times Q \setminus \{q_0\} \mapsto \mathbb{R}$ is the Shapley-based cost sharing mechanism that ensures the fairness and stability of the institution. For any pair $i \in N$ and $q \in Q \setminus \{q_0\}$, we have that $\Phi(i, q) = \frac{1}{2}[O + T_i - T_{N\setminus\{i\}}]$ where O and T_i are derived from $\mathcal{S}_q$.

In an ISR institution $\mathcal{I}$, the behavior of the institution is modeled using a two-person GEGS $\mathcal{M} = \langle N, Q, Act, \sim_1, \sim_2, d, o \rangle$ where: N consists of two agents (representing the two firms involved in $\mathcal{I}$); Q is the set of all possible institutional states (representing all the possible implementations of the ISR); Act is the global set of actions that are available to firms (representing all the possible decisions that firms may take); $\sim_i$ is the indistinguishability relation for agent $i \in N$ (representing epistemic limitations of firms with respect to possible implementations of the ISR); d is the function that determines the local set of actions that are available to each firm in each state (representing all the possible decisions that each firm may take in each state); and o is the transition function that determines the next state of the institution given the current state and the joint action profile of agents in N (representing the evolution of the ISR institution as the result of agents' joint decisions).

The following example illustrates a scenario to show how an ISR opportunity can be modeled as an industrial institution. In Section 6, we analyze a realistic case study to show how a more complex ISR opportunity can be modeled and evaluated using the FISOFmethod.

Example 1 (*An ISR Scenario*)**.** Imagine a case where an industrial symbiosis platform identified an ISR opportunity between firms A and B.[10] In this scenario, A's discharge cost is 5 utils,[11] B's traditional purchase cost is 10 utils, and the total 3T operational costs for implementing a direct and a substitution-based ISR are 13 and 10 utils, respectively. Moreover, according to regional regulations, B enjoys 3 utils of incentive if it implements the relation while A can enjoy no encouraging incentives. With respect to expectations, A prefers to

[10] In principle, when a firm produces a waste that another firm listed as its required resource, industrial symbiosis platforms consider this as a potential ISR and suggest it to both firms.

[11] A *util* can be any form of transferable utility, e.g., say a *util* is one thousand Euros.

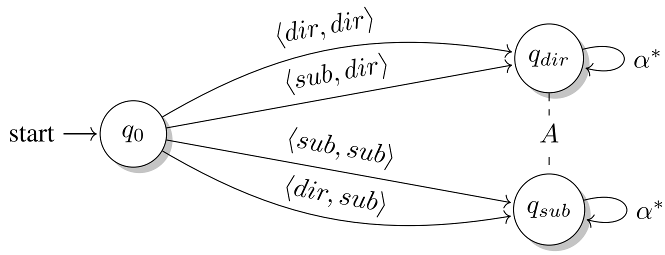

Fig. 3. ISR's states and possible transitions: State q_0 represents the initial situation in which the ISR is not materialized. In q_{dir} and q_{sub} the direct and substitution-based ISRs are implemented, respectively. Moreover, dir and sub refer to the act of opting to implementing a *direct* and *substitution-based* ISR, respectively, while α^* refers to any action profile possible. Finally, the indistinguishability of states q_{dir} and q_{sub} to A is represented with a labeled dashed line between the two states.

pursue negotiations for implementing either a direct or a substitution-based ISR only if it gains at least 1.5 utils. But for B, 1.5 utils is only sufficient for a substitution-based ISR while it expects 2.5 utils for a direct one (as in the latter case B needs to invest on some required facilities which cost 1 extra util). Finally, it is not observable to A whether B uses the resource to substitute an input or to establish a direct ISR business (in case the two firms do not share information with that regard).

This scenario can be modeled by the ISR institution $\mathcal{I} = \langle \mathcal{M}, q_0, \mathcal{S}_Q, \Phi\rangle$ where in $\mathcal{M}$: $N = \{A, B\}$, $Q = \{q_0, q_{dir}, q_{sub}\}$, $Act = \{dir, sub\}$, $\sim_A = \{q_{dir}, q_{sub}\}$, $\sim_B = \emptyset$, $d(i, q) = Act$ for $i \in N$ and $q \in Q$, and transition function o is as illustrated in Fig. 3, e.g., the arrow from q_0 to q_{dir} with the label $\langle dir, sub\rangle$ says that the system goes from q_0 to q_{sub} if A and B execute dir and sub, respectively.

The other elements of this ISR institution, i.e, $\mathcal{S}_Q = \{\mathcal{S}_{q_{dir}}, \mathcal{S}_{q_{sub}}\}$ and Φ, are as follows. The industrial symbiosis settings $\mathcal{S}_{q_{dir}}$ and $\mathcal{S}_{q_{sub}}$ are equal to $\langle 13, 5, 10, 0, 3, 1.5, 2.5, 0, 1\rangle$ and $\langle 10, 5, 10, 0, 3, 1.5, 1.5, 0, 0\rangle$, respectively. Finally, with respect to values in these industrial symbiotic settings, we have that $\Phi(A, q_{dir}) = 4$, $\Phi(A, q_{sub}) = 2.5$, $\Phi(B, q_{dir}) = 9$, and $\Phi(B, q_{sub}) = 7.5$.

