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An Optimization-Based Cooperative Game Approach for Allocation of Costs and Benefits in Interplant Process Integration

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Process Integration (PI) techniques have been established as an effective means of reducing resource consumption and emissions in industrial operations. Insight-based, mathematical programming and hybrid approaches have been developed to enable integration schemes to be optimized rigorously. More recently, the use of PI tools in conjunction with Industrial Ecology (IE) concepts, particularly Industrial Symbiosis (IS), has been proven to unlock the possibility of even greater gains than from integration of process units within a single player/company site. Such integration is facilitated by the advent of Eco-Industrial Parks (EIPs) which uses geographic clustering to promote sustainable exchange of materials and energy streams among different plants and companies. On the other hand, such interplant integration is not easily dealt with using classical PI methods, since the ownership of each company by an independent entity introduces a complicating aspect to the system. Specifically, each potential partner company will participate in a symbiosis scheme specifically with the motivation of increasing its own profits. However, the self-interest of each partner company often results in a conflict of interest. If such conflict is not resolved, it may result in the failure of the symbiosis scheme. To address this problem, different approaches have been developed. One general approach based on cooperative game theory involves pooling the benefits, and then subsequently developing a rational and defensible scheme for sharing the incremental profits among the partners. Maali (2009) proposed an optimization-based cooperative game model that includes theorems in a linear programming model to solve multi-objective problems and it was proved that the solutions are always Pareto-optimal. In this work, we propose an application of Maali's method for interplant heat integration. The approach is demonstrated using a literature case study, and the results are compared with those determined via alternative cooperative game techniques.

1. Introduction

Sustainability issues pertaining to climate change and natural resource consumption are now considered to be an essential aspect of decision-making in many contexts (Rockström, 2009). Process Integration (PI) techniques are well established approaches for maximizing heat recovery and thus reducing energy consumption in industrial plants (Linnhoff et al., 1982). Such reductions have also been linked to consequent reduction of emissions in Total Sites comprised of multiple plants (Dhole and Linnhoff, 1993). Furthermore, four decades of development have seen parallel development of Pinch Analysis and Mathematical Programming methods (Klemeš and Kravanja, 2013). These can be viewed as complementary approaches, with the former being suited to insight-based decision-making, and the latter being better for detailed problem solving.

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On the other hand, Industrial Ecology (IE) emerged as a framework for improving the sustainability of industrial systems by emulating highly cyclical flows found in natural ecosystems (Frosch and Gallopoulos, 1989). This philosophy underpins many aspects of IE, such as concepts involving “loop closing” through recycling and through Industrial Symbiosis (IS). The concept of IS utilizes opportunities for mutually beneficial exchanges of process wastes among different plants, so that a reduction is achieved in both the overall system-wide demand for resources and generation of wastes. It is notable that, despite the clear potential for systematic PI tools to be used as aids in planning IS schemes, historically many actual cases of IS have emerged spontaneously out of the initiative of participating firms; an excellent example is the Kalundborg IS system in Denmark (Chertow, 2007). Nowadays, there are clear attempts to induce symbiosis programs by providing close proximity and shared services to plants within so-called Eco-Industrial Parks (EIP). Also, Chertow (2007) noted that initial exchange of key industrial utilities such as energy or water often serves as a vital initial step towards more comprehensive IS networks. It has been noted that such low-risk exchanges are essential to establishing trust among companies who might potentially pursue full-fledged symbiosis as a subsequent step. PI techniques have been developed to facilitate such sharing of utilities in EIPs (Chen and Lin, 2012). Furthermore, PI approaches for Total Sites have recently been extended to account for the effects of process changes (Chew et al., 2015), uncertainties in utility price (Nemet et al., 2015), capital cost reduction (Chew et al., 2014) and sensible heat recovery (Liew et al., 2014).

One of the main challenges to the emergence of IS lies in the inherent conflicts of interest among potential partners. As noted by Jackson and Clift (1998), every firm is a “self-interested maximizer of individual profit” who might not necessarily be interested in optimizing the benefits for the entire system. By comparison, most optimization frameworks within PI implicitly assume the existence of a single decision-maker. Thus, an alