H2020 – SPIRE-06-2015

Energy and resources management systems for improved efficiency in the process industries

Title: Secure Management Platform for Shared Process Resources

Acronym: SHAREBOX

Grant Agreement No: 680843

SHAREBOX
SECURE SHARING

Deliverable 3.10	One (conference and ISI-journal) article with the results of ABM-based IS network design.
Associated WP	WP3
Associated Tasks	Tasks 3.2 and 3.3
Due Date	M36
Date Delivered	June 2018
Prepared by (Lead Partner)	UT
Partners involved	UT
Authors	Vahid Yazdanpanah, Devrim Murat Yazan, Henk Zijm (UT)
Dissemination Level	

Table of contents

Introduction

The research contributions presented in this document focus on (1) allocation of operational costs among firms involved in Industrial Symbiotic Relations (ISRs) and (2) incentive allocation to enable fair and stable implementation of Industrial Symbiotic Networks (ISNs). We model such relations as cooperative games and show the implementability in (one-to-one) ISRs. Then, for (many-to-many) ISNs, we show the cases in which monetary incentives are required and provide a practical multi-agent framework for incentive allocations—that guarantee the implementability of ISNs in a fair and stable manner.

The papers that address these issues and in general, our approach for modeling ISRs and implementing ISNs are:

1. Yazdanpanah, V., & Yazan, D.M. Industrial Symbiotic Relations as Cooperative Games. In Proceedings of the 7th International Conference on Industrial Engineering and Systems Management (IESM-2017), 11-13 October 2017, Saarbrucken (Germany) [to be submitted to *International Journal of Production Research*].
2. Yazdanpanah, V., Yazan, D.M., & Zijm H. Industrial Symbiotic Networks and Coordinated Games. In Proceedings of the the 17th International Conference on Autonomous Agents and MultiAgent Systems (AAMAS-2018), 10-15 July 2018, Stockholm (Sweden) [to be submitted to *International Journal of Computational Intelligence*].

In the first paper, we introduce a game-theoretical formulation for Industrial Symbiotic Relation (ISRs) and provide a formal framework to model, verify, and support collaboration decisions in this new class of two-person operational games. ISR games are formalized as cooperative cost-allocation games with the aim to allocate the total ISR-related operational cost to involved industrial firms in a fair and stable manner—by taking into account their contribution to the total traditional ISR-related cost. We tailor two types of allocation mechanisms using which firms can implement cost allocations that result in a collaboration that satisfies the fairness and stability properties. Moreover, while industries receive a particular ISR proposal, our introduced methodology is applicable as a managerial decision support to systematically verify the quality of the ISR in question.

In the second paper, we present an approach for implementing a specific form of collaborative industrial practices—called Industrial Symbiotic Networks (ISNs)—as MC-Net cooperative games and address the so called ISN implementation problem. This is, the characteristics of ISNs may lead to inapplicability of fair and stable benefit allocation methods even if the collaboration is a collectively desired one. Inspired by realistic ISN scenarios and the literature on normative multi-agent systems, we consider regulations and normative socioeconomic policies as two elements that in combination with ISN games resolve the situation and result in the concept of coordinated ISNs.

Industrial Symbiotic Relations as Cooperative Games

Vahid Yazdanpanah and Devrim Murat Yazan
University of Twente, Drienerlolaan 5, 7522 NB, Enschede, The Netherlands.
Email: {v.yazdanpanah,d.m.yazan}@utwente.nl

Proceedings of the 7th International Conference on Industrial Engineering and Systems Management (IESM-2017)

October 11-13, 2017 - Saarbrucken, Germany

Industrial Symbiotic Relations as Cooperative Games

(Presented at the 7^{th} IESM Conference, October 11–13, 2017, Saarbrücken, Germany)

Vahid Yazdanpanah and Devrim Murat Yazan
University of Twente, Drienerlolaan 5, 7522 NB, Enschede, The Netherlands.
Email: {v.yazdanpanah,d.m.yazan}@utwente.nl

***Abstract*—In this paper, we introduce a game-theoretical formulation for a specific form of collaborative industrial relations called "Industrial Symbiotic Relation (ISR) games" and provide a formal framework to model, verify, and support collaboration decisions in this new class of two-person operational games. ISR games are formalized as cooperative cost-allocation games with the aim to allocate the total ISR-related operational cost to involved industrial firms in a fair and stable manner by taking into account their contribution to the total traditional ISR-related cost. We tailor two types of allocation mechanisms using which firms can implement cost allocations that result in a collaboration that satisfies the fairness and stability properties. Moreover, while industries receive a particular ISR proposal, our introduced methodology is applicable as a managerial decision support to systematically verify the quality of the ISR in question. This is achievable by analyzing if the implemented allocation mechanism is a stable/fair allocation.**

I. Introduction

The multi-dimensional concept of *Industrial Symbiosis* focuses on analysis, design, and operation of collaborative relations between traditionally disjoint industrial enterprises with the aim of keeping reusable resources, e.g., recyclable material or waste energy, in their (loosely connected) value chains [1–3]. As *Industrial Symbiotic Relations* (ISRs) aim at the lowest possible discharge of resources, they can be considered as a tool for implementing the concept of *circular economy* [4] in the context of industrial relations. Moreover, ISRs are closely related to *Industry 4.0* paradigm and practice of *Collaborative Networked Organizations* as they all are concerned about the necessity for interrelation between traditionally disconnected industrial firms [5, 6]. Reviewing industrial symbiosis literature, we encounter recent contributions focused on different aspects of this concept. In [3], they present the concept of *perfect industrial symbiosis* and verify the quality of any given ISR by measuring its distance to such a perfect form. Introduced method in [7] focuses on efficiency measuring while [8] studies dynamics of profits in ISRs. Despite contributions that discuss static (multi-criteria) decision analysis in industrial symbiosis (see [9]), one aspect of ISRs that we believe requires more attention is *dynamic decision analysis*. In our view, while we shift from ISR in theory to ISR in practice, two missed elements are 1) applicable decision analysis methods and 2) practical decision support tools that are aware of dynamic operational aspects of ISRs, e.g., methods for analyzing and mechanisms for designing fair and stable collaborations. This asks for formal frameworks tailored to model, verify, and support such decisions (i.e., decision process modeling, decisions verification methods, and decision support tools). In a general view, decisions in ISRs can be categorized in two classes, *selection decisions* and *collaboration decisions*. The former is about choosing among firms and learning about potential ISRs (exploration) while the latter is about getting engaged in (or rejecting) a particular ISR proposal (exploitation). To deal with these two operational decision problems, the mature field of of cooperative game theory [10] and more specifically subfield of Operations Research (OR) games [11] provide vigorous analytical methods and design mechanisms.

In this work, we aim to fill the gap by tailoring analytical tools based on game-theoretical solution concepts to support the second form of decisions, i.e., collaboration decisions, in ISRs. For this purpose, we represent ISRs as market games and model them as cooperative cost-allocation games (see [12, 13]). Accordingly, the focus is on operational aspects of ISRs, analysis of collaboration decisions in ISRs, and tailoring cost-allocation mechanisms that respect the operation of ISRs. Note that in this work we analyze collaboration decisions in bilateral industrial symbiotic relations as the nuclear building blocks for various industrial symbiotic topologies, e.g., Industrial Symbiotic Networks (ISNs) [14].

The paper is structured as follows. In Section II we provide a conceptual analysis of ISRs from an operational point of view. Section III presents the game-theoretical preliminaries and our proposed class of ISR games. In Sections IV we introduce the two tailored solution concepts for allocation of costs in ISRs. Using these notions, firms can reason about stability and fairness of any given ISR. Finally, concluding remarks and future work directions are presented in Section V.

II. Conceptual Analysis

To discuss the intuition behind our proposed operational semantics for the game-theoretical formulation of Industrial Symbiotic Relations (ISRs) and to elaborate nuances of collaboration decisions in ISRs, we present the following running example. Imagine a glass manufacturer firm A and a ceramics manufacturer firm B. Firm A produces glass powder as its excess resource r that (after recycling) can be substituted with i, the primary input of B for its production processes (Figure 1).

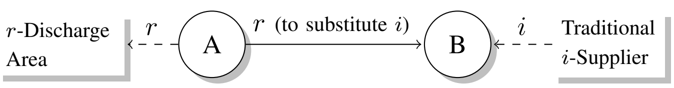

Fig. 1. Schematic industrial symbiotic relation between (glass manufacturer) firm A and (ceramics manufacturer) firm B on resource r (glass powder).

A. Collaboration Decision and Cost-Allocation

In our ISR example, having the potential to form a symbiotic relation over r may enable both A and B to reduce the costs affiliated with discharging excess r (7 units of util[1]) and purchasing i (11 units of util), respectively. However, establishing such a collaboration has its corresponding operational costs, e.g., costs of transportation and recycling (15 units of util). Intuitively, such an ISR would be feasible if total traditional costs in case of non-cooperation ($7 + 11$ utils) be more than total operational costs in case of cooperation (15 utils). Such a feasibility condition is necessary but not sufficient for firms to collaborate. One main question is about the method(s) to allocate the operational costs of collaboration such that the contribution of each party will be respected. Should both firms A and B equally pay (7.5 utils) or should firm B pay more as it is enjoying more cost reduction thanks to the collaboration? Although the collaboration may reduce the total cost, how to allocate the total cost of ISR operationalization will be at stake. This relates the practice of ISRs to the concept of *coopetition* [15] in which the players are interested in cooperation but also compete to gain as much as possible out of the benefits created by such a cooperation. Accordingly, studying if an ISR is a stable and fair relation calls for methods to analyze and mechanisms to guarantee its performance in the operationalization stage.