The main purpose behind modeling ISR opportunities as industrial institutions is to enable reasoning about their behavior and to provide operational semantics to managers of the involved firms.[12] For instance, in the above ISR scenario, firms are interested to learn about ISR states (i.e., potential implementations of the ISR opportunity) that are in-line with their preferences.[13] This can be realized by answering: "*which states in $\mathcal{I}$ satisfy firm i's minimum expected cost reduction ϵ_i?*".

Definition 2 (*Promising States*)**.** Let $\mathcal{I} = \langle \mathcal{M}, q_0, \mathcal{S}_Q, \Phi\rangle$ be an ISR institution, $i \in N$ be an industrial firm, and $q \in Q \setminus \{q_0\}$ be a state (representing a potential ISR implementation). We say q is a promising state for i iff $T_i - \Phi(i, q) - E_i + R_i \geq \epsilon_i$ where T_i, E_i, R_i, and ϵ_i are derived from $\mathcal{S}_q \in \mathcal{S}_Q$. Moreover, Π_i denotes the set of all promising states for i.

Simply stated, an ISR implementation (i.e., a state in $Q \setminus \{q_0\}$) is a promising one – for a firm – only if it brings about an amount of cost reduction that the firm considers sufficient.[14] For instance, in the ISR scenario (Example 1), q_{sub} is promising for both firms while q_{dir} is a promising state only for firm B. However, due to A's epistemic limitations, it cannot distinguish q_{dir} from q_{sub}. Moreover, with respect to A's available actions in q_0, it has no strategy to avoid q_{dir}. In other words, although a specific implementation of the ISR (in q_{dir}) is a promising one for A, the ISR opportunity is not necessarily a promising one for A. This is mainly due to *epistemic* as well as *strategic* limitations that firm A is facing—in the process of ISR opportunity evaluation. We later elaborate how information sharing may resolve such situations.

4.2. Promising ISRs and decision support algorithm

In this section, we build on the notion of *promising states* and introduce the more general notion of *promising ISRs*. While the former merely focuses on possible ISR implementations that are desirable for a firm, the latter takes into account firms' epistemic as well as strategic abilities to enforce such implementations. Accordingly, an ISR *opportunity* would be seen promising by a firm only if it can enforce a promising *implementation* of the ISR in question.

Definition 3 (*Promising ISRs*)**.** Let $\mathcal{I} = \langle \mathcal{M}, q_0, \mathcal{S}_Q, \Phi\rangle$ be an ISR institution and $i \in N$ be an industrial firm. We say $\mathcal{I}$ is a promising ISR opportunity for i iff there exists a strategy ζ_i such that for all $\lambda \in out(q_0, \zeta_i)$ and $u \geq 1$ we have that $\lambda[u] \in \Pi_i$. Moreover, the immediate guaranteed value of such a ζ_i in $\mathcal{I}$ is $v(\zeta_i, \mathcal{I}) := \min_{\lambda \in out(q_0,\zeta_i)}(\{k \mid k = T_i - \Phi(i, \lambda[1]) - E_i + R_i - \epsilon_i\})$ where T_i, E_i, R_i, and ϵ_i are derived from $\mathcal{S}_{\lambda[1]} \in \mathcal{S}_Q$. Finally, $\mathfrak{I}_i$ denotes the set of all promising ISRs for i.

Roughly speaking, the promisingness of an ISR opportunity (modeled by the ISR institution) $\mathcal{I}$ for a firm i is characterized by all the preconditions that guarantee the existence of a strategy to *reach to and stay in* an ISR implementation in Π_i.

Example 2 (*A Promising ISR?*)**.** In the ISR scenario between firms A and B, the ISR opportunity is a promising ISR for B because by executing a strategy that starts with either dir or sub, it can enforce a B-promising ISR implementation. On the other hand, the ISR is not a promising one for A although there exists an specific ISR implementation that is promising for A, i.e., the substitution-based ISR with B. In Section 5, we show how firms can avoid missing such a mutually beneficial opportunity by sharing information with a secure third-party ISR information system.

The following proposition shows cases where the promisingness of an ISR opportunity for a firm, can be determined regardless of its abilities but mainly with respect to industrial symbiosis settings.

Proposition 1 (*Necessarily Unpromising ISR*)**.** *Let $\mathcal{I} = \langle \mathcal{M}, q_0, \mathcal{S}_Q, \Phi\rangle$ be an ISR institution and $i \in N$ be an industrial firm. If $\Pi_i = \emptyset$ then $\mathcal{I}$ is necessarily not a promising ISR for i.*

Having all the required components for representing an ISR, modeling its institutional behavior, and considering the operational semantics based on which firms can reason about the promisingness of a given ISR, we next formulate the fourth component of the FISOFmethod. The FISOFmethod is a practice-oriented model-checking algorithm to supports firms' decisions in the process of filtering ISR opportunities.

