A Multiagent Framework for Coordinating Industrial Symbiotic Networks

Vahid Yazdanpanah[a], Devrim M. Yazan[b] and W. Henk M. Zijm[b]

[a]*Agents, Interaction and Complexity (AIC) Research Group, School of Electronics and Computer Science, University of Southampton, Southampton, SO17 1BJ, United Kingdom*

[b]*Department Industrial Engineering and Business Information Systems, Faculty of Behavioural, Management and Social Sciences, University of Twente, Enschede, 7500 AE, The Netherlands*

Abstract

We present a formal multiagent framework for coordinating a class of collaborative industrial practices called "*Industrial Symbiotic Networks* (ISNs)" as cooperative games. The game-theoretic formulation of ISNs enables systematic reasoning about what we call the ISN implementation problem. Specifically, the characteristics of ISNs may lead to the inapplicability of standard *fair* and *stable* benefit allocation methods. Inspired by realistic ISN scenarios and following the literature on normative multiagent systems, we consider *regulations* and normative socio-economic *policies* as coordination instruments that in combination with ISN games resolve the situation. In this multiagent system, employing Marginal Contribution Nets (MC-Nets) as rule-based cooperative game representations foster the combination of regulations and ISN games with no loss in expressiveness. We develop algorithmic methods for generating regulations that ensure the implementability of ISNs and as a policy support, present the policy requirements that guarantee the implementability of desired ISNs in a *balanced-budget* way.

Keywords

Multiagent Systems, Agent-Oriented Coordination, Normative Methods, Industrial Symbiosis

1. Introduction

Industrial Symbiotic Networks (ISNs) are circular economic networks of industries with the aim to reduce the use of virgin material by circulating reusable resources (e.g., physical waste material and energy) among the network members [1, 2, 3]. In such networks, symbiosis leads to socio-economic and environmental benefits for involved industrial agents and the society (see [4, 5]). One barrier against stable ISN implementations is the lack of frameworks able to secure such networks against unfair and unstable allocation of obtainable benefits among the involved industrial firms. In other words, although in general ISNs result in the reduction of the total cost, a remaining challenge for operationalization of ISNs is to tailor reasonable mechanisms for allocating the total obtainable cost reductions—in a fair and stable manner—among the contributing firms. Otherwise, even if economic benefits are foreseeable, lack of

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V.Yazdanpanah@soton.ac.uk (V. Yazdanpanah); D.M.Yazan@utwente.nl (D. M. Yazan); W.H.M.Zijm@utwente.nl (W. H. M. Zijm)
https://www.ecs.soton.ac.uk/people/vy1y20 (V. Yazdanpanah); https://people.utwente.nl/d.m.yazan (D. M. Yazan); https://www.utwente.nl/en/bms/iebis/staff/former/zijm (W. H. M. Zijm)
0000-0002-4468-6193 (V. Yazdanpanah); 0000-0002-4341-2529 (D. M. Yazan); 0000-0002-4227-2624 (W. H. M. Zijm)

stability and/or fairness may lead to non-cooperative decisions. This will be the main focus of what we call the *industrial symbiosis implementation* problem. Reviewing recent contributions in the field of industrial symbiosis research, we encounter studies focusing on the necessity to consider interrelations between industrial enterprises [6, 2] and the role of contract settings in the process of ISN implementation [7, 8]. We believe that a missed element for shifting from *theoretical* ISN design to *practical* ISN implementation is to model, reason about, and support ISN decision processes in a dynamic way (and not by using case-specific snapshot-based modeling frameworks).

For such a multiagent setting, the mature field of cooperative game theory provides rigorous methodologies and established solution concepts, e.g. the core of the game and the Shapley allocation [9]. However, for ISNs modeled as a cooperative game, these established solution concepts may be either non-feasible (due to properties of the game, e.g. being *unbalanced*) or non-applicable (due to properties that the industrial domain asks for but solution concepts cannot ensure, e.g. individual as well as collective rationality). This calls for contextualized multiagent solutions that take into account both the complexities of ISNs and the characteristics of the employable game-theoretical solution concepts. Accordingly, inspired by realistic ISN scenarios and following the literature on normative multiagent systems [10, 11, 12], we consider *regulative* rules and normative socio-economic *policies* as two elements that in combination with ISN games result in the introduction of the novel concept of *Coordinated* ISNs ($\mathcal{C}-$ISNs). We formally present regulations as monetary incentive rules to enforce desired industrial collaborations with respect to an established policy. Regarding our representational approach, we use Marginal Contribution Nets (MC-Nets) as rule-based cooperative game representations. This simply fosters the combination of regulative rules and ISN games with no loss in expressiveness. Accordingly, applying regulatory rules to ISNs enables ISN policy-makers to transform ISN games and ensure the implementability of desired ones in a fair and stable manner.

For the first time, this work provides a multiagent framework—using MC-net cooperative games—for the implementation phase of ISNs.[1] We develop algorithmic methods for generating regulations that ensure the implementability of ISNs (methodological contribution) and as a policy support, present the ISN policy requirements (practical contribution) that guarantee the implementability of all the desired industrial collaborations in a *balanced-budget* way.