B. Dynamics of ISR-Related Costs

Following [16], we deem that economic profitability can be seen as the main driver for industries to get involved in a potential ISR (*collaboration decision*). In brief, for firms with the potential to establish an ISR, it is reasonable to compare the total cost of ISR-operationalization with their current ISR-related costs, e.g., excess-resource discharge costs. Note that we circumscribe our focus on costs that can be reduced or costs that will be introduced, in case of ISR materialization and not the costs that remain uninfluenced, e.g., costs related to processes that are independent of the ISR in question. In the following, we provide a brief cost analysis for firms on both sides of a potential ISR. This results in two classes of ISR-related *operational* and *traditional* costs. The former refers to costs involved in the process of ISR operationalization while the latter is about traditional costs that firms should take into account if they do not implement the ISR.

In our example, firm B should traditionally purchase i from its i-supplier(s) and firm A has to pay the cost of discharging r. We call the former, *traditional purchasing cost* and the latter, *traditional discharge cost*. On the other hand, the three main ISR-related operational costs are *Treatment*, *Transportation*, and *Transaction* costs [17, 18]. *Treatment Cost*: When a resource based on which an ISR can be established, e.g., glass powder, is out of a production process, it needs to be treated. Depending on the resource type, treatment processes may include sorting, dismantling, liquefaction, etc. [19, 20]. Based on the set of treatment processes required to make the resource usable for the resource-receiver side of an ISR, the implementation of waste treatment facility may change. In general, the treatment process results in a total treatment cost for any particular ISR. *Transportation Cost*: Resource transportation can be done via land vehicles, sea freights, or even combined transportation modes (see [21]) with respect to the resource type and geographical boundaries. Moreover, potential partners may decide to invest in implementation of new infrastructures, e.g., a pipeline system, and paying the investment cost for this. In this work, we abstract from such subtleties in decision-making for the mode of transportation and assume a standard total transportation cost for a given ISR. *Transaction Cost*: The role of transaction costs in establishment of ISRs is studied in the industrial symbiosis literature, e.g., in [22, 23]. According to [24, 25], transaction costs include the costs of market research, contracting negotiations, coordination, and adapting to the use of non-traditional resources, e.g., wastes. As discussed, the former two operational costs are very much dependent on the resource type while the transaction cost merely depends on the administrative aspects of the ISR. As we are focused on industrial symbiotic relations (and not networks), we take into account a single value for transaction cost for a given ISR.

In this work, we consider the two classes of ISR-related operational and traditional costs as the main quantitative parameters for our game-theoretical formalization of ISRs. This is to tailor mechanisms for allocation of *ISR-related operational costs* based on the contribution of the involved firms to *ISR-related traditional costs*. For notational convenience, while discussing about a given industrial symbiotic relation σ between two arbitrary firms A and B, we denote the total σ-related traditional costs for the firm $i \in \{A, B\}$ with $T_i(\bar{\sigma})$ and refer to total σ-related operational costs as $T(\sigma)$. So, the aim is to allocate $T(\sigma)$ to both A and B in a stable and fair manner by taking into account $T_A(\bar{\sigma})$ and $T_B(\bar{\sigma})$. We later discuss about and distinguish between stability and fairness of cost-allocations in ISRs.

C. Game-Theoretical Cost-Allocation Mechanisms

As we discussed in Section II-A, allocation mechanisms can play a key role in the process of ISR operationalization since a fair allocation of operational costs can foster the collaboration. For developing such practical allocation mechanisms, cooperative game theory [10] and Operation Research (OR) games [11] provide theoretical solution concepts to allocate costs to involved players in market games. Notions such as *core of the game* and *Shapley value* guarantee desired properties such that it is reasonable for firms not to deviate from cooperation [10]. In the following, we briefly analyze properties of these two types of game-theoretical solution concepts as two notions that we aim to tailor for allocation of the total operational cost in ISRs.

We first discuss the concept of *core of the game* as the set of all cost-allocations that (1) allocate a cost to each player lower than their traditional cost and (2) guarantee that the total allocated cost is equal to the total operational cost. In our ISR example, the total ISR-related operational cost is 15 utils while firms A and B had to traditionally pay 7 and 11 utils, respectively. In this case, cooperation results in total cost reduction by 3 utils. However, cooperating will be rational for each player, only if they individually pay less than what they had to pay traditionally. When a cost-allocation mechanism satisfies this, it regards the so called *individual rationality (INR)* property [13]. On the other hand, the summation of allocated costs to players should be equal to the total operational cost. Mechanisms that satisfy this property, are called *efficient (EFF)* cost-allocations. The set

[1] A *util* can be any sort of transferable utility, e.g., say that each *util* is one thousand Euros.

of cost allocations that satisfy both INR and EFF form the *core of the game* [10]. The second game-theoretic notion for allocation of costs, is the concept of *Shapley value* [26] as the unique efficient (EFF) mechanism for allocation of a cost among players such that (1) symmetric players pay the same costs, (2) players that their presence in the cooperation results in no cost reduction (referred as dummy players) pay their traditional costs, and (3) if players get involved in another game, the total allocated costs to each player in these two games, can be simply added. These three properties respectively referred to *symmetry (SYM)*, *dummy/null player (DUM)*, and *additivity (ADD)* properties in the cooperative game theory literature [10]. Note that Shapley value is the unique mechanism that allocates a cost value to each player such that all EFF, SYM, DUM, and ADD are satisfied.

III. Industrial Symbiotic Relations as Games

Dynamics of costs and cost-saving values that result from collaboration in market games are often modeled by cooperative games with *Transferable Utility* (TU) games [10, 12]. Such games specify all the possible collaborative agent groups and represent the corresponding cost values. This formal representation enables reasoning about cost-saving as a quantitative outcome of cooperation among agents.

Definition 1 (Cooperative TU Games). [10] A cooperative cost-allocation game with transferable utility (a TU game) is a tuple (N, c) where $N = \{a_1, a_2, \ldots, a_n\}$ is the finite set of agents and $c : 2^N \mapsto \mathbb{R}_{\geq 0}$ is a characteristic cost function that associates a real number $c(S)$ with each subset $S \subseteq N$. By convention, we always assume that $c(\emptyset) = 0$.

In the following definition, we recall two properties that axiomatize the behavior of the cost function in response to structural relations between agent groups.

Definition 2 (Subadditive and Submodular Games). [10] Let $G = (N, c)$ be a cost-allocation TU game. We say G is *subadditive* iff $c(S) + c(T) \geq c(S \cup T)$ for all disjoint agent groups S and T in N (i.e., $S, T \subseteq N$ and $S \cap T = \emptyset$). Moreover, we say G is *submodular* iff $c(S) + c(T) \geq c(S \cup T) + c(S \cap T)$ for all agent groups S and T in N (i.e., $S, T \subseteq N$).

Roughly speaking, in *subadditive* games, agents have rational incentives to cooperate because the total cost will be higher in case of no-cooperation. In most applications, cost-allocation games are usually subadditive. Desirable properties of *submodular* games (also referred as *concave* games) will be elaborated while we focus on cost allocation mechanisms for TU games (in Section IV).

With respect to our scope of application, i.e., bilateral symbiotic relations between industrial agents, we focus on two-person TU games and formalize our Industrial Symbiotic Relation (ISR) games as such. Moreover, following our presented analysis in Section II-A about the feasibility of ISRs (in case they result in the reduction of the total cost), we assume subadditivity as it corresponds to the nature of our application context.

Definition 3 (ISR Games). Let σ be an ISR between firms A and B. Moreover, let $T(\sigma)$ and $T_i(\bar{\sigma})$ respectively represent the total σ-related operational cost and the total σ-related traditional costs for $i \in \{A, B\}$. We say σ-based ISR cost allocation game (ISR game σ) between firms A and B is a subadditive cooperative TU-game (N, c) where $N = \{A, B\}$, $c(N) = T(\sigma)$, $c(\emptyset) = 0$, and $c(\{i\}) = T_i(\bar{\sigma})$ for $i \in N$.

According to Definition 3, the cost function of ISR games characterizes industrial symbiotic relations by associating to each singleton group $\{i\}$[2], the total cost that they will face (individually) in case of no-cooperation. Moreover, it ascribes the total ISR-related operational cost to the two member group N as the amount that members of N have to pay (collectively) in case of cooperation. In addition, the assumed subadditivity of ISR games reflects the feasibility of ISRs, i.e., in ISR games we have that $T(\sigma) \leq \sum_{i \in N} T_i(\bar{\sigma})$. So, regardless of the mechanisms for the allocation of ISR-related operational costs, the total amount to be paid in case of cooperation is at most equal to the sum of the amounts to be paid individually. The following property shows that in general, ISR games are submodular regardless of their particular settings. We later discuss that such a property results in applicability of a large class of game-theoretical cost allocation mechanisms, i.e., mechanisms that are based on the concept of *core of the game*.

Proposition 1 (Submodularity of ISR Games). *Let σ be an arbitrary ISR game. It always holds that σ is submodular.*

Proof: According to Definition 2, a game is submodular iff the $c(S) + c(T) \geq c(S \cup T) + c(S \cap T)$ inequality holds for all possible agent groups S and T in N. In ISR games, by checking the validity of this inequality for all 6 possible combinations of agent groups (for S and T), the claim will be proved. For $S = \emptyset$, we have the following valid inequality $c(\emptyset) + c(T) \geq c(\emptyset \cup T = T) + c(\emptyset)$. For $S = N$, the inequality can be reformulated in the following form that always holds $c(N) + c(T) \geq c(N \cup T = N) + c(N \cap T = T)$. Finally, when S and T are equal to the only two possible disjoint groups, we have the following inequality $c(S) + c(T) \geq c(N) + c(\emptyset)$. This inequality always holds thanks to the subadditivity of ISR games. ∎

Note that *submodularity* is not a general property of *subadditive* cooperative games but holds for the class of ISR games. In the following, we recall our ISR scenario between the glass manufacturer firm A and the ceramics manufacturer firm B, and describe the game-theoretical formulation of this scenario.