[12] Note that our approach differs from Belief-Desire-Intention (BDI) cognitive/mental models (Bordini et al., 2006; Rao and Georgeff, 1995). In principle, BDI-oriented languages focus on modeling and programming the internal reasoning process of agents – i.e., how an agent plans to reach a desirable situation based on its (dynamic) internal beliefs and intentions – while the focus of this contribution is mainly on modeling the evolution of multi-agent system's environment (assuming no access to agent's internal state of mind). As argued in Yazdanpanah et al. (2019) – for agent-based industrial symbiosis models – it is not reasonable to assume having access to and control over firms' intra-organizational decision-making processes (which is a required input for BDI-based models). Therefore, instead of using accessibility (belief, desire, intention) relations to represent the epistemic dynamics of firms, we employ indistinguishability relations and game structures to represent the limited observability of firms on possible implementations of any given ISR opportunity.

[13] Note that a given ISR *opportunity* may have different potential *implementations*—represented by CEGS states. For instance, the direct ISR between A and B in state q_{dir} and the substitution-based ISR in state q_{sub} are the two ISR implementations of the modeled ISR opportunity in this scenario.

[14] We highlight that assigning a negative value to ϵ_i in an ISR setting is valid. Such a value represents a case in which a firm i opts to negotiate an ISR implementation if it loses at most ϵ_i.

Decision support algorithm. Using the introduced notion of promising ISR, a particular ISR opportunity can be evaluated. However, this notion is applicable only for cases in which no other competing firm exists (i.e., when the evaluation is concerned with a particular ISR opportunity and not a set of opportunities). As we discussed in Section 2, in real-life ISR scenarios, a resource-providing/-receiving firm (mostly) has to evaluate multiple ISR opportunities. This is mainly because there exist competitor resource-providing/-receiving firms. Then, the ISR evaluation question has two folds: *"which ISR opportunities are promising?"* and "*which are more promising?*". To tackle both parts, we use a straightforward transformation of the *evaluation* problem (i.e., if an ISR is promising) in order to answer the *ranking* problem (i.e., the order of promisingness).

We simply incorporate the possibility of having competitors by enabling the decision support algorithm: to receive a list of ISR opportunities for a firm (as the algorithm's input) and to generate a ranked list of promising ISRs for the firm (as the algorithm's output). Such a ranking considers the maximum obtainable cost reduction as the parameter to sort the list of promising ISRs for the firm in question. In other words, the existence of a promising ISR $\mathcal{I} \in \mathfrak{I}_i$ for a firm i implies the existence of a nonempty set of strategies that each guarantees a promising ISR implementation for the firm. Then, within this set, an optimal strategy ζ_i would be a strategy that results in the highest value $v(\zeta_i, \mathcal{I})$ for i (in the promising ISR $\mathcal{I}$). We consider this maximum value, denoted by $\vartheta_i(\mathcal{I})$, as a property of a promising ISR $\mathcal{I}$ (for firm i) and employ it as the ranking factor in the model checking Algorithm 1.

Algorithm 1 FISOFDecision Support Algorithm.

function FISOF(i, Γ) returns Γ_i^* a sorted subset of Γ where i is a firm and $\Gamma = \{\mathcal{I} \mid \mathcal{I} = \langle \mathcal{M}, q_0, \mathcal{S}_Q, \Phi \rangle\}$ is a set of ISR opportunities
    $\Gamma_i \leftarrow \emptyset$
    for each $\mathcal{I} \in \Gamma$ **do**
        if $\mathcal{I} \in \mathfrak{I}_i$ **then**
            $v \leftarrow \vartheta(\mathcal{I}_i)$
            $\Gamma_i \leftarrow \Gamma_i \cup \{\langle \mathcal{I}, v \rangle\}$
        end if
    end for
    $\Gamma_i^* \leftarrow sort(\Gamma_i = \{\langle \mathcal{I}, v \rangle\})\ wrt\ v$
    return Γ_i^*
end function

The FISOFalgorithm generates a ranked list of promising ISRs available to a particular firm. Based on such a list, firms can reason about the most-promising ISR opportunities and strategize about the ISR negotiation process. We later go through a run of this algorithm in a case study.

Next, we study the conditions for occurrence of an ISR negotiation and discuss how some limitations can be resolved using collective strategies that rely on information sharing.

5. Negotiation equilibrium and information sharing

When firms receive a notice about the potential to establish an ISR, e.g., from an ISR platform that matches firms, the execution of the FISOFalgorithm – seeing it integrated into the ISR platform – can show that the ISR is promising: (1) for both, (2) for neither of, or (3) only for one of, the firms involved in the opportunity. Accordingly, firms opt to negotiate the ISR opportunity only if it is a promising one for them. In this section, we first present a game-theoretic analysis on the cases in which the ISR negotiation takes place in a so called Nash equilibrium and then show a resolution for cases where firms can overcome some strategic/epistemic barriers by means of information sharing.

5.1. ISR negotiation in equilibrium

Relying on the FISOFmethod that filters ISR opportunities using their operational properties on the micro-level, we now focus on the macro-level with the aim to analyze the occurrence of the ISR negotiation on a particular ISR opportunity. This is mainly to show when negotiations take place. We assume that, using the FISOFmethod, firms have sufficient capacities to negotiate with all the promising ISRs and reject any unpromising ISR. In a game-theoretic structure, such meta-level decisions can be presented in a two-person non-cooperative game where firms can either *negotiate* or *reject* an ISR opportunity. The following proposition shows that the ISR negotiation on an ISR opportunity occurs in a Nash equilibrium[15] only if it is a mutually promising ISR.