2. ISN as a Multiagent Practice

To explain the dynamics of implementing ISNs as multiagent industrial practices, we use a running example. Imagine three industries i, j, and k in an industrial park such that r_i, r_j, and r_k are among recyclable resources in the three firms' wastes, respectively. Moreover, i, j, and k require r_k, r_i, and r_j as their primary inputs, respectively. In such scenarios, discharging wastes and purchasing traditional primary inputs are transactions that incur cost. Hence, having the chance to reuse a material, firms prefer recycling and transporting reusable resources to other enterprises if such transactions result in obtainable cost reductions for both parties—meaning that it reduces the related costs for discharging wastes (on the resource provider side) and

[1] The foundations of the ideas developed in this article were presented at AAMAS'18 [13] and explored further in [14]. Through the text—to appreciate the space limit—we refer the reader to [14] for details and complete proofs.

purchasing cost (on the resource receiver side). On the other hand, the implementation of such an industrial network involves transportation, treatment, and transaction costs. In principle, aggregating resource treatment processes using refineries, combining transaction costs, and coordinating joint transportation may lead to significant cost reductions at the collective level.

What we call the *industrial symbiosis implementation* problem focuses on challenges—and accordingly seeks solutions—for sharing this *collectively obtainable* benefit among the involved firms. Simply stated, the applied method for distributing the total obtainable benefit among involved agents is crucial while reasoning about implementing an ISN. Imagine a scenario in which symbiotic relations ij, ik, and jk, respectively result in 4, 5, and 4 utility units of benefit, the symbiotic network ijk leads to 6 units of benefit, and each agent can be involved in at most one symbiotic relation. To implement the ijk ISN, one main question is about the method for distributing the benefit value 6 among the three agents such that they all be induced to implement this ISN. For instance, as i and k can obtain 5 utils together, they will defect the ISN ijk if we divide the 6 units of util equally (2 utils to each agent). Note that allocating benefit values lower than their "traditional" benefits—that is obtainable in case firms defect the collaboration—results in unstable ISNs. Moreover, unfair mechanisms that disregard the contribution of firms may cause the firms to move to other ISNs that do so. In brief, even if an ISN results in sufficient cost reductions (at the collective level), its implementation and applied allocation methods determine whether it will be realized and maintained. Our main objective in this work is to provide a multiagent implementation framework for ISNs that enables fair and stable allocation of obtainable benefits. In further sections, we review two standard allocation methods, discuss their applicability for benefit-sharing in ISNs, and introduce our normatively-coordinated multiagent system to guarantee stability and fairness in ISNs.

Regulations as Socio-Economic Norms: In real cases, ISNs take place under regulations that concern environmental as well as societal policies. Hence, industrial agents have to comply to a set of rules. For instance, avoiding waste discharge may be encouraged (i.e., normatively promoted) by the local authority or transporting a specific type of hazardous waste may be forbidden (i.e., normatively prohibited) in a region. Accordingly, to nudge the collective behavior, monetary incentives in the form of subsidies and taxes are well-established solutions. This shows that the ISN implementation problem is not only about decision processes among strategic utility-maximizing industry representatives (at a microeconomic level) but in addition involves regulatory dimensions—such as presence of binding/encouraging monetary incentives (at a macroeconomic level). To capture the regulatory dimension of ISNs, we apply a normative policy that respects the socio-economic as well as environmental desirabilities and categorizes possible coalitions of industries in three classes of: *promoted*, *permitted*, and *prohibited*. Accordingly, the regulatory agent respects this classification and allocates incentives such that industrial agents will be induced to: implement promoted ISNs and avoid prohibited ones (while permitted ISNs are neutral from the policy-maker's point of view). For instance, in our ISN scenario, allocating 10 units of incentive to ijk and 0 to other possible ISNs induces all the rational agents to form the grand coalition and implement ijk—as they cannot benefit more in case they defect. We call the ISNs that take place under regulations, *Coordinated* ISN*s* ($\mathcal{C}-$ISNs). Note that the term "coordination" in this context refers to the application and efficacy of monetary incentive mechanisms in the ISN implementation phase, and should not be confused with ISN administration (i.e., managing the evolution of relations).

Dealing with firms that perform in a complex multiagent industrial context calls for implementation platforms that can be tuned to specific settings, can be scaled for implementing various ISN topologies, do not require industries to sacrifice financially, and allow industries to practice their freedom in the market. We deem that the quality of an ISN implementation framework should be evaluated by (1) *Generality* as the level of flexibility in the sense of independence from agents' internal reasoning processes (i.e., how much the framework adheres to the principle of *separation of concerns*), (2) *Expressivity* as the level of scalability in the sense of independence from size and topology of the network, (3) *Rationality* as the level that the employed allocation mechanisms comply to the collective as well as individual rationality axiom (i.e., the framework should assume that no agent (group) participates in a cooperative practice if they expect higher utility otherwise), and (4) *Autonomy* as the level of allowance (i.e., non-restrictiveness) of the employed coordination mechanisms. Then an ideal framework for implementing ISNs should be general—i.e., it should allow for manipulation in the sense that the network designer does not face any re-engineering/calibration burden—sufficiently expressive, rationally acceptable for all firms, and respect their autonomy. The goal of this paper is to develop a multiagent framework with properties close to the ideal one.