Example 1 (ISR Scenario as a Game). In the ISR scenario from section II, we assume that the amount of recycled excess r in A completely substitutes the required amount of i in B. Hence, in case the firms operationalize this symbiotic relation, neither of the firms has to deal with associated traditional costs for discharging excess r and purchasing required i. This ISR scenario can be modeled as cooperative game $\sigma = (N, c)$ where $N = \{A, B\}$, $c(A) = 7$, $c(B) = 11$, $c(\emptyset) = 0$, and $c(N) = 15$. This game is both subadditive and submodular. To check subadditivity, we survey all possible couples of agent groups in N. The only two disjoint agent groups are $\{A\}$ and $\{B\}$ for which the cost of the union group

[2] In further references, whenever it is clear from the context that we are referring to a singleton group $\{i\} \subset N$, we use i instead of $\{i\}$.

(c($\{A, B\}$) $= c(N) = 15$) is lower than the summation of the individual costs ($c(\{A\}) + c(\{B\}) = 18$). Thus, the game σ is subadditive. For submodularity, we can rely on Proposition 1.

IV. Allocation Mechanisms and Decision Support

Having Industrial Symbiotic Relations (ISRs) modeled as cooperative games (ISR games), one decision that firms are faced with is either "to get engaged in" or "to reject" a potential ISR. This is mainly to determine the *collaboration decision* (as discussed in Section II-A). Following rational decision-making perspectives presented in [27, page. 210-211], we deem that to support the collaboration decision in ISRs, analyzing two key aspects of collaborations, namely *stability* and *fairness*, results in practical decision support tools for ISRs. In other words, "goodness" of a collaboration can be characterized and validated by checking if it is *stable*, *fair*, or both. In the following, we introduce two methods from game-theoretical literature that axiomatize the *stability* and *fairness* properties. These methods formulate both the stability and fairness of collaborations with respect to distribution of the value that agents can gain thanks to the collaboration. Accordingly, tailoring these mechanisms for ISR games leads to tools for supporting the *collaboration decision* in industrial symbiotic relations. In this case, the way that industrial agents allocate the total ISR-related operational cost specifies the stability and fairness of the ISR.

A. Core Allocations for ISR Games

Core-based mechanisms in cooperative games are mainly concerned about *stability* of possible collaborations [10]. In relation to cost allocation in games, a collaboration is stable iff (1) the summation of allocated costs to individual agents in a collaborative group is equal to the total cost that the group should pay (efficiency) and (2) the allocated costs to individuals is at most equal to their costs in case they defect from the collaborative group (rationality). It is observable that if the agent groups follow a cost allocation method that does not satisfy the two above properties, they end in an *unstable* situation either due to inefficient distribution of costs or as the result of (rational) agents leaving the group. In the following, we define our core-based cost allocation mechanism for ISR games and describe its properties.

Definition 4 (Core Allocations for ISRs). Let σ be an ISR game (as defined in Definition 3) between firms A and B. The core of σ is the set $\Psi(\sigma) := \{\langle T_A^\Psi(\sigma), T_B^\Psi(\sigma)\rangle\}$ such that for $i \in \{A, B\}$ we have that (1) $T_i^\Psi(\sigma) \in \mathbb{R}_{\geq 0}$ (non-negative valued), (2) $\sum_{i\in\{A,B\}} T_i^\Psi(\sigma) = T(\sigma)$ (efficient), and (3) $T_i^\Psi(\sigma) \leq T_i(\bar{\sigma})$ (individually rational).

Following the discussion about stability of collaborations, an ISR σ is stable with respect to the allocation of its operationalization costs, if it implements a cost allocation that belongs to the core of σ. Thus, the presented core allocation for ISRs can be applied as (1) a mechanism for guaranteeing the stability of an ISR (ISR design) and (2) as a verification method to analyze if an ISR is stable (ISR assessment). The set of core allocations for a given ISR, construct a segment representable in two-dimensional space (see Figure 2). Due to the linear formulation of ISRs' core, computing the set of stable allocations is not computationally expensive and can be computed applying linear programming techniques to solve a two-variable system of inequalities [28].

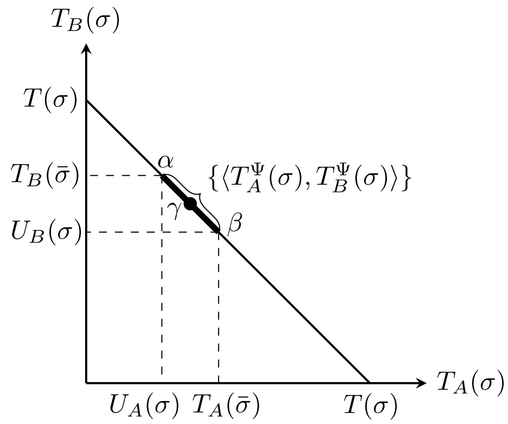

Fig. 2. Schematic core and Shapley allocations for ISR game σ: In this diagram, allocated costs to firms A and B are illustrated on the horizontal and vertical axes, respectively. Moreover, $U_A(\sigma) = T(\sigma) - T_B(\bar{\sigma})$, $U_B(\sigma) = T(\sigma) - T_A(\bar{\sigma})$, and γ represents the Shapley allocation of the game $\Phi(\sigma)$.

Two main concerns with respect to applicability of the concept of *core* are about its *existence* and *fairness*. In other words, is the set of core allocations a nonempty one and does it always provide a fair distribution of costs among involved firms in an ISR game? In the following, we first illustrate that ISR games have a nonempty core and core allocations cannot guarantee the fairness property. This motivates the introduction of a fair cost allocation mechanism, i.e., a Shapley-based allocation mechanism for ISR games.

Proposition 2 (Existence Property of Core of ISR Games). *Let $\Psi(\sigma)$ be the core of ISR game σ between firms A and B. It always holds that $\Psi(\sigma) \neq \emptyset$.*

Proof: According to the *Bondareva-Shapley* theorem (as described in [10]), submodular games have a nonempty core. We already proved in Proposition 1 that ISR games are submodular. Hence, we have that for any ISR game σ, the core is not empty. ■

Note that the concept of *core of the game*, provides a set of allocations that guarantee the stability of the collaboration. Having a range of stable cost distributions is appropriate for ISR scenarios in which firms are allowed to practice their bargaining power (see [29]) in the negotiation process in order to pay the smallest possible share of the ISR-related operational costs. E.g., as illustrated in Figure 2, the most desirable (albeit stable) allocation form for firms A and B occurs in points α and β, respectively. For instance in α, firm A enjoys paying the lowest stable share of the total ISR-related operational cost while B is paying the highest. In this case, B suffers because of this intuitively unfair allocation and pays equal to its total traditional cost. This shows that the concept of core provides a method to verify the stability of an ISR and can be applied as a tool to support the *collaboration decision* in ISRs, i.e., accepting an out of core cost-distribution results in an *unstable* ISR. Nevertheless, it does not grasp the fairness and neither provides a method for choosing a specific cost allocation to implement among the set of stable cost allocations. In the following, we tailor a solution concept that axiomatize the concept of fairness and provides a single-point allocation that satisfies the fairness property.

B. Shapley Allocation for ISR Games

Regarding the allocation of costs in collaborative groups, there exist various interpretations of the complex notion of fairness (see [30]). In cooperative game theory, the well-established concept of *Shapley value* [26] is a central concept that regards the *fairness* of a cost distribution among members of a collaborative agent group by taking into account their contributions to the collaborative group. In this work, we follow Shapley's view and expect a *fair* allocation to satisfy the following four properties: *efficiency*, *symmetry*, *dummy player*, and *additivity* (as discussed in Section II-C). In brief, if a group G follows an *efficient* method to allocate cost C among its members, the summation of allocated costs to members of group G will be equal to C. The *symmetry* property says that agents that make the same contribution to the total cost, should be allocated the same individual cost shares. The *dummy player* property says that if the presence of an agent A does not result in any cost reduction (in all the possible agent groups), the allocated cost to A should be equal to its individual total traditional cost. Finally, the *additivity* property says that if you combine two games V and U, the allocated cost to an agent A (involved in both the games) should be the sum of the costs allocated to A in the individual games, i.e., playing more than once does not lead to any (dis)advantages for A. For formal axiomatization of these properties, we refer the reader to [26]. In the following, we present our tailored Shapley value for ISR games.

Definition 5 (Shapley Allocation for ISRs). Let σ be an ISR game (as defined in Definition 3) between firms A and B. The Shapley allocation for σ is the tuple $\Phi(\sigma) := \langle T_A^{\Phi}(\sigma), T_B^{\Phi}(\sigma)\rangle$ where for $i \in N = \{A, B\}$ we have $T_i^{\Phi}(\sigma) = \frac{1}{2}[T(\sigma) + T_i(\bar{\sigma}) - T_{N\setminus\{i\}}(\bar{\sigma})]$.