Proposition 2 (*ISR Negotiation in Equilibrium*). *Let $\mathcal{I} = \langle \mathcal{M}, q_0, \mathcal{S}_Q, \Phi \rangle$ be an ISR institution. With no prior communication, ISR negotiation on $\mathcal{I}$ occurs in a Nash equilibrium iff $\mathcal{I} \in \mathfrak{I}_i$ for all $i \in N$.*

Proof. "$\Rightarrow$": In this four state game – as the result of negotiate/reject decisions of two players – the negotiation (i.e., negotiate–negotiate state) takes place only if both parties opt to negotiate. Assume that the ISR opportunity is not among the promising ISRs for both parties, then it is either unpromising for both or only for one. In both cases, one or both parties opt to reject which contradicts with the premise.

"$\Leftarrow$": Having $I \in \mathfrak{I}_i$ for all $i \in N$ implies that for both forms, $\vartheta(\mathcal{I})_i$ is larger than zero, i.e., both can obtain sufficient cost reductions in some implementations of the ISR opportunity. Accordingly, both have no incentive to deviate and hence the negotiate–negotiate state would be a Nash equilibrium. □

While this result shows the cases where the negotiation takes place,[16] it also illustrates that some mutually beneficial ISRs will not qualify to be negotiated—as a result of epistemic or strategic limitations of individual firms. To see this, we recall the ISR scenario in Example 2. In this scenario, A rejects the ISR due to its inability to distinguish the promising state q_{sub} (which represents a promising ISR implementation for both firms) from q_{dir} (which represents an unpromising ISR implementation for A but a promising one for B). This shows that although A and B can mutually benefit from the ISR, A rejects the ISR opportunity, hence an obtainable cost reduction will be dismissed. A natural solution – supported by empirical results in Fraccascia and Yazan (0000) – is to provide a secure information sharing platform with which all the involved firms can share information. This is mainly to delegate the ISR evaluation process to automated processes that can enjoy the so called *distributed knowledge* (Fagin et al., 1995) among the set of involved delegates.

5.2. The fostering effect of information sharing

As we have shown earlier, there might be promising ISR implementations that firms dismiss to negotiate merely due to their lack of information. Roughly speaking, firms opt to reject an ISR opportunity if they cannot *individually* enforce a promising implementation of it. While sharing sensitive information with other firms is not a realistic solution in the industrial context, sharing information with a secure multi-agent decision-making platform is a feasible resolution to this issue. Such a framework can directly use and explore the set of ISR implementations (i.e., the set of all possible promising states in Q) instead of making the decision to negotiate under epistemic limitations that firms may suffer from.

[15] The materialization of a situation, as the result of a mutual decision, in a Nash equilibrium (Mas-Colell et al., 1995) implies that no party has rational incentives to deviate from the decision that results in the situation.

[16] Note that this result is about the selection (filtering) of the most promising symbiotic relationships, and not the coordination of the negotiation process as such.

The next proposition shows that due to monotonicity of power (Holler and Napel, 2004), aggregation of firms in the grand coalition empowers them and makes more states (that represent ISR implementations) collectively reachable.

Proposition 3 (*More is More*). *Let $\mathcal{I} = \langle \mathcal{M}, q_0, \mathcal{S}_Q, \Phi \rangle$ be an ISR institution and let $\mathcal{S}_{next} \subseteq \mathcal{S}_q$ be a set of successors of q_0. Then the set of states that any $i \in N$ can guarantee in $\mathcal{S}_{next}$ (denoted by $\mathcal{S}^i_{next}$) is a subset of the set of states that N can guarantee in $\mathcal{S}_{next}$ (denoted by $\mathcal{S}^N_{next}$); formally, $\mathcal{S}^i_{next} \subseteq \mathcal{S}^N_{next}$.*

Proof. To prove $\mathcal{S}^i_{next} \subseteq \mathcal{S}^N_{next}$, we show that for any individual strategy ζ_i that guarantees a state $q \in \mathcal{S}_{next}$ (i.e., for all $\lambda \in out(q_0, \zeta_i)$ we have that $\lambda[1] = q$ regardless of what other agents in N choose to do) there exist a collective strategy Z_N able to guarantee the same q. For any arbitrary ζ_i that guarantees a q, we can construct a collective strategy Z_N in which i follows ζ_i in q_0 while other agents in N have arbitrary actions. Such a Z_N guarantees q. Note that the equality, i.e., $\mathcal{S}^i_{next} = \mathcal{S}^N_{next}$, does not hold necessarily due to the point that $\sim^D_N \subseteq \sim_i$ for any $i \in N$. □

Using Proposition 3, the next theorem illustrates that using distributed knowledge and collective strategies, firms will be able to recognize and immediately enforce any ISR implementation that is mutually promising.

Theorem 1 (*Collectively Enforceable Promising States*). *Let $\mathcal{I} = \langle \mathcal{M}, q_0, \mathcal{S}_Q, \Phi \rangle$ be an ISR institution. Moreover, let $q \in \bigcap_{i \in N} \Pi_i$ be a successor of q_0. If $q_0 \notin \sim^D_N$ then there exists a collective strategy Z_N such that for all $\lambda \in out(q_0, \zeta_N)$ we have that $\lambda[1] \in \bigcap_{i \in N} \Pi_i$.*

Proof. As q is a mutually promising state (i.e., ISR implementation of $\mathcal{I}$), we can prove the theorem by showing the ability of firms to reach q. As illustrated in Proposition 3, having that the grand coalition's strategic ability to enforce a successor state is only limited to its epistemic limitation and given that $q_0 \notin \sim^D_N$, we have that the two firms in N can collectively enforce q as a mutually promising implementation of $\mathcal{I}$. □

This result shows that relying on the knowledge that is distributed among firms, they can collectively make sure that no mutually promising state (i.e., ISR implementation) will be dismissed. Accordingly, we present the FISOF^+ algorithm – a variation of FISOF– that assumes the availability of distributed knowledge and hence applicability of collective strategies for evaluating a set of ISR opportunities (Algorithm 2).

Algorithm 2 FISOF^+ Decision Support Algorithm.

1: **function** $\mathsf{FISOF}^+(i, \Gamma)$ returns a sorted set $\Delta^*_i \subseteq \bigcup_{\mathcal{I} \in \Gamma} \mathcal{S}_Q$ where i is a firm and $\Gamma = \{\mathcal{I} \mid \mathcal{I} = \langle \mathcal{M}, q_0, \mathcal{S}_Q, \Phi \rangle\}$ is a set of ISR opportunities
2: $\quad \Delta_i \leftarrow \emptyset$
3: $\quad$ **for each** $\mathcal{I} \in \Gamma$ **do**
4: $\quad\quad$ **for each** $q \in Q$ **do**
5: $\quad\quad\quad$ **if** $q \in \Pi_i \wedge q \in \Pi_{N \setminus \{i\}}$ **then**
6: $\quad\quad\quad\quad v \leftarrow T_i - \Phi(i, q) - E_i + R_i - \epsilon_i$ *under* $\mathcal{S}_q$
7: $\quad\quad\quad\quad \Delta_i \leftarrow \Delta_i \cup \{\langle q, v \rangle\}$
8: $\quad\quad\quad$ **end if**
9: $\quad\quad$ **end for**
10: $\quad$ **end for**
11: $\quad \Delta^*_i \leftarrow sort(\Delta_i = \{\langle q, v \rangle\})$ *wrt* v
12: $\quad$ return Δ^*_i
13: **end function**

Note that FISOF^+ takes a set of ISR opportunities as its input and generates a sorted list of mutually promising ISR implementations as its output. We discussed earlier that (using FISOF) epistemic limitations of firms result in the occurrence of ISR negotiations only on mutually promising ISRs and illustrated that some mutually promising implementations may be dismissed accordingly. Then, the question is whether using the extended method, i.e., using FISOF^+, provides the chance of ISR negotiation on implementations that are dismissed in FISOF. The following theorem shows that using distributed knowledge and collective strategies in FISOF^+, we can capture all mutually promising ISR implementations that FISOFcovers in addition to those that it may dismiss.

Theorem 2 (FISOF*vs.* FISOF^+). *Let $\Gamma = \{\mathcal{I} \mid \mathcal{I} = \langle \mathcal{M}, q_0, \mathcal{S}_Q, \Phi \rangle\}$ be a set of ISR opportunities, i be a firm, and $\Lambda_i = \bigcup_{\mathcal{I} \in \mathsf{FISOF}(i,\Gamma)} \{q \mid q \in \Pi_i\}$ be the set of promising ISR implementations for i under* FISOF*. We have that the set of possible ISR negotiations (in equilibrium) under FISOF^+ includes the set of possible ISR negotiations (in equilibrium) under* FISOF*, formally that $\bigcap_{i \in N} \Lambda_i \subseteq \bigcap_{i \in N} \mathsf{FISOF}^+(i, \Gamma)$.*

Proof. According to Algorithm 2 (line 5), the results of FISOF^+ includes any mutually promising ISR implementation (possible in Γ). This shows that possible negotiations under FISOFare included in the set of possible negotiations under FISOF^+. To prove, we then have to show the inequality of the two sets (i.e., $\bigcap_{i \in N} \Lambda_i$ and $\bigcap_{i \in N} \mathsf{FISOF}^+(i, \Gamma)$). Relying on Proposition 3 and Theorem 1, we have that the two sets are not equal (in principle) as firms may face epistemic/strategic limitations that avoid them to negotiate on some mutually promising ISR implementations. In particular, any mutually promising implementation of unpromising ISRs. □

This result shows the importance of secure industrial symbiosis information sharing frameworks to support firms during the process of ISR evaluation by taking into account ISRs' operational as well as epistemic dimensions.

6. An ISR opportunity filtering case study

In this section, we present a case study (adopted from Andiappan et al., 2016) to illustrate the applicability of our method and the way our decision support algorithms perform in practice.