Past Work: The idea of employing cooperative game theory for analysis and implementation of industrial symbiosis have been sparsely explored [15, 16, 17]. In [15], Grimes-Casey et al. used both cooperative and non-cooperative games for analyzing the behavior of firms engaged in a case-specific industrial ecology. While the analysis is expressive, the implemented relations are specific to refillable/disposable bottle life-cycles. In [16], Chew et al. tailored a mechanism for allocating costs among participating agents that expects an involved industry to "bear the extra cost". Although such an approach results in collective benefits, it is not in-line with the individual rationality axiom. In [17], Yazdanpanah and Yazan model bilateral industrial symbiotic relations as cooperative games and show that in such a specific class of symbiotic relations, the total operational costs can be allocated fairly and stably. Our work relaxes the limitation on the number of involved industries and—using the concept of Marginal Contribution Nets (MC-Nets)—enables a representation that is sufficiently expressive to capture the regulatory aspect of ISNs.

3. Game-Theoretic Notions

In this work, we build on the *transferable utility* assumption in game-theoretic multiagent settings. This is to assume that the payoff to a group of agents involved in an ISN (as a cooperative practice) can be freely distributed among the group members, e.g., using monetary transactions.[2]

[2]The presented material on basics in cooperative games is based on [9] while for the MC-Net notations, we build on [18, 19].

Cooperative Games: Multiagent cooperative games with transferable utility are often modeled by the tuple (N, v), where N is the finite set of agents and $v : 2^N \mapsto \mathbb{R}$ is the characteristic function that maps each possible agent group $S \subseteq N$ to a real-valued payoff $v(S)$. In such games, the so-called *allocation problem* focuses on methods to distribute $v(S)$ among all the agents (in S) in a reasonable manner. That is, $v(S)$ is the result of a potential cooperative practice, hence ought to be distributed among agents in S such that they all be induced to cooperate (or remain in the cooperation). Various solution concepts specify the utility each agent receives by taking into account properties like fairness and stability. The two standard solution concepts that characterize fair and stable allocation of benefits are the Shapley value and the Core, respectively.

Shapley Value and Fairness: The Shapley value prescribes a notion of *fairness.* It says that assuming the formation of the grand coalition $N = \{1, \ldots, n\}$, each agent $i \in N$ should receive its average marginal contribution over all possible permutations of the agent groups. Let s and n, represent the cardinality of S and N, respectively. Then, the Shapley value of i under characteristic function v, denoted by $\Phi_i(v)$, is formally specified as $\Phi_i(v) = \sum_{S \subseteq N \setminus \{i\}} \frac{s!(n-s-1)!}{n!}(v(S \cup \{i\}) - v(S))$. For a game (N, v), the unique list of real-valued payoffs $x = (\Phi_1(v), \cdots, \Phi_n(v)) \in \mathbb{R}^n$ is called the Shapley allocation for the game. The Shapley allocation have been extensively studied in the game theory literature and satisfies various desired properties in multiagent practices. Moreover, it can be axiomatized using the following properties:

- *Efficiency (EFF):* the overall available utility $v(N)$ is allocated to the agents in N, i.e., $\sum_{i \in N} \Phi_i(v) = v(N)$;
- *Symmetry (SYM):* any arbitrary agents i and j that make the same contribution receive the same payoff, i.e., $\Phi_i(v) = \Phi_j(v)$;
- *Dummy Player (DUM):* any arbitrary agent i of which its marginal contribution to each group S is the same, receives the payoff that it can earn on its own, i.e., $\Phi_i(v) = v(\{i\})$;
- *Additivity (ADD):* for any two cooperative games (N, v) and (N, w), $\Phi_i(u + w) = \Phi_i(v) + \Phi_i(w)$ for all $i \in N$, where for all $S \subseteq N$, the characteristic function $v + w$ is defined as $(v + w)(S) = v(S) + w(S)$.

In the following, we refer to an allocation that satisfies these properties as a *fair* allocation.

Core and Stability: In core allocations, the focus is on the notion of *stability.* In brief, an allocation is stable if no agent (group) benefits by defecting the cooperation. Formally, for a game (N, v), any list of real-valued payoffs $x \in \mathbb{R}^n$ that satisfies the following conditions is a core allocation for the game:

- *Rationality (RAT):* $\forall S \subseteq N : \sum_{i \in S} x_i \geq v(S)$;
- *Efficiency (EFF):* $\sum_{i \in N} x_i = v(N)$.

One main question is whether for a given game, the core is non-empty (i.e., that there exists a stable allocation for the game). A game for which there exist a non-empty set of stable allocations should satisfy the *balancedness* property, defined as follows. Let $1_S \in \mathbb{R}^n$ be the membership vector of S, where $(1_S)_i = 1$ if $i \in S$ and $(1_S)_i = 0$ otherwise. Moreover, let $(\lambda_S)_{S \subseteq N}$ be a vector of weights $\lambda_S \in [0, 1]$. A vector $(\lambda_S)_{S \subseteq N}$ is a *balanced* vector if for all $i \in N$, we have that $\sum_{S \subseteq N} \lambda_S (1_S)_i = 1$. Finally, a game is *balanced* if for all balanced vectors of weights, we have that $\sum_{S \subseteq N} \lambda_S v(S) \leq v(N)$. According to the Bondereva-Shapley theorem, a game has a non-empty core if and only if it is balanced [20, 21]. In the following, we refer to an allocation that satisfies RAT and EFF as a *stable* allocation.