A reader familiar with the notion of Shapley value might expect the two notions of *orders* and *marginal contributions* to be a part of our tailored concept of Shapley value for ISRs. We highlight that due to our domain of application, i.e, bilateral industrial relations, there are two possible orders in ISR games (reflected by the constant value $\frac{1}{2}$). Moreover, the marginal contribution of a given firm $i \in N = \{A, B\}$ can be reformulated in terms of the most desirable stable cost for i and the most undesirable one, i.e., $U_i(\sigma) = T(\sigma) - T_{N\setminus\{i\}}(\bar{\sigma})$ and $T_i(\bar{\sigma})$, respectively. Note that as the Shapley value is defined following a constructive method (in contrast to condition-based definition of core in Definition 4), the existence of the Shapley value for any arbitrary ISR game is guaranteed. Following our discussion about the fairness of collaborations, the next property shows that the Shapley value is the unique fair method for allocation of the total ISR-related operational cost in ISR games.

Proposition 3 (Uniqueness of the Shapley Value). *Let $\Phi(\sigma)$ be the Shapley allocation for ISR game σ between firms A and B. For any fair allocation of costs in σ, denoted by $\Phi'(\sigma)$, we have that $\Phi'(\sigma) = \Phi(\sigma)$.*

Proof: Importing results from [26], we have that for any cooperative game, the Shapley value is the unique allocation method that satisfies all the four properties of fair cost allocations, i.e., efficiency, symmetry, dummy player, and additivity, regardless of the characteristics of the cost function of the game. Accordingly, the uniqueness property holds for ISR games as two-person cost allocation games. ∎

Considering core of ISR games and their unique Shapley allocation, the following proposition relates these two forms of solution concepts and shows that in ISR games the Shapley allocation is in the core.

Proposition 4 (Membership in the Core). *Let $\Psi(\sigma)$ and $\Phi(\sigma)$ be respectively the set of core allocations, and the Shapley allocation for ISR game σ between firms A and B. It always holds that $\Phi(\sigma) \in \Psi(\sigma)$.*

Proof: Based on [13, 26], the core of submodular games is nonempty and includes the Shapley value. For ISR games, according to Proposition 2, the core is nonempty. Thus, we have that for any ISR game σ, it holds that $\Phi(\sigma) \in \Psi(\sigma)$. ∎

Note that the membership of the Shapley allocation in the core is a property of ISR games and not a general property of the Shapley cost allocation for any class of cooperative games. Accordingly, we have that the Shapley allocation of any ISR game can be illustrated in two dimensional space. More precisely, the Shapley allocation γ (see Figure 2) is the midpoint of the core allocation segment.

Example 2 (Allocations in the ISR Scenario). Considering the presented scenario in Example 1, any cost allocation $\langle T_A, T_B\rangle$ such that $4 \leq T_A \leq 7$ and $8 \leq T_B \leq 11$ and $T_A + T_B = 15$ is a core allocation. Moreover, $\langle 5.5, 9.5\rangle$ is the Shapley allocation.

In general, Shapley allocation does not satisfy the *individual rationality* property. I.e., it might be the case that some agents in a collaborative group should pay higher than their traditional cost in order to guarantee the fairness property. In such cases, we have a fair albeit unstable collaboration because any sacrificing firm has incentive to rationally defect the collaboration. However, the next proposition shows that for ISR games, the Shapley allocation is individually rational.

Proposition 5 (Fairness and Stability). *Let $\Phi(\sigma)$ be the Shapley allocation for ISR game σ between firms A and B. It always holds that for $i \in \{A, B\}$, we have that $T_i^{\Phi}(\sigma) \leq T_i(\bar{\sigma})$.*

Proof: According to Proposition 4, the Shapley allocation of ISR game σ is also a core allocation. Hence, it also satisfies the *individual rationality* condition in Definition 4. ∎

Based on proposition 5, in case the two firms agree to implement the Shapley allocation, it is guaranteed that the relation will be both fair and stable. Although implementing the Shapley allocation seems natural due to its desirable properties, firms may prefer to negotiate among cost allocations in the core with the aim to practice their bargaining power and enjoy more cost reduction. However, industrial agents that suffer from unfair allocations in such cases may defect the collaboration, leave/reject the ISR, and join other ISRs that are practicing fair allocation methods.

V. Conclusions and Future Work

In this work, we present a game-theoretical representation of Industrial Symbiotic Relations (ISRs) and tailor two types of solution concepts for cost allocation in such relations, i.e., *core allocation* and *Shapley allocation* for ISR games. These two notions can also be seen as two approaches for decision support while firms are faced with the collaboration decision, to reject or accept an ISR proposal. This is by enabling firms to systematically reason about and verify *stability* and *fairness* of a particular ISR. Range of stable collaborations, provided by the concept of *core*, allows further negotiation while the *Shapley* allocation leads to a uniquely fair solution. We then show that due to the characteristics of industrial symbiotic relations, ISR games can always be operationalized in both a fair and stable manner. In addition to practical contributions by providing managerial decision support tools, we introduced ISR games as a new class of two-person Operations Research (OR) games. In ISR games, we have the non-emptiness of the core and it is guaranteed that the Shapley value in this class of OR games is an individually rational solution. As a future work, we aim to analyze the validity of presented results using multiagent-based simulations [31]. We also plan to extend our game-theoretical analysis to network level, relate our notions to the concept of *willingness to cooperate* [32], and study Industrial Symbiotic Networks (ISNs). Due to complexities of ISNs (see [14]) guaranteeing *fairness* and *stability* in such networks calls for mechanisms to coordinate agent interactions [33] and governance platforms for, as discussed in [34], "administration of stakeholders by stakeholders".

Acknowledgment

The project leading to this work has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement *No. 680843*.

References

[1] M. R. Chertow, "Industrial symbiosis: literature and taxonomy," *Annual review of energy and the environment*, vol. 25, no. 1, pp. 313–337, 2000.

[2] D. R. Lombardi and P. Laybourn, "Redefining industrial symbiosis," *Journal of Industrial Ecology*, vol. 16, no. 1, pp. 28–37, 2012.

[3] D. M. Yazan, V. A. Romano, and V. Albino, "The design of industrial symbiosis: an input–output approach," *Journal of cleaner production*, vol. 129, pp. 537–547, 2016.

[4] D. W. Pearce and R. K. Turner, *Economics of natural resources and the environment*. JHU Press, 1990.

[5] T. Stock and G. Seliger, "Opportunities of sustainable manufacturing in industry 4.0," *Procedia CIRP*, vol. 40, pp. 536–541, 2016.

[6] L. M. Camarinha-Matos, H. Afsarmanesh, N. Galeano, and A. Molina, "Collaborative networked organizations - concepts and practice in manufacturing enterprises," *Computers & Industrial Engineering*, vol. 57, no. 1, pp. 46–60, 2009.

[7] L. Fraccascia, V. Albino, and C. A. Garavelli, "Technical efficiency measures of industrial symbiosis networks using enterprise input-output analysis," *International Journal of Production Economics*, vol. 183, pp. 273–286, 2017.

[8] T. Jackson and R. Clift, "Where's the profit in lndustrial ecology?" *Journal of Industrial Ecology*, vol. 2, no. 1, pp. 3–5, 1998.

[9] C. Yu, G. P. Dijkema, and M. Jong, "What makes eco-transformation of industrial parks take off in china?" *Journal of Industrial Ecology*, vol. 19, no. 3, pp. 441–456, 2015.

[10] T. S. Driessen, *Cooperative games, solutions and applications*. Springer Science & Business Media, 2013, vol. 3.

[11] P. Borm, H. Hamers, and R. Hendrickx, "Operations research games: A survey," *Top*, vol. 9, no. 2, p. 139, 2001.

[12] L. S. Shapley, "Markets as cooperative games," DTIC Document, Tech. Rep., 1955.

[13] H. P. Young, *Cost allocation: methods, principles, applications*. North Holland Publishing Co., 1985.

[14] V. Yazdanpanah, D. M. Yazan, and W. H. M. Zijm, "Normative industrial symbiotic networks: A position paper," in *Multi-Agent Systems and Agreement Technologies*. Springer, 2016, pp. 314–321.

[15] M. Bengtsson and S. Kock, "Coopetition in business networks: to cooperate and compete simultaneously," *Industrial marketing management*, vol. 29, no. 5, pp. 411–426, 2000.

[16] V. Albino, L. Fraccascia, and I. Giannoccaro, "Exploring the role of contracts to support the emergence of self-organized industrial symbiosis networks: an agent-based simulation study," *Journal of Cleaner Production*, vol. 112, pp. 4353–4366, 2016.

[17] D. C. Esty and M. E. Porter, "Industrial ecology and competitiveness," *Journal of Industrial Ecology*, vol. 2, no. 1, pp. 35–43, 1998.

[18] K. Sinding, "Environmental management beyond the boundaries of the firm: definitions and constraints," *Business strategy and the environment*, vol. 9, no. 2, p. 79, 2000.

[19] S. F. Magram, "Worldwide solid waste recycling strategies: A review," *Indian Journal of Science and Technology*, vol. 4, no. 6, pp. 692–702, 2011.

[20] E. M. Lovelady and M. M. El-Halwagi, "Design and integration of eco-industrial parks for managing water resources," *Environmental progress & sustainable energy*, vol. 28, no. 2, pp. 265–272, 2009.

[21] H. Zijm, M. Klumpp, U. Clausen, and M. Ten Hompel, *Logistics and Supply Chain Innovation: Bridging the Gap between Theory and Practice*. Springer, 2015.

[22] A. C. Carpenter and K. H. Gardner, "Use of industrial by-products in urban transportation infrastructure: argument for increased industrial symbiosis," in *Electronics and the Environment, 2008. ISEE 2008. IEEE International Symposium on*. IEEE, 2008, pp. 1–7.

[23] X. Chen, T. Fujita, S. Ohnishi, M. Fujii, and Y. Geng, "The impact of scale, recycling boundary, and type of waste on symbiosis and recycling," *Journal of Industrial Ecology*, vol. 16, no. 1, pp. 129–141, 2012.