6.1. Case description

The case study that we analyze here consists of three firms active in the Malaysian palm oil industry as one of the key industries in Malaysia's developing economy. The first firm is a Palm Oil Mill (POM) that generates solid biomass waste during the process of palm oil extraction. Although this biomass has the potential to be used for biogas generation, POM (traditionally) discharges this waste. The other two firms in this case study are a firm owning a Biomass-based Tri-generation System (BTS) and a Palm-Based Biorefinery (PBB). The biomass waste (generated by POM) can substitute primary inputs of the other two firms and also can be used directly to establish new production lines (in both PBB and BTS). This shows the potential to establish ISRs among these firms. In particular, POM would be seen as a firm on the provider side of two ISR opportunities with PBB and BTS (as potential resource receivers). Then, all the three firms are interested to learn whether such relations are sufficiently promising to negotiate. E.g., if POM has the potential to reduce its waste discharge cost at a sufficient level, such that ϵ_{POM} will be met.

The potential industrial symbiotic relations between POM-BTS and POM-PBB are the two ISR opportunities that we are aiming to model and analyze using provided values in the case and some reasonable assumptions about missed values. As each ISR can be implemented either as a direct or substitution-based ISR, we will have four ISR settings illustrated in Tables 1 and 2. Note that our focus in this section is to illustrate the applicability of our decision support algorithms and not to analyze the detailed subtleties of the case neither methods for estimating cost values.

In the following, we analyze the case assuming that POM has to discharge 1000 kg of its biomass waste while PBB and BTS require 1000 kg and 900 kg of this waste, respectively.

Table 1
ISR settings for $\mathcal{I}_{POM-PBB}$.

ISR settings for $\mathcal{I}_{POM-PBB}$	$\mathcal{S}_{dir}$	$\mathcal{S}_{sub}$
Treatment cost (€/kg)	0.24000	0.24000
Transportation cost (€/kg)	0.00100	0.00100
Transaction cost (€/kg)	0.01268	0.01268
Biomass discharge cost (€/kg)	0.00230	0.00230
Biomass purchase cost (€/kg)	0.04140	0.04140
Incentive (POM) (€/kg)	0.10000	0.20000
Incentive (PBB) (€/kg)	0.10000	0.20000
Acceptable reduction ϵ_{POM} (€/kg)	0.01522	0.01522
Acceptable reduction ϵ_{PBB} (€/kg)	0.01522	0.01522
POM's extra cost E_{POM} (€/kg)	0.00000	0.00000
PBB's extra costs E_{PBB} (€/kg)	0.00100	0.00000

Table 2
ISR settings for $\mathcal{I}_{POM-BTS}$.

ISR settings for $\mathcal{I}_{POM-BTS}$	$\mathcal{S}_{dir}$	$\mathcal{S}_{sub}$
Treatment cost (€/kg)	0.20000	0.20000
Transportation cost (€/kg)	0.00100	0.00100
Transaction cost (€/kg)	0.01058	0.01058
Biomass discharge cost (€/kg)	0.00230	0.00230
Biomass purchase cost (€/kg)	0.04140	0.04140
Incentive (POM) (€/kg)	0.10000	0.20000
Incentive (BTS) (€/kg)	0.10000	0.20000
Acceptable reduction ϵ_{POM} (€/kg)	0.01269	0.01269
Acceptable reduction ϵ_{BTS} (€/kg)	0.01269	0.01269
POM's extra cost E_{POM} (€/kg)	0.00026	0.00026
BTS's extra costs E_{BTS} (€/kg)	0.00560	0.00460

Table 3
ISR implementations of $\mathcal{I}_{POM-PBB}$.

$\mathcal{I}_{POM-PBB}$	v	Promisingness
q_{dir} for POM	€−20.21316	Unpromising for POM ✗
q_{dir} for PBB	€−21.21316	Unpromising for PBB ✗
q_{sub} for POM	€79.78684	Promising for POM ✓
q_{sub} for PBB	€79.78684	Promising for PBB ✓

6.2. ISR modeling and decision support algorithms

In this case study, the potential to establish ISRs between firms results in a set of ISR opportunities $\Gamma = \{\mathcal{I}_{POM-PBB}, \mathcal{I}_{POM-BTS}\}$. To enable the use of FISOFand FISOF$^+$, we follow Definition 1 and model these two opportunities as ISR institutions. This is $\mathcal{I} = \langle \mathcal{M}, q_0, \mathcal{S}_Q, \Phi \rangle$ for $\mathcal{I} \in \Gamma$ where $\mathcal{M}$ and q_0 are identical to Example 1, $\mathcal{S}_Q$ is presented in Tables 1 and 2, and Φ is the Shapley-based cost sharing mechanism (as formulated in Definition 1). Accordingly, in $\mathcal{I}_{POM-PBB}$, we have that $\Phi(POM, q_{dir}) = \Phi(POM, q_{dir}) =$ €107.29211 and $\Phi(PBB, q_{dir}) = \Phi(PBB, q_{dir}) =$ €146.39211. Moreover, in $\mathcal{I}_{POM-BTS}$, we have that $\Phi(POM, q_{dir}) = \Phi(POM, q_{dir}) =$ €77.61553 and $\Phi(BTS, q_{dir}) = \Phi(BTS, q_{dir}) =$ €112.80553. Considering (1) the traditional costs of resource-receivers/providers, (2) the total costs that firms face with in each of the potential implementations of ISR opportunities in Γ, and (3) their minimum acceptable cost reductions, we can compute the "excess" cost reduction that firms can enjoy, i.e., $(T_i - \Phi(i,q) - E_i + R_i) - \epsilon_i$. For instance, in $\mathcal{I}_{POM-BTS}$, the firm POM can obtain €104.22447 which is €92.79921 above its minimum acceptable cost reduction ϵ_{POM} for implementing this relation (on 900 kg of biomass). In Tables 3 and 4 we present the value $v = T_i - \Phi(i,q) - E_i + R_i - \epsilon_i$ for each potential implementation and use Definition 3 to determine weather an ISR implementation is a promising one (from a firm's perspective). Figs. 4, 5, and 6, display the dynamics of value v—as a ranking/evaluation parameter—among all the available ISR implementations for firms POM, PBB, and BTS, respectively.