Marginal Contribution Nets (MC-Nets): Representing cooperative games by their characteristic functions (i.e., specifying values $v(S)$ for all the possible coalitions $S \subseteq N$) may become unfeasible in large-scale applications. In this work, as we are aiming to implement ISNs in a scalable manner, we employ a *basic MC-Net* [18] representation that uses a set of rules to specify the value of possible agent coalitions. Moreover, attempting to capture the regulatory aspect of ISNs makes employing rule-based game representations a natural approach. A basic MC-Net represents the cooperative game among agents in N as a finite set of rules $\{\rho_i : (\mathcal{P}_i, \mathcal{N}_i) \mapsto v_i\}_{i \in K}$, where $\mathcal{P}_i \subseteq N$, $\mathcal{N}_i \subset N$, $\mathcal{P}_i \cap \mathcal{N}_i = \emptyset$, $v_i \in \mathbb{R} \setminus \{0\}$, and K is the set of rule indices. For an agent coalition $S \subseteq N$, a rule ρ_i is *applicable* if $\mathcal{P}_i \subseteq S$ and $\mathcal{N}_i \cap S = \emptyset$ (i.e., S contains all the agents in $\mathcal{P}_i$ and no agent in $\mathcal{N}_i$). Let $\Pi(S)$ denote the set of rule indices that are applicable to S. Then the value of S, denoted by $v(S)$, will be equal to $\sum_{i \in \Pi(S)} v_i$. In further sections, we present an MC-Net representation of the ijk ISN scenario and show how this rule-based representation enables applying norm-based coordination to ISNs.

4. ISN Games

As discussed in [7, 17], the total obtainable cost reduction—as the economic benefit—and its allocation among involved firms are key drivers behind the stability of ISNs. For any set of industrial agents S, this total value can be computed based on the total *traditional* cost, denoted by $T(S)$, and the total ISN *operational* cost, denoted by $O(S)$. In brief, $T(S)$ is the summation of all the costs that firms have to pay in case the ISN does not occur (i.e., to discharge wastes and to purchase traditional primary inputs). On the other hand, $O(S)$ is the summation of costs that firms have to pay collectively in case the ISN is realized (i.e., the costs for recycling and treatment, for transporting resources among firms, and finally the transaction costs). Accordingly, for a non-empty finite set of industrial agents S the obtainable symbiotic value $v(S)$ is equal to $T(S) - O(S)$. In this work, we assume a potential ISN, with a positive total obtainable value, and aim for tailoring game-theoretic value allocation and accordingly coordination mechanisms that guarantee a fair and stable implementation of the symbiosis.

Our ijk ISN scenario can be modeled as a cooperative game in which $v(S)$ for any empty/singleton S is 0 and agent groups ij, ik, jk, and ijk have the values 4, 5, 4, and 6, respectively. Note that as the focus of ISNs are on the benefit values obtainable due to potential cost reductions, all the empty and singleton agent groups have a zero value because cost reduction is meaningless in such cases. In the game theory language, the payoffs in ISN games are normalized. Moreover, the game is superadditive in nature.[3] So, given the traditional

[3]Superadditivity implies that forming a symbiotic coalition of industrial agents either results in no value or in a positive value. Implicitly, growth of a group can never result in decrease of the value.

and operational cost values for all the possible agent groups S (i.e., $T(S)$ and $O(S)$) in the non-empty finite set of industrial agents N, the ISN among agents in N can be formally modeled as follows.

Definition 1 (ISN Games). *Let N be a non-empty finite set of industrial agents. Moreover, for any agent group $S \subseteq N$, let $T(S)$ and $O(S)$ respectively denote the total traditional and operational costs for S. We say the ISN among industrial agents in N is a normalized superadditive cooperative game (N, v) where $v(S)$ is 0 if $|S| \leq 1$ and equal to $T(S) - O(S)$ otherwise.*

According to the following proposition, basic MC-Nets can be used to represent ISNs. MC-Net representations aid combining ISN games with normative coordination rules.

Proposition 1 (ISNs as MC-Nets). *Any ISN can be represented as a basic MC-Net.*

Proof. To prove, we do not rely on the expressivity of MC-Nets but provide a constructive proof that respects the context of industrial symbiosis. See [14] for the complete proof. □

Example 1. Our running example can be represented by the basic MC-Net[4] $\{\rho_1 : (ij, k) \mapsto 4, \rho_2 : (ik, j) \mapsto 5, \rho_3 : (jk, i) \mapsto 4, \rho_4 : (ijk, \emptyset) \mapsto 6\}$.

As discussed earlier, how firms share the obtainable ISN benefits plays a key role in the process of ISN implementation, mainly due to stability and fairness concerns. Industrial firms are economically rational entities that defect non-beneficial relations (instability) and mostly tend to reject ISN proposals in which benefits are not shared with respect to their contribution (unfairness). In this work, we focus on Core and Shapley allocation mechanisms as two standard methods that characterize stability and fairness in cooperative games, receptively. We show that these concepts are applicable in a specific class of ISNs but are not generally scalable for value allocation in the implementation phase of ISNs. This motivates introducing incentive mechanisms to guarantee the implementability of "desired" ISNs.

Two-Person Industrial Symbiosis Games: When the game is between two industrial firms (i.e., a bilateral relation between a resource receiver/provider couple), it has additional properties that result in applicability of both Core and Shapley allocations. We denote the class of such ISN games by ISN_Λ. This is, $\mathsf{ISN}_\Lambda = \{(N, v) : (N, v)$ is an ISN game and $|N| = 2\}$. Moreover, the ISN games in which three or more agents are involved will form ISN_Δ. The class of ISN_Λ games corresponds to the so called ISR games in [17]. The difference is on the value allocation perspective as in [17], they assume the elimination of traditional costs (thanks to implementation of the symbiotic relation) and focus on the allocation of operational costs; while we focus on the allocation of the total benefit, obtainable due to potential cost reductions.

Lemma 1 (ISN_Λ Balancedness). *Let (N, v) be an arbitrary ISN_Λ game. It always holds that (N, v) is balanced.*

Proof. See [14] for the complete proof. □

[4] For notational simplicity, we avoid brackets around agent groups, e.g., we write ij instead of $\{i, j\}$.

Relying on Lemma 1, we have the following result that focuses on the class of ISN_Λ relations and shows the applicability of two standard game-theoretic solution concepts for implementing fair and stable industrial symbiotic networks.

Theorem 1. *Let (N, v) be an arbitrary ISN_Λ game. The symbiotic relation among industrial agents in N is implementable in a unique stable and fair manner.*

Proof. See [14] for the complete proof. □

ISN Games: Here, we focus on ISN_Δ games as the class of ISN games with three or more participants and discuss the applicability of the two above mentioned allocation mechanisms for implementing such industrial games.

Example 2. Recall the ijk ISN_Δ scenario from Section 2. To have a stable allocation (x_i, x_j, x_k) in the core, the EFF condition implies $x_i + x_j + x_k = 6$ while the RAT condition implies $x_i+x_j \geq 4 \wedge x_i+x_k \geq 5 \wedge x_j+x_k \geq 4$. As these conditions cannot be satisfied simultaneously, we can conclude that the core is empty and there exists no way to implement this ISN in a stable manner. Moreover, although the Shapley allocation provides a fair allocation $(13/6, 10/6, 13/6)$, it is not rational for firms to implement the ISN. E.g., i and k obtain $30/6$ in case they defect while according to the Shapley allocation, they ought to sacrifice as they collectively have $26/6$.

As illustrated in this example, the Core of ISN_Δ games may be empty which implies the inapplicability of this solution concept as a general method for implementing ISNs.

Theorem 2. *Let (N, v) be an arbitrary ISN_Δ game. The symbiotic relation among industrial agents in N is not generally implementable in a stable manner.*

Proof. See [14] for the complete proof. □

Note that the fair implementation of ISN_Δ games is not always in compliance with the rationality condition. This theorem—in accordance with the intuition presented in example 2—shows that we lack general methods that guarantee stability and fairness of ISN implementations. So, even if an industrial symbiotic practice could result in *collective* economic and environmental benefits, it may not last due to instable or unfair implementations. One natural response which is in-line with realistic ISN practices is to employ monetary incentives as a means of coordination.

5. Coordinated ISN

In realistic ISNs, the symbiotic practice takes place in the presence of economic, social, and environmental *policies* and under *regulations* that aim to enforce the policies by nudging the behavior of agents towards desired ones. In other words, while the policies generally indicate whether an ISN is “good (bad, or neutral)", the regulations are a set of norms that—in case of agents’ compliance—result in a spectrum of acceptable (collective) behaviors. Note that the acceptability, i.e., goodness, is evaluated and ought to be verified from the point of view of the policy-makers as community representatives. In this section, we follow this normative approach and aim at using normative coordination to guarantee the implementability of desirable ISNs in a stable and fair manner[5].

Normative Coordination of ISNs: Following [10, 11], we see that during the process of ISN implementation as a game, norms can be employed as game transformations, i.e., as "ways of transforming existing games in order to bring about outcomes that are more desirable from a welfaristic point of view"[11]. For this account, given the economic, environmental, and social dimensions and with respect to potential socio-economic consequences, industrial symbiotic networks can be partitioned in three classes, namely *promoted*, *permitted*, and *prohibited* ISNs. Such a classification can be modeled by a normative socio-economic policy function $\wp : 2^N \mapsto \{p^+, p^\circ, p^-\}$, where N is the finite set of industrial firms. Moreover, p^+, p°, and p^- are labels—assigned by a third-party authority—indicating that the ISN among any given agent group is either promoted, permitted, or prohibited, respectively. The three sets $P^+_\wp$, $P^\circ_\wp$, and $P^-_\wp$ consist of all the $\wp$-promoted, -permitted, and -prohibited agent groups, respectively. Formally $P^+_\wp = \{S \subseteq N : \wp(S) = p^+\}$ ($P^\circ_\wp$ and $P^-_\wp$ can be formulated analogously). Note that $\wp$ is independent of the ISN game among agents in S, its economic figures, and corresponding cost values—in general, it is independent of the value function of the game. E.g., a symbiotic relation may be labeled with p^- by policy $\wp$—as it is focused on exchanging a hazardous waste—even if it results in a high level of obtainable benefit.