[24] C. J. Dahlman, "The problem of externality," *The journal of law and economics*, vol. 22, no. 1, pp. 141–162, 1979.

[25] O. E. Williamson, "The economics of organization: The transaction cost approach," *American journal of sociology*, pp. 548–577, 1981.

[26] L. S. Shapley, "A value for n-person games," *Contributions to the Theory of Games*, vol. 2, no. 28, pp. 307–317, 1953.

[27] T. W. Sandholm, "Distributed rational decision making," *Multiagent systems: a modern approach to distributed artificial intelligence*, pp. 201–258, 1999.

[28] G. Dantzig, *Linear programming and extensions*. Princeton university press, 2016.

[29] R. W. Coff, "When competitive advantage doesn't lead to performance: The resource-based view and stakeholder bargaining power," *Organization science*, vol. 10, no. 2, pp. 119–133, 1999.

[30] A. P. Rosenbusch, "Fairness considerations in cooperative games," Ph.D. dissertation, Technische Universität, 2011.

[31] F. Dignum, J. Bradshaw, B. G. Silverman, and W. van Doesburg, *Agents for games and simulations: Trends in techniques, concepts and design*. Springer, 2009, vol. 5920.

[32] D. Yazan, J. Clancy, J. Lovett *et al.*, "Appendix: supply chains, techno-economic assessment and market development for second generation biodiesel." *Advances in biodiesel production: processes and technologies*, pp. 254–280, 2012.

[33] M. Dastani, L. van der Torre, and N. Yorke-Smith, "Commitments and interaction norms in organisations," *Autonomous Agents and Multi-Agent Systems*, pp. 1–43, 2015.

[34] M. P. Singh, "Norms as a basis for governing sociotechnical systems," *ACM Transactions on Intelligent Systems and Technology (TIST)*, vol. 5, no. 1, p. 21, 2013.

Industrial Symbiotic Networks as Coordinated Games

ABSTRACT

We present a framework for implementing a specific form of collaborative industrial practices called “Industrial Symbiotic Networks (**ISN**s)” as cooperative games. The game-theoretic formulation of **ISN**s enables systematic reasoning about what we call the **ISN** implementation problem. Specifically, the characteristics of **ISN**s may lead to inapplicability of *fair* and *stable* benefit allocation methods even if the collaboration is a collectively desired one (from a socioeconomic and environmental point of view). Inspired by realistic **ISN** scenarios and following the literature on normative multi-agent systems, we consider *regulations* and normative socioeconomic *policies* as two elements that in combination with **ISN** games resolve the situation and result in the introduction of the novel concept of “Coordinated **ISN**s ($C-$**ISN**s)". Applied regulations are mainly monetary incentive allocation rules to enforce desired industrial collaborations with respect to an established policy. In our framework, employing Marginal Contribution Nets (MC-Nets) as rule-based cooperative game representations fosters the combination of regulations and **ISN** games with no loss in expressiveness. We develop algorithmic methods for generating regulations that ensure the implementability of **ISN**s and as a policy support, show the policy requirements that ensure the implementability of all the desired **ISN**s in a *balanced-budget* way.

KEYWORDS

Game Theory for Practical Applications; Industrial Symbiosis; MC-Net Cooperative Games; Normative Coordination; Policy and Regulation.

1 INTRODUCTION

Industrial Symbiotic Networks (**ISN**s) are mainly seen as collaborative networks of industries with the aim to reduce the use of virgin resources by circulating reusable resources (e.g, physical waste material and energy) among the network members [6, 19, 27]. In such networks, symbiosis leads to socioeconomic and environmental benefits for involved industrial agents and the society. 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 **ISN**s result in the reduction of the total cost, a remaining challenge for operationalization of **ISN**s 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 stability and/or fairness may lead to no-cooperation decisions. This will be the main focus of what we call the **ISN** *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 [27] and the role of contract settings in the process of **ISN** implementation [1]. 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 snapshot-based modeling frameworks).

The mature field of cooperative game theory and Operations Research (OR) games provides rigorous methodologies and established solution concepts, e.g. the core of the game and the Shapley allocation [5, 9, 20, 23]. However, for **ISN**s 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 solutions that take into account both the complexities of **ISN**s and the characteristics of the employable game-theoretical solution concepts. Accordingly, inspired by realistic **ISN** scenarios and following the literature on normative multi-agent systems [3, 12, 26], we consider *regulative* rules and normative socioeconomic *policies* as two elements that in combination with **ISN** games result in the introduction of the novel concept of *Coordinated* **ISN**s ($C-$**ISN**s). We formally present regulations as monetary incentives 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. Applying regulatory rules to **ISN**s enables **ISN** policy-makers to transform **ISN** games and ensure the implementability of desired ones in a fair and stable manner.

In this work, we provide a succinct game-theoretic framework for the implementation phase of **ISN**s. Moreover, we develop algorithmic methods for generating regulations that ensure the implementability of an **ISN**. Finally, as a policy support, we show the **ISN** policy requirements that guarantee the implementability of all the desired industrial collaborations in a *balanced-budget* way.

2 CONCEPTUAL ANALYSIS

In this section, we 1) present the intuition behind our approach using a running example, 2) discuss our norm-based perspective for capturing **ISN** regulations, 3) describe the evaluation criteria for an ideal **ISN** implementation framework, and 4) review previous work on tailoring game-theoretic solution concepts for industrial symbiosis implementation problem.

ISN as a Cooperative Practice. To explain the dynamics of implementing **ISN**s as cooperative 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

Proc. of the 17th International Conference on Autonomous Agents and Multiagent Systems (AAMAS 2018), M. Dastani, G. Sukthankar, E. Andre, S. Koenig (eds.), July 2018, Stockholm, Sweden

https://doi.org/doi

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. I.e., if it reduces the related costs for discharging wastes (on the resource provider side) and purchasing cost (on the resource receiver side). 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 **ISN** *implementation* problem focuses on methods for sharing this obtainable collective benefit among involved firms. Simply stated, the applied method for allocating 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 the benefit obtainable in case firms defects the collaboration results in unstable **ISN**s and unfair mechanisms that disregard contribution of firms may cause the firms to move to other **ISN**s 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 game-theoretic implementation framework for **ISN**s that enables fair and stable allocation of obtainable benefits.

ISN Regulations as Norms. In real cases, **ISN**s take place under regulations that concern environmental as well as societal policies. For instance, avoiding waste discharge may be encouraged by the local authority or transporting a specific type of hazardous waste may be forbidden 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 industry representatives (at a microlevel) but in addition involves regulatory dimensions (at a macrolevel).

To capture the regulatory dimension of **ISN**s, we apply a normative policy that respects the socioeconomic 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 a promoted **ISN** and avoid prohibited ones (while permitted **ISN**s are neutral from the policy-maker's point of view). We call the **ISN**s that take place under regulations, *Coordinated* **ISN***s* ($C-$**ISN**s). Note that the term "coordination" in this context refers to monetary incentive mechanisms in the **ISN** implementation phase, and should

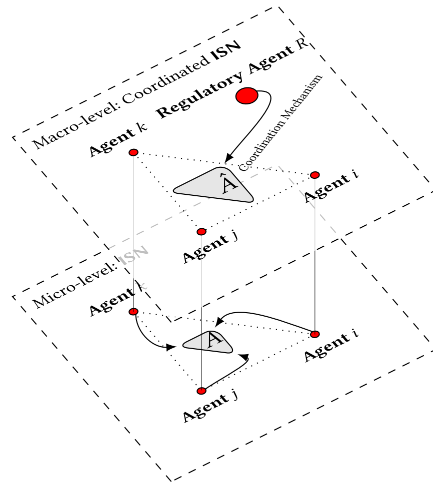

Figure 1: At the micro level, A represents the set of all benefit allocation methods that are preferable for all the firms. At the macro level, due to introduced coordination mechanism by the regulatory agent (respecting the established socioeconomic policy), we have the allocation set $\hat{A}$ either equal to A or as a shrunk/extended version of it.

not be confused with **ISN** administration (i.e., managing the evolution of relations). Figure 1 presents a schematic view on the role of the regulatory agents in $C-$**ISN**s.

Evaluation Criteria for ISN Implementation. Dealing with agents that perform in a complex 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 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 **ISN**s should be general, sufficiently expressive, rationally acceptable for all firms, and respect their autonomy. The goal of this paper is to develop an implementation framework for **ISN**s that has properties close to the ideal one.

Previous Work. The idea of employing cooperative game theory for analyzing industrial symbiosis or implementing symbiotic relations as a cooperative games have only been sparsely explored in the past [7, 11, 28]. In [11], Grimes-Casey et al. used both cooperative and non-cooperative game theory for analyzing the behavior of firms engaged in a case-specific industrial ecology. While the analysis is expressive and scalable, the implemented relations are specific to refillable/disposable bottle life-cycles. In [7], 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 [28], 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 MC-Nets, enables a representation that is sufficiently expressive to capture the regulatory aspect of **ISN**s. We will give a more detailed review of these papers in Section 3.2 after covering the technical background.

3 PRELIMINARIES

In this section, we recall the preliminary notions in cooperative games, the MC-Net representation of such games, and the two principal solution concepts, the Shapley value and the Core[1]. Moreover, we discuss in more detail the technical aspects of previous work that applied game-theoretical methods for **ISN** modeling and analysis.

3.1 Technical Background

In this work, we build on the *transferable utility* assumption. 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 group members.

Cooperative Games. 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. 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. I.e., as $v(S)$ 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. 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.

The Shapley Value. The Shapley value prescribes a notion of *fairness*. It says that assuming the formation of the grand coalition 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 cooperative multi-agent 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 $(v + w)(S) = v(S) + w(S)$.