To illustrate how our ISR opportunity filtering algorithms perform in practice, here we go through a run of each in this case study and compare their results.

Table 4
ISR implementations of $\mathcal{I}_{POM-BTS}$.

$\mathcal{I}_{POM-BTS}$	v	Promisingness
q_{dir} for POM	€2.79921	Promising for POM ✓
q_{dir} for BTS	€−2.01079	Unpromising for BTS ✗
q_{sub} for POM	€92.79921	Promising for POM ✓
q_{sub} for BTS	€88.88921	Promising for BTS ✓

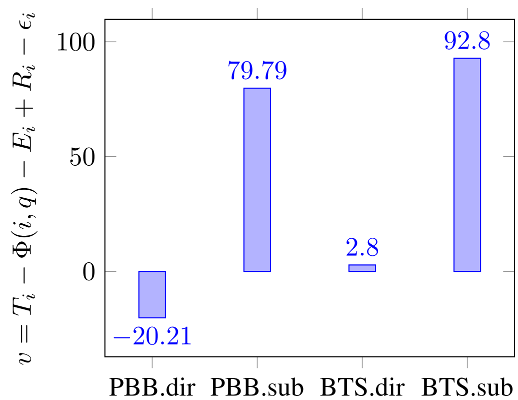

Fig. 4. v value for POM's potential ISR implementations.

FISOF Algorithm. Using FISOF, firms can learn whether a given ISR is a promising one (Definition 3). In this case study, FISOF(POM, Γ) returns $\mathcal{I}_{POM-BTS}$ as the unique promising ISR for POM. Accordingly, POM rejects $\mathcal{I}_{POM-PBB}$ due to its epistemic limitations while PBB and BTS respectively opt to negotiate $\mathcal{I}_{POM-PBB}$ and $\mathcal{I}_{POM-BTS}$ thanks to their epistemic observability. This leads to (in equilibrium) occurrence of ISR negotiation only on $\mathcal{I}_{POM-BTS}$. Note that although there exists a mutually promising ISR implementation of $\mathcal{I}_{POM-PBB}$, namely its direct implementation, firms are not able to realize it due to their strategic/epistemic limitations.

FISOF$^+$ Algorithm. Using FISOF$^+$, firms can learn about all the mutually promising implementations of ISR opportunities thanks to information sharing. In this case study, FISOF$^+(POM, \Gamma)$ returns a ranked set that starts with *substitution-based ISR with BTS* (as the most promising implementation for POM) and ends with *substitution-based ISR with PBB* (as the least promising implementation for POM). Note that although the *direct ISR with BTS* is a promising implementation for POM, it is not among the generated outputs of FISOF$^+$ because it is not mutually promising for both sides of the relation. By applying FISOF$^+$, we also have that FISOF$^+(PBB, \Gamma)$ and FISOF$^+(BTS, \Gamma)$ both return *substitution-based ISR with POM*. Accordingly, we have that thanks to the fostering effect of information sharing, the ISR negotiations on all the mutually promising implementations occur in equilibrium.

As illustrated in this case study and following what we formally evaluated in Section 5.2, information sharing enables the use of FISOF$^+$ and accordingly the chance to negotiate all the mutually promising ISR implementations (that may be dismissed under FISOF). We highlight that dismissing mutually promising implementations may avoid the occurrence of negotiations to form *Industrial Symbiotic Networks (ISNs)* (Yazdanpanah et al., 2018). For instance, in our case study, POM may opt to implement ISRs with both PBB and BTS. While FISOFavoids such ISN negotiations, FISOF$^+$ enables it as it relies on collectively available strategies under distributed knowledge.

7. Concluding remarks

In this section, we highlight different aspects of our contribution, present its applicability domains, briefly discuss the validity of presented ISR dimensions, and conclude with further research directions.