Example 3. In our ijk ISN scenario, imagine a policy $\wp_1$ that assigns p^- to all the singleton and two-member groups (e.g., because they discharge hazardous wastes in case they operate in one- or two-member groups) and p^+ to the grand coalition (e.g., because in that case they have zero waste discharge). So, according to $\wp_1$, the ISN among all the three agents is "desirable" while other possible coalitions lead to "undesirable" ISNs.

As illustrated in Example 3, any socio-economic policy function merely indicates the desirability of a potential ISN among a given group of agents and is silent with respect to methods for *enforcing* the implementability of promoted or unimplementability of prohibited ISNs. Note that ISN_Λ games are always implementable. So, ISNs' implementability refers to the general class of ISN games including ISN_Δ games.

The rationale behind introducing socio-economic policies for ISNs is to make sure that promoted ISNs are implementable in a fair and stable manner while prohibited ones are instable. In real ISN practices, the regulatory agent (i.e., the regional or national government) introduces regulations—to support the policy—in the form of monetary incentives[6]. This is to ascribe subsidies to promoted and taxes to prohibited collaborations (see [24] for an implementation theory approach on mechanisms that employ monetary incentives to achieve desirable resource allocations). We follow this practice and employ a set of rules to ensure/avoid the implementability of desired/undesired ISNs among industrial agents in N via allocating incentives. Incentive rules can be represented by an MC-Net $\Re = \{\rho_i : (\mathcal{P}_i, \mathcal{N}_i) \mapsto \iota_i\}_{i \in K}$ in which K is the set of rule indices. Let $\Im(S)$ denote the set of rule indices that are applicable to $S \subseteq N$. Then, the incentive value for S, denoted by $\iota(S)$, is defined as $\sum_{i \in \Im(S)} \iota_i$. This is, a set of incentive rules

[5]In the following, we simply say *implementability* of ISNs instead of *implementability in a fair and stable* manner.
[6]See [22, 23] for similar approaches on incentivizing cooperative agent systems.

can be represented also as a cooperative game $\Re = (N, \iota)$ among agents in N. In the following proposition, we show that for any ISN game there exists a set of incentive rules to guarantee the implementability of the ISN in question.

Proposition 2 (Implementability Ensuring Rules). *Let G be an arbitrary* ISN *game among industrial agents in N. There exists a set of incentive rules to guarantee the implementability of G.*

Proof. Recall that according to Proposition 1, G can be represented as an MC-Net. To prove the claim, we provide Algorithm 1 that takes the MC-Net representation of G as the input and generates a set of rules that guarantee the implementability of G.

Algorithm 1 Generating rule set $\Re$ for ISN game G.

Data: ISN game $G = \{\rho_i : (\mathcal{P}_i, \mathcal{N}_i) \mapsto v_i\}_{i \in K}$ among agents in N; K the set of rule indices for G.
Result: Incentive rule set $\Re$ for G.
$n \leftarrow length(K)$ and $\Re = \{\}$
for $i \leftarrow 1$ **to** n **do**
    if $i \in \Pi(N)$ **then**
        $\Re \leftarrow \Re \cup \{\rho_i : (\mathcal{P}_i, \mathcal{N}_i) \mapsto 0\}$
    else
        $\Re \leftarrow \Re \cup \{\rho_i : (\mathcal{P}_i, \mathcal{N}_i) \mapsto -v_i\}$
    end if
end for

By allocating $-v_i$ to rules that are not applicable to N, any coalition other than the grand coalition will be faced with a tax value. As the original game is superadditive, the agents will have a rational incentive to cooperate in N and the ISN is implementable in a stable manner thanks to the provided incentive rules. □

Till now, we introduced socio-economic policies and regulations as required (but not yet integrated) elements for modeling coordinated ISNs. In the following section, we combine the idea behind incentive regulations and normative socio-economic policies to introduce the concept of *Coordinated* ISN*s* ($\mathcal{C}-$ISNs) as a multiagent system for implementing industrial symbiosis.

Coordinated ISNs: As discussed above, ISN games can be combined with a set of regulatory rules that allocate incentives to agent groups (in the form of subsidies and taxes). We call this class of games, ISNs in presence of coordination mechanisms, or *Coordinated* ISN*s* ($\mathcal{C}-$ISNs) in brief.

Definition 2 (Coordinated ISN Games ($\mathcal{C}-$ISN)). *Let G be an* ISN *and $\Re$ be a set of regulatory incentive rules, both as MC-Nets among industrial agents in N. Moreover, for each agent group $S \subseteq N$, let $v(S)$ and $\iota(S)$ denote the value of S in G and the incentive value of S in $\Re$, respectively. We say the Coordinated* ISN *Game ($\mathcal{C}-$ISN) among industrial agents in N is a cooperative game (N, c) where for each agent group S, we have that $c(S) = v(S) + \iota(S)$.*

Note that as both the ISN game G and the set of regulatory incentive rules $\Re$ are MC-Nets among industrial agents in N, then for each agent group $S \subseteq N$ we have that $c(S)$ is equal to the summation of all the applicable rules to S in both G and $\Re$. Formally, $c(S) = \sum_{i \in \Pi(S)} v_i + \sum_{j \in \Im(S)} \iota_j$ where $\Pi(S)$ and $\Im(S)$ denote the set of applicable rules to S in G and $\Re$, respectively. Moreover, v_i and ι_j denote the value of applicable rules i and j in $\Pi(S)$ and $\Im(S)$, respectively. We sometime use $G+\Re$ to denote the game C as the result of incentivizing G with $\Re$. The next result shows the role of regulatory rules in the enforcement of socio-economic policies.