The Core of the Game. 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.

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 since 2^n values are required. In this work, as we are aiming to implement (potentially large) **ISN**s in a scalable manner, we use basic MC-Net [14] representation that uses a set of rules to specify the value of possible agent coalitions. Moreover, attempting to capture the regulatory aspect of **ISN**s 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 illustrate how this rule-based representation enables applying norm-based coordination to **ISN**s.

3.2 Revisiting Previous Work

Chew et al. in [7] analyze the interaction of participating companies in an Eco-industrial park seeking to develop a game-theoretic implementation framework for inter-plant water integration. In their cooperative game model, by assuming the compliance of agents

[1]The presented material on basics in cooperative games is based on [20, 23] while for the MC-Net notations, we build on [14, 17].

to their commitments, the optimum collective benefit is achievable. As the authors mention, in case the cooperation takes place, their allocation mechanism results in higher collective payoff in comparison to their non-cooperative game scheme. This result is achieved through adding contextualized interaction protocols that compel the industries to act in a desired manner. Roughly speaking, it is assumed that the network manager has control over internal operations and decision processes of involved agents (which may be applicable in specific case studies but is in contrast with the principle of *separation of concerns*). For instance, given the availability of an optimal *wastewater interchange scheme*, it is shown that in case the agents adopt the scheme and act accordingly, they can benefit both individually and collectively. In other words, the focus is shifted towards providing methods for optimizing the scheme in a specific case.

In a more recent work, Yazdanpanah and Yazan looked into the modeling and implementation of industrial symbiotic relations as two person cooperative games [28]. Their focus is on allocation of the total operational cost among involved agents using a tailored version of the Shapley value and the standard notion of core. They show that for industrial symbiotic relation games, core is non-empty and hence such symbiotic practices are implementable in a stable manner. Moreover, as the Shapley value will be in the core, it is rational for industries to implement the Shapley allocation (with no need for interruption from the regulatory agent). Notice that although their industrial symbiosis implementation satisfies desired properties, e.g., autonomy and rationality, it is not expressive for implementing symbiotic relations among three or more industries. This is basically because their analysis is based on properties of two-person games.

Finally, Grimes-Casey et al. [11] focus on cooperative decision-making and heterogeneity of the involved agents (with respect to their epistemic states) in an industrial symbiosis scenario. They employ cost-based mechanisms to nudge the behavior of manufacturer as well as consumer agents towards using refillable beverage containers. Although their cooperative management framework is problem-specific, it is expressive and scalable as they employ profit values that are computable in low complexity. They also discuss that in real cases, the applicability of most cooperative game solution concepts depends on government enforcement. This is in-line with our attempt to capture the regulatory aspect of industrial symbiosis using incentive mechanisms.

4 ISN GAMES

As discussed in [1, 28], the total obtainable cost reduction (as an economic benefit) and its allocation among involved firms are key drivers behind the stability of **ISN**s. 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 mechanisms that guarantee a fair and stable implementation of the symbiosis.

4.1 ISNs as Cooperative Games

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 **ISN**s 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[2] in nature. So, given the traditional 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 4.1 (**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:

$$v(S) = \begin{cases} 0, & \text{if } |S| \leq 1 \\ T(S) - O(S), & \text{otherwise} \end{cases}$$

According to the following proposition, basic MC-Nets can be used to represent **ISN**s. In further sections, this representation aids combining **ISN** games with normative coordination rules.

Proposition 4.2 (**ISN**s as MC-Nets). *Any **ISN** can be represented as a basic MC-Net.*

Proof. We provide a constructive proof by (1) introducing an algorithm for specification of all the required MC-Net rules and (2) showing that the constructed MC-Net is equal to the original **ISN** game. *(1)* - Let (N, v) be an arbitrary **ISN** game among industrial agents in N. Moreover, let $S_{\geq 2} = \{S \subseteq N : |S| \geq 2\}$ be the set of all agent groups with two or more members and let $K = |S_{\geq 2}|$ denote its cardinality. We start with an empty set of rules. Then for all agent groups $S_i \in S_{\geq 2}$, for $i = 1, \ldots, K$, we add a rule $\{\rho_i : (S_i, N \backslash S_i) \mapsto v_i = T(S_i) - O(S_i)\}$. *(2)* - As in all the constructed rules ρ_i it holds that $\mathcal{P}_i \cap \mathcal{N}_i = \emptyset$ and $\mathcal{P}_i \cup \mathcal{N}_i = N$, we have that $\sum_{i \in \Pi(S)} v_i$ is equal to $v(S)$ for all the members of $S_{\geq 2}$. Moreover, $\Pi(S)$ for empty and singleton agent groups would be empty, hence reflects the 0 value for such groups in the original game. □

Note that the proof does not simply rely on the representation power and expressivity of MC-Nets (as shown in [14]) but provides a constructive method that respects the context of industrial symbiosis and related cost values to generate all the required rules for representing **ISN**s as MC-Nets. Our running example can be

[2]Superadditivity implies that forming a symbiotic coalition of industrial agents either results in no value or in a positive value.

represented by the basic MC-Net[3] $\{\rho_1 : (ij,k) \mapsto 4, \rho_2 : (ik,j) \mapsto 5, \rho_3 : (jk,i) \mapsto 4, \rho_4 : (ijk,\emptyset) \mapsto 6\}$.

4.2 Allocation Mechanisms and ISN Games

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. Roughly speaking, industrial firms are economically rational firms 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 solution concepts are applicable in a specific class of **ISN**s but are not generally scalable for value allocation in the implementation phase of **ISN**s. This motivates introducing incentive mechanisms to guarantee the implementability of "desired" **ISN**s.

4.2.1 Two-Person ISN 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 $\mathbf{ISN}_\Lambda$. This is, $\mathbf{ISN}_\Lambda = \{(N,v) : (N,v)$ is an **ISN** game $\wedge\ |N| = 2\}$. Moreover, the **ISN** games in which three or more agents are involved will form $\mathbf{ISN}_\Delta$. The class of $\mathbf{ISN}_\Lambda$ games corresponds to the so called ISR games in [28]. The difference is on the value allocation perspective as 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 4.3 ($\mathbf{ISN}_\Lambda$ Balancedness). *Let (N,v) be an arbitrary $\mathbf{ISN}_\Lambda$ game. It always holds that (N,v) is balanced.*

Proof. We show that any $\mathbf{ISN}_\Lambda$ game is supermodular which directly implies balancedness. A game (N,v) is supermodular iff for any couple of arbitrary agent groups $S,T \subseteq N$, we have $v(S) + v(T) \leq v(S \cup T) + v(S \cap T)$. In $\mathbf{ISN}_\Lambda$ games, by checking the validity of this inequality for all the six possible S,T combinations, the claim will be proved. For $S = \emptyset$, we have the following valid inequality $v(\emptyset) + v(T) \leq v(\emptyset \cup T = T) + v(\emptyset)$. For $S = N$, the inequality can be reformulated in the following valid form $v(N) + v(T) \leq v(N \cup T = N) + v(N \cap T = T)$. Finally, when S and T are equal to the only possible (disjoint) singleton groups, we have $v(S) + v(T) \leq v(N) + v(\emptyset)$ which holds thanks to the superadditivity of **ISN** games. □

Relying on Lemma 4.3, we have the following result.

Theorem 4.4 (Fair and Stable $\mathbf{ISN}_\Lambda$ Games). *Let (N,v) be an arbitrary $\mathbf{ISN}_\Lambda$ game. The symbiotic relation among industrial agents in N is always implementable in a stable manner. Moreover, the symbiotic relation is always implementable in a unique stable and fair manner.*

Proof. *Stability*: As discussed in 3.1, core allocations guarantee the stability conditions (i.e., RAT and EFF). However, the core is only an applicable solution concept for *balanced* games. According to Lemma 4.3, we have that $\mathbf{ISN}_\Lambda$ games are balanced. Hence, the core of any arbitrary $\mathbf{ISN}_\Lambda$ game is nonempty and any allocation in the core guarantees the stability. *Stability and Fairness*: As discussed in 3.1, the Shapley allocation guarantees the fairness conditions (i.e., EFF, SYM, DUM, ADD). However, it does not always satisfy the rationality (RAT) condition (which is necessary for stability). According to Lemma 4.3, we have that $\mathbf{ISN}_\Lambda$ games are balanced. Moreover, according to [25, Theorem 7], in balanced games, the Shapley allocation is a member of the core and hence satisfies the rationality condition. Accordingly, for any $\mathbf{ISN}_\Lambda$ game, the Shapley allocation guarantees both the stability and fairness. □

4.2.2 General ISN Games. In this section we focus on $\mathbf{ISN}_\Delta$ 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. Recall the ijk $\mathbf{ISN}_\Delta$ 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 are not simultaneously satisfiable, 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 are ought to sacrifice as they collectively have $26/6$. As illustrated in this example, the Core of $\mathbf{ISN}_\Delta$ games may be empty which implies the inapplicability of this solution concept as a general method for implementing **ISN**s. We now generalize the exemplified idea to the following nonexistence theorem about implementability of $\mathbf{ISN}_\Delta$ games in a fair and stable manner.

Theorem 4.5 (Unimplementability of $\mathbf{ISN}_\Delta$ Games). *Let (N,v) be an arbitrary $\mathbf{ISN}_\Delta$ game. The symbiotic relation among industrial agents in N is not always implementable in a stable manner.*

Proof. Although all $\mathbf{ISN}_\Delta$ games are superadditive and hence result in a positive obtainable benefit, they may be unbalanced (as illustrated in the running example). Accordingly, for any unbalanced $\mathbf{ISN}_\Delta$ game, the Core is empty. In such cases, the symbiotic relation is not implementable in a stable manner. □

Note that the fair implementation of $\mathbf{ISN}_\Delta$ games is not always in compliance with the rationality condition. 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 GAMES

In realistic **ISN**s, the symbiotic practice takes place in the presence of economic, social, and environmental *policies* and under *regulations* that aim to enforce the policies and nudge 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,

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

result in an acceptable spectrum of 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 for using normative coordination to guarantee the implementability of desirable **ISN**s in a stable and fair manner[4].