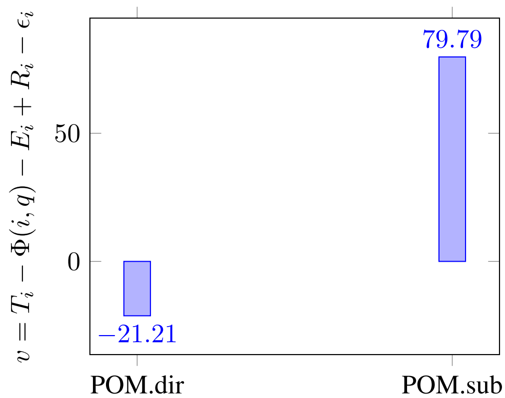

Fig. 5. v value for PBB's potential ISR implementations.

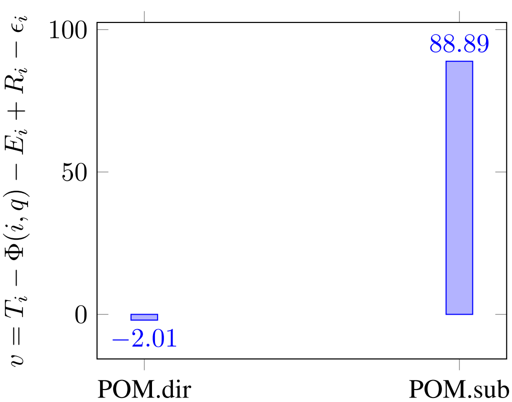

Fig. 6. v value for BTS's potential ISR implementations.

Contributions and applicability. In this work, we presented a formal decision support method that takes into account operational and epistemic aspects of ISRs for filtering industrial symbiosis opportunities (FISOF). Using this method, firms can evaluate any particular ISR opportunity with respect to obtainable cost reductions under some observable implementations of the opportunity. This in turn enables ranking the set of promising ISR opportunities for a firm. Accordingly, firms learn about a spectrum that begins with the most-promising and ends with least-promising ISR opportunities. Then, a firm may develop strategies how to pursue the contract negotiations with members of this spectrum and dismisses other (unpromising) ISR opportunities. This results in a quantitative operations-oriented decision support algorithm for ISR evaluation. Moreover, we show that firms' epistemic limitations may avoid learning about all the mutually promising ISR implementations. As a resolution, we developed a method (FISOF$^+$) that employs firms' distributed knowledge and enables learning about all the mutually promising ISR implementations (that may be dismissed if firms opt not to share information). In addition to the algorithmic account of these two methods, we introduced new operational semantics for industrial symbiosis research and presented novel concepts for reasoning about ISRs. Such operational semantics enable systematic reasoning about ISR behavior and foster the computation of ISR properties (e.g. by employing multiagent-based simulation methods (Yazan et al., 2017)).

The other application of our work is to support policy-making and fine-tuning the regulations that foster the transition to circular economy. For instance, due to lack of regulations, firms may face no prohibition on disposal of some particular (hazardous) wastes or may receive no incentives in case of substituting some of their raw material with reusable waste inputs. Using our method, policy-makers can analyze ISRs towards which they can aim their encouraging incentives or binding regulations. Moreover, policy-makers can learn if by means of modifications in regulations or/and incentives, an unpromising ISR implementation can turn to a promising one (if-then analysis).

Validity of ISR dimensions and algorithms. The presented ISR dimensions (Figs. 1 and 2) and the ISR 3T operational costs, i.e. transportation, treatment, and transaction costs, are supported by industrial symbiosis research literature (see Section 2). In addition, to back-up the theory with expert knowledge, we circulated an earlier version of this work among our industrial partners in the EU-funded *SHAREBOX* project (SHAREBOX), presented the framework as well as various implementations of FISOFand FISOF$^+$ to their representatives in validation sessions, and have taken into account their practice-oriented feedback.

Future work. We illustrated that negotiations on an ISR implementation that is not mutually promising do not occur in an equilibrium even if it is a desirable one (e.g., from an environmental point of view). Then, as we discussed earlier, policy-makers can learn about symbiotic relations that are not implementable and introduce monetary incentives to foster them. This leads to the so called *incentive engineering* problem. Roughly speaking, "how a limited amount of incentive can be optimally distributed among unpromising ISRs such that the outcome meets a policy" would be a question that calls for policy support tools. As an extension, we plan to address this problem using computational methods for incentive allocation (Wooldridge et al., 2013) and auction mechanisms in multi-agent systems (Vulkan and Jennings, 2000).

In this work, we presented ISR opportunity evaluation methods—usable as prenegotiation decision support tools. In future work, we plan to develop an automated procedure that acts as a middle-ware in between FISOF$^+$ and established negotiation methods. For such a purpose, we aim to build on multiagent-based implementations of Delphi (García-Magariño et al., 2008) and agent-based methods (García-Magariño, 2013) that enable representing potential transformations of ISR institutions.

We also aim to extend our methods and operational semantics to capture symbiotic relations with more players and evaluate Industrial Symbiotic Networks (ISNs) (Yazdanpanah et al., 2016). We emphasize that structural properties and dynamics of power relations in ISNs result in more complex institutional behaviors, hence calls for (1) representations that take into account the symbiotic network as a coordinated institution (Yazdanpanah et al., 2018) and (2) dynamic contracts able to monitor and enforce the commitment of involved firms to the codes of conduct (Dastani et al., 2015).

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