Proposition 3 (Policy Enforcing Rules). *For any promoted* ISN *game G under policy $\wp$, there exist an implementable $\mathcal{C}-$*ISN *game C.*

Proof. See [14] for the complete proof. □

Analogously, similar properties hold for *avoiding* prohibited ISNs or *allowing* permitted ones. Avoiding prohibited ISNs can be achieved by making the $\mathcal{C}-$ISN (that results from introducing regulatory incentives) unimplementable. On the other hand, allowing permitted ISNs would be simply the result of adding an empty set of regulatory rules. The presented approach for incentivizing ISNs, is advisable when the policy-maker is aiming to ensure the implementability of a promoted ISN in an ad-hoc way. In other words, an $\Re$ that ensures the implementability of a promoted ISN G_1 may ruin the implementability of another promoted ISN G_2. This highlights the importance of some structural properties for socio-economic policies that aim to foster the implementability of desired ISNs. As we discussed in Section 2, we aim for implementing ISNs such that the rationality axiom will be respected. In the following, we focus on the subtleties of socio-economic policies that are enforced by regulatory rules. The question is, what are the requirements of a policy that can ensure the rationality of staying in desired ISNs? We first show that to respect the rationality axiom, promoted agent groups should be disjoint. We illustrate that in case the policy-maker takes this condition into account, industrial agents have no economic incentive to defect an implementable promoted ISN.

Proposition 4. *Let G_1 and G_2 be arbitrary* ISN*s, respectively among promoted (nonempty) agent groups S_1 and S_2 under policy $\wp$ (i.e., $S_1, S_2 \in P^+_\wp$). Moreover, let $\Re_1$ and $\Re_2$ be rule sets that ensure the implementability of G_1 and G_2, respectively. For $i \in \{1, 2\}$, defecting from $\mathcal{C}-$*ISN *$C_i = G_i + \Re_i$ is not economically rational for any agent $a \in S_i$ iff $S_1 \cap S_2 = \emptyset$.*

Proof. See [14] for the complete proof. □

Accordingly, given a set of industrial agents in N and a socio-economic policy $\wp$ we directly have that:

Proposition 5. *For $n = |P^+_\wp|$ if $\bigcap_{i=1}^{n} S_i \in P^+_\wp = \emptyset$ then any arbitrary $S_i \in P^+_\wp$ is minimal (i.e., $S'_i \notin P^+_\wp$ for any $S'_i \subset S_i$).*

Roughly speaking, the exclusivity condition for promoted agent groups entails that any agent is in at most one promoted group. Hence, deviation of agents does not lead to a larger promoted group as no promoted group is part of a promoted super-group, or contains a promoted sub-group. In the following, we show that the mutual exclusivity condition is sufficient for ensuring the implementability of all the ISNs that take place among promoted groups of firms.

Theorem 3. *Let G be an arbitrary* ISN_Δ *game under policy $\wp$ among industrial agents in N and n be the cardinality of $P^+_\wp$. If $\bigcap_{i=1}^{n} S_i \in P^+_\wp = \emptyset$, then there exists a set of regulatory rules $\Re$, such that all the promoted symbiotic networks are implementable in the coordinated* ISN *defined by $C = G + \Re$. Moreover, any* ISN *among prohibited agent groups in $P^-_\wp$ will be unimplementable.*

Proof. To prove, we provide a method to generate such an implementability ensuring set of rules. We start with an empty $\Re$. Then for all n promoted $S_i \in P^+_\wp$, we call Algorithm 1. Each single run of this algorithm results in a $\Re_i$ that guarantees the implementability of the industrial symbiosis among the set of firms in the promoted group S_i. As the set of promoted agent groups comply to the mutual exclusivity condition, the unification of all the regulatory rules results in a general $\Re$. Formally, $\Re = \bigcup_{i=1}^{n} \Re_i$. Moreover, as the algorithm applies taxation on non-promoted groups, no ISN among prohibited agent groups will be implementable. □

Example 4. Recalling the ISN scenario in Example 3, the only promoted group is the grand coalition while other possible agent groups are prohibited. To ensure the implementability of the unique promoted group and to avoid the implementability of other groups, the result of executing our algorithm is $\Re = \{\rho_1 : (ij, k) \mapsto -4, \rho_2 : (ik, j) \mapsto -5, \rho_3 : (jk, i) \mapsto -4\}$. In the $\mathcal{C}-$ISN that results from adding $\Re$ to the original ISN, industrial symbiosis among firms in the promoted group is implementable while all the prohibited groups cannot implement a stable symbiosis.