5.1 Normative Coordination of ISNs

Following [12, 26], 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". For this account, given the economic, environmental, and social dimensions and with respect to potential socioeconomic consequences, industrial symbiotic networks can be partitioned in three classes, namely *promoted*, *permitted*, and *prohibited* **ISN**s. Such a classification can be modeled by a normative socioeconomic policy function $\wp : S \mapsto \{p^+, p^\circ, p^-\}$, where S is a finite set of industrial firms. Moreover, p^+, p°, and p^- are labels indicating that the **ISN** among agents in S 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 (e.g., $P^+_\wp = \{S : \wp(S) = p^+\}$). Note that $\wp$ is independent of the **ISN** game among agents in S and its characteristic value function. E.g., a symbiotic relation may be labeled with p^- by policy $\wp$ even if it results in a high level of obtainable benefit.

Example 5.1 (Normative **ISN***s).* 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" **ISN**s.

As illustrated in Example 5.1, any socioeconomic 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 **ISN**s[5]. The rationale behind introducing socioeconomic policies for **ISN**s is mainly to make sure that the set of promoted **ISN**s are implementable in a fair and stable manner while prohibited ones are instable. To ensure this, in real **ISN** practices, the regulatory agent (i.e., the regional or national government) introduces regulations in the form of monetary incentives. This is to ascribe subsidies to promoted and taxes to prohibited collaborations (see [16] 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 **ISN**s among industrial agents in N via allocating incentives. Such a set of incentive rules can be represented by an MC-Net $\mathfrak{R} = \{\rho_i : (\mathcal{P}_i, \mathcal{N}_i) \mapsto \iota_i\}_{i \in K}$ in which K is the set of rule indices. Let $\mathfrak{I}(S)$ 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 $\sum_{i \in \mathfrak{I}(S)} \iota_i$[6]. The following proposition shows that for any **ISN** game there exist a set of incentive rules to guarantee the implementability of the **ISN** in question.

Proposition 5.2 (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 4.2, 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.

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 $\mathfrak{R}$ for G

$n \leftarrow length(K)$ and $\mathfrak{R} = \{\}$;
for $i \leftarrow 1$ **to** n **do**
  if $i \in \Pi(N)$ **then**
    $\mathfrak{R} \leftarrow \mathfrak{R} \cup \{\rho_i : (\mathcal{P}_i, \mathcal{N}_i) \mapsto 0\}$;
  else
    $\mathfrak{R} \leftarrow \mathfrak{R} \cup \{\rho_i : (\mathcal{P}_i, \mathcal{N}_i) \mapsto -v_i\}$;
  end
end

Algorithm 1: Generating incentive rule set $\mathfrak{R}$ for **ISN** game G.

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 have both socioeconomic policies and regulations as required (but not yet integrated) elements for modeling coordinated **ISN**s. In the following section, we combine the idea behind incentive regulations and normative socioeconomic policies to introduce the concept of *Coordinated* **ISN***s* ($C-$**ISN**s).

5.2 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, **ISN** games in presence of coordination mechanisms, or *Coordinated* **ISN***s* ($C-$**ISN**s) in brief.

Definition 5.3 (Coordinated **ISN** *Games ($C-$***ISN***)).* Let G be an **ISN** and $\mathfrak{R}$ 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 $\mathfrak{R}$, respectively. We say the Coordinated **ISN** Game ($C-$**ISN**) among industrial agents in N is a cooperative game (N, c) where for each agent group S, we have that $c(S) = v(S) + \iota(S)$.

[4] In the following, we simply say *implementability* of **ISN**s instead of *implementability in a fair and stable* manner.

[5] Note that **ISN**$_\Lambda$ games are always implementable. So, **ISN**s' implementability refers to the general class of **ISN** games including **ISN**$_\Delta$ games.

[6] This is, a set of incentive rules can be represented also as a cooperative game $\mathfrak{R} = (N, \iota)$ among agents in N.

Note that as both the **ISN** game G and the set of regulatory incentive rules $\mathfrak{R}$ 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 $\mathfrak{R}$. Formally, $c(S) = \sum_{i \in \Pi(S)} v_i + \sum_{j \in \mathfrak{I}(S)} \iota_j$ where $\Pi(S)$ and $\mathfrak{I}(S)$ denote the set of applicable rules to S in G and $\mathfrak{R}$, respectively. Moreover, v_i and ι_j denote the value of applicable rules i and j in $\Pi(S)$ and $\mathfrak{I}(S)$, respectively. We sometime use $G + \mathfrak{R}$ to denote the game C as the result of incentivizing G with $\mathfrak{R}$. The next proposition shows the role of regulatory rules in enforcement of socioeconomic policies.

Proposition 5.4 (Policy Enforcing Rules). *For any promoted* **ISN** *game G under policy $\wp$, there exist an implementable $C-$***ISN** *game C.*

Proof. To prove, for any arbitrary promoted G, we require a set of regulatory incentive rules $\mathfrak{R}$ such that its combination with G results in a stable C implementation. The algorithm for generating such a $\mathfrak{R}$ is presented in the proof of Proposition 5.2. □

Analogously, similar properties hold while *avoiding* prohibited **ISN**s or *allowing* permitted ones. Avoiding prohibited **ISN**s can be achieved by making the $C-$**ISN** (that results from introducing regulatory incentives) unimplementable. On the other hand, allowing permitted **ISN**s would be simply the result of adding an empty set of regulatory rules. The presented approach for incentivizing **ISN**s, 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 $\mathfrak{R}$ 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 socioeconomic policies that aim to foster the implementability of desired **ISN**s. As we discussed in Section 2, we aim for implementing **ISN**s such that the rationality axiom will be respected. In the following, we focus on the subtleties of socioeconomic policies that are enforced by regulatory rules. The question is, what are the properties of a policy that can ensure the irrationality of defecting desired **ISN**s? 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 5.5 (Mutual Exclusivity of Promoted **ISN**s). *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 $\mathfrak{R}_1$ and $\mathfrak{R}_2$ be rule sets that ensure the implementability of G_1 and G_2, respectively. For $i \in \{1,2\}$, defecting from $C-$***ISN** *$C_i = G_i + \mathfrak{R}_i$ is not economically rational for any agent $a \in S_i$ iff $S_1 \cap S_2 = \emptyset$.*

Proof. " $\Rightarrow$ ": Suppose $S_1 \cap S_2 \neq \emptyset$. Accordingly, we have an agent a which is both a member of S_1 and S_2. For a it is rational to defect either S_1 or S_2 as both the two $C-$**ISN**s that are based on the two groups are implementable.

" $\Leftarrow$ ": Suppose S_1 and S_2 are disjoint promoted agent groups under $\wp$. As $\mathfrak{R}_1$ and $\mathfrak{R}_2$ can respectively ensure the implementability of these two groups and based on Proposition 4.2, we have that **ISN**s among firms in S_1 and S_2 are both implementable in a stable manner. Hence, they satisfy the rationality axiom. Moreover, as the two agent groups share no agent, there will be no economic incentive to deviate between the two stable **ISN**s. □

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

Proposition 5.6 (Minimality of Promoted **ISN**s). *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 **ISN**s that take place among promoted groups of firms.

Theorem 5.7 (Implementability of Promoted $C-$**ISN**s under Exclusivity Condition). *Let G be an arbitrary* **ISN**$_\Delta$ *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 $\mathfrak{R}$, such that all the promoted symbiotic networks are implementable in the coordinated* **ISN** *defined by $C = G + \mathfrak{R}$. 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 $\mathfrak{R}$. Then for all n promoted $S_i \in P^+_\wp$, we call the provided algorithm in Proposition 5.2. Each single run of this algorithm results in a $\mathfrak{R}_i$ 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 $\mathfrak{R}$. Formally, $\mathfrak{R} = \bigcup_{i=1}^{n} \mathfrak{R}_i$. Moreover, as the algorithm applies taxation on non-promoted groups, no **ISN** among prohibited agent groups will be implementable. □

*Example 5.8 (ijk as a Normatively Coordinated $C-$***ISN***).* Recalling the **ISN** scenario in Example 5.1, 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 $\mathfrak{R} = \{\rho_1 : (ij, k) \mapsto -4, \rho_2 : (ik, j) \mapsto -5, \rho_3 : (jk, i) \mapsto -4\}$. In the $C-$**ISN** that results from adding $\mathfrak{R}$ to the original **ISN**, industrial symbiosis among firms in the promoted group is implementable while all the prohibited groups cannot implement a stable symbiosis.

5.3 Realized ISNs and Budget-Balancedness

As we mentioned in the beginning of Section 5, regulations are set of norms that in case of agents' compliance bring about the desired behavior. For instance, in Example 5.8, 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 $C-$**ISN** with respect to an established policy $\wp$. So, assuming that based on evidences the set of implemented **ISN**s are realizable, we have the following abstract definition of $C-$**ISN**'s normative behavior under a socioeconomic policy.

*Definition 5.9 ($C-$**ISN**'s Normative Behavior).* Let C be a $C-$**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 **ISN**s 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 **ISN**s, the real behavior may deviate from a desired one. As our introduced method for guaranteeing the implementability of **ISN**s among promoted agent groups is mainly tax-based, if a $C-$**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 [13, 18, 24]) 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 **ISN**s.