Realized ISNs and Budget-Balancedness: As we mentioned in the beginning of Section 5, regulations are norms that in case of agents' compliance bring about the desired behavior. For instance, in Example 4, although according to the provided tax-based rules, defecting the grand coalition is not economically rational, it is probable that agents act irrationally—e.g., due to trust-/reputation-related issues—and go out of the promoted group. This results in possible normative behavior of a $\mathcal{C}-$ISN with respect to an established policy $\wp$. So, assuming that based on evidences the set of implemented ISNs are realizable, we have the following abstract definition of $\mathcal{C}-$ISN's normative behavior under a socio-economic policy.

Definition 3 ($\mathcal{C}-$ISN's Normative Behavior). *Let C be a $\mathcal{C}-$*ISN *among industrial agents in N under policy $\wp$ and let E be the evidence set that includes all the implemented* ISN*s among agents in N. We say the behavior of C complies to $\wp$ according to E iff $E = P^+_\wp$; and violates it otherwise.*

Given an ISN under a policy, we introduced a set of regulatory rules to ensure that all the promoted ISNs will be implementable. However, although providing incentives makes them implementable, the autonomy of industrial agents may result in situations that not all the promoted agent groups implement their ISN. So, although we can ensure the implementability of all the promoted ISNs, the real behavior may deviate from a desired one. As our introduced method for guaranteeing the implementability of ISNs among promoted agent groups is mainly tax-based, if a $\mathcal{C}-$ISN violates the policy, we end up with collectible tax values. In such cases, our tax-based method can become a *balanced-budget* monetary incentive mechanism (as discussed in [25, 26, 27]) by employing a form of "Robin-Hood" principle and redistributing the collected amount among promoted agent groups that implemented their ISN. In the following, we provide an algorithm that guarantees budget-balancedness by means of a Shapley-based redistribution of the collectible tax value among agents that implemented promoted ISNs. We establish the correctness of Algorithm 2 in Proposition 6.

Algorithm 2 Tax Redistribution for $\mathcal{C}-$ISN game C.

Data: $C = G + \Re$ the $\mathcal{C}-$ISN game among industrial agents in N under policy $\wp$ such that all the ISNs among promoted groups in $P^+_\wp$ are implementable; E the set of implemented ISNs; The collectible tax value τ.
Result: $\Omega_i(C, \wp)$ the distributable incentive value to $i \in N$.
$S^+ \leftarrow E \cap P^+_\wp$, $S^+_u \leftarrow \bigcup_{S \in S^+} S$
for all $i \in (S^+_u, v)$ the sub-game of G **do**
  $k \leftarrow \Phi_i(v)$ the Shapley value of i in (S^+_u, v)
  $\Omega_i(C, \wp) = (1/v(S^+_u)).\tau.k$
end for

We establish the correctness of Algorithm 2 in Proposition 6.

Proposition 6. *Let $C = G + \Re$ be a $\mathcal{C}-$ISN among industrial agents in N under policy $\wp$ such that all the ISNs among promoted groups are implementable (using the provided method in Theorem 3) and let E be the set of implemented ISNs. For any $\mathcal{C}-$ISN, the incentive values returned by Algorithm 2 ensures budget balancedness while preserving fairness (i.e., EFF, SYM, DUM, and ADD).*

Proof. See [14] for the complete proof. □

Note that the redistribution phase takes place after the implementation of the ISNs and with respect to the evidence set E. Otherwise, there will be cases in which the redistribution process provides incentives for agent groups to defect the set of promoted collaborations. Moreover, we highlight that the use of an MC-net enables calculating the Shapley value in a scalable manner (see [18] for complexity results).

6. Conclusions and Future Work

This paper provides a coordinated multiagent system—rooted in cooperative game theory—for implementing ISNs that take place under a socio-economic policy. The use of MC-Nets enables combining the game with the set of policies and regulations in a natural way. The paper also provides algorithms that generate regulatory rules to ensure the implementability of "good" symbiotic collaborations in the eye of the policy-maker. This extends previous work that merely focused on operational aspects of industrial symbiotic relations–as we introduce the analytical study of the regulatory aspect of ISNs. Finally, it introduces a method for redistribution of collectible tax values. The presented method ensures the budget-balancedness of the monetary incentive mechanism for coordination of ISNs in the implementation phase.

In practice, such a framework supports decision-makers in the ISN implementation phase by providing operational tools for reasoning about the implementability of a given ISN in a fair and stable manner. Moreover, it supports policy-makers aiming to foster socio-economically desirable ISNs by providing algorithms that generate the required regulatory rules.

This paper focuses on a unique socio-economic policy and a set of rules to ensure it. One question that deserves investigation is the possibility of having multiple policies and thus analytical tools for policy option analysis (e.g., using [28, 29]) in ISNs. Such a framework assists ranking and investigating the applicability of a set of policies in a particular ISN scenario.

We also aim to focus on the administration of ISNs. Then, modeling the compliance of involved agents to their commitments and capturing trust dynamics [30, 31] will be the main concerns for automated trading in industrial symbiosis systems. For that, we plan to model ISNs as normative organizations [32, 33] and investigate how responsibility reasoning and norm-aware coordination [34, 35, 36] can ensure the robustness and reliability of such organizations.

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