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

Algorithm 2: Tax Redistribution for $C-$**ISN** game C.

The correctness of Algorithm 2 is established in Proposition 5.10.

Proposition 5.10 (Budget Balancedness and Fairness). *Let $C = G + \mathfrak{R}$ be a $C-$**ISN** among industrial agents in N under policy $\wp$ such that all the **ISN**s among promoted groups are implementable (using the provided method in Theorem 5.7) and let E be the set of implemented **ISN**s. For any $C-$**ISN**, the incentive values returned by Algorithm 2 ensures budget balancedness while preserving fairness (i.e., EFF, SYM, DUM, and ADD).*

Proof. To have budget balancedness, we have to show that the total collectible[7] tax value (using the provided method in Theorem 5.7) is equal to allocated subsidies. If the $C-$**ISN** is $\wp$-compliant, this is obvious as τ is equal to zero (thanks to the implementation of all the promoted **ISN**s). When the $C-$**ISN** is $\wp$-violating, we use the Shapley value of each agent that contributes to the sub-game of implemented promoted **ISN**s. As we employ a Shapley-based method, the monetary incentive is budget-balanced thanks to the EFF property and in addition preserves the other three properties (i.e., SYM, DUM, and ADD). □

[7] Considering a disposal account (under control of the regulatory agent) for each firm, it is reasonable to assume that *collectible* τ is equal to *collected* τ.

Note that the redistribution phase takes place after the implementation of the **ISN**s 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.

6 CONCLUDING REMARKS

This paper provides a game-theoretic framework for implementing **ISN** games that take place under a socioeconomic policy. This extends the previous work that merely focused on operational aspects of industrial symbiotic relations by introducing the analytical study of the regulatory aspect of **ISN**s. In practice, such a framework supports decision-makers in the **ISN** implementation phase by providing tools for reasoning about the implementability of a given **ISN** in a fair and stable manner. Moreover, it supports policy-makers aiming to foster socioeconomically desirable **ISN**s by providing algorithms that generate the required regulatory rules. Finally, it shows that MC-Net is an expressive game representation for applying normative coordination mechanisms to cooperative games.

This paper focuses on a unique socioeconomic policy and a set of rules to ensure it. In this regard, one question that deserves investigation is the possibility of having multiple policy options and policy-support tools for policy option analysis [21] in **ISN**s. Such a framework assists ranking and investigating the applicability of a set of policies in a particular **ISN** scenario. Along this line, we aim to generate a regulation toolbox for **ISN** policy-makers since a regulation may be incapable of ensuring all the desired collaborations under potentially conflicting policies. In that case, possible conflicts among regulations can be resolved using prioritized rule sets (inspired by methods for dealing with potential extensions in argumentation theory [15, 22]). Accordingly, we will have distinguishable potential **ISN** worlds where in each a set of promoted **ISN**s are implementable while others are not.

In future work, we also aim to focus on administration of **ISN**s. Then, compliance of involved agents to their commitments during the evolvement of the relations will be the main concern. For that, we plan to model **ISN**s as normative multi-agent organizations in which agents are related to roles and are able to reason about organizational goals [4, 29]. Thence, we can rely on norm-aware organization frameworks that focus on operation of normative organizations [2, 8] to monitor the organization's behavior. Finally, we aim to illustrate the validity of our formally verified framework using realistic case studies and multiagent-based simulations (as presented in [10]).

REFERENCES

[1] Vito Albino, Luca Fraccascia, and Ilaria Giannoccaro. 2016. Exploring the role of contracts to support the emergence of self-organized industrial symbiosis networks: an agent-based simulation study. *Journal of Cleaner Production* 112 (2016), 4353–4366.
[2] Huib Aldewereld, Frank Dignum, Andrés García-Camino, Pablo Noriega, Juan Antonio Rodríguez-Aguilar, and Carles Sierra. 2007. Operationalisation of norms for electronic institutions. In *Coordination, Organizations, Institutions, and Norms in Agent Systems II*. Springer, 163–176.
[3] Giulia Andrighetto, Guido Governatori, Pablo Noriega, and Leendert WN van der Torre. 2013. *Normative multi-agent systems*. Vol. 4. Schloss Dagstuhl-Leibniz-Zentrum fuer Informatik.
[4] Olivier Boissier and M Birna Van Riemsdijk. 2013. Organisational reasoning agents. In *Agreement Technologies*. Springer, 309–320.
[5] Peter Borm, Herbert Hamers, and Ruud Hendrickx. 2001. Operations research games: A survey. *Top* 9, 2 (2001), 139.
[6] Marian R Chertow. 2000. Industrial symbiosis: literature and taxonomy. *Annual review of energy and the environment* 25, 1 (2000), 313–337.
[7] Irene Mei Leng Chew, Raymond R Tan, Dominic Chwan Yee Foo, and Anthony Shun Fung Chiu. 2009. Game theory approach to the analysis of inter-plant water integration in an eco-industrial park. *Journal of Cleaner Production* 17, 18 (2009), 1611–1619.
[8] Mehdi Dastani, Leendert van der Torre, and Neil Yorke-Smith. 2016. Commitments and interaction norms in organisations. *Autonomous Agents and Multi-Agent Systems* (2016), 1–43.
[9] Theo SH Driessen. 2013. *Cooperative games, solutions and applications*. Vol. 3. Springer Science & Business Media.
[10] Luca Fraccascia, Ilaria Giannoccaro, and Vito Albino. 2017. Efficacy of Landfill Tax and Subsidy Policies for the Emergence of Industrial Symbiosis Networks: An Agent-Based Simulation Study. *Sustainability* 9, 4 (2017), 521.
[11] Hilary G Grimes-Casey, Thomas P Seager, Thomas L Theis, and Susan E Powers. 2007. A game theory framework for cooperative management of refillable and disposable bottle lifecycles. *Journal of Cleaner Production* 15, 17 (2007), 1618–1627.
[12] Davide Grossi, Luca Tummolini, and Paolo Turrini. 2013. Norms in game theory. In *Agreement Technologies*. Springer, 191–197.
[13] Mingyu Guo and Vincent Conitzer. 2008. Optimal-in-expectation redistribution mechanisms. In *Proceedings of the 7th international joint conference on Autonomous agents and multiagent systems-Volume 2*. International Foundation for Autonomous Agents and Multiagent Systems, 1047–1054.
[14] Samuel Ieong and Yoav Shoham. 2005. Marginal contribution nets: a compact representation scheme for coalitional games. In *Proceedings of the 6th ACM conference on Electronic commerce*. ACM, 193–202.
[15] Souhila Kaci and Leendert van der Torre. 2008. Preference-based argumentation: Arguments supporting multiple values. *International Journal of Approximate Reasoning* 48, 3 (2008), 730–751.
[16] Ali Kakhbod. 2013. *Resource allocation in decentralized systems with strategic agents: an implementation theory approach*. Springer Science & Business Media.
[17] Julien Lesca, Patrice Perny, and Makoto Yokoo. 2017. Coalition Structure Generation and CS-core: Results on the Tractability Frontier for games represented by MC-nets. In *Proceedings of the 16th Conference on Autonomous Agents and Multi-Agent Systems*. International Foundation for Autonomous Agents and Multiagent Systems, 308–316.
[18] Cuihong Li, Uday Rajan, Shuchi Chawla, and Katia Sycara. 2003. Mechanisms for coalition formation and cost sharing in an electronic marketplace. In *Proceedings of the 5th international conference on Electronic commerce*. ACM, 68–77.
[19] D Rachel Lombardi and Peter Laybourn. 2012. Redefining industrial symbiosis. *Journal of Industrial Ecology* 16, 1 (2012), 28–37.
[20] Andreu Mas-Colell, Michael Dennis Whinston, Jerry R Green, et al. 1995. *Microeconomic theory*. Vol. 1. Oxford university press New York.
[21] Sara Mehryar, Richard Sliuzas, Ali Sharifi, Diana Reckien, and Martin van Maarseveen. 2017. A structured participatory method to support policy option analysis in a social-ecological system. *Journal of Environmental Management* 197 (2017), 360–372.
[22] Sanjay Modgil and Henry Prakken. 2013. A general account of argumentation with preferences. *Artificial Intelligence* 195 (2013), 361–397.
[23] Martin J Osborne and Ariel Rubinstein. 1994. *A course in game theory*. MIT press.
[24] Steve Phelps, Peter McBurney, and Simon Parsons. 2010. Evolutionary mechanism design: a review. *Autonomous Agents and Multi-Agent Systems* 21, 2 (2010), 237–264.
[25] Lloyd S Shapley. 1971. Cores of convex games. *International journal of game theory* 1, 1 (1971), 11–26.
[26] Yoav Shoham and Moshe Tennenholtz. 1995. On social laws for artificial agent societies: off-line design. *Artificial intelligence* 73, 1-2 (1995), 231–252.
[27] Devrim Murat Yazan, Vincenzo Alessio Romano, and Vito Albino. 2016. The design of industrial symbiosis: An input–output approach. *Journal of cleaner production* 129 (2016), 537–547.
[28] Vahid Yazdanpanah and Devrim Murat Yazan. 2017. Industrial Symbiotic Relations as Cooperative Games. In *Proceedings of the 7th International Conference on Industrial Engineering and Systems Management (IESM-2017)*. International Institute for Innovation, Industrial Engineering and Entrepreneurship, to appear.
[29] Vahid Yazdanpanah, Devrim Murat Yazan, and W Henk M Zijm. 2016. Normative Industrial Symbiotic Networks: A Position Paper. In *Multi-Agent Systems and Agreement Technologies*. Springer, 314–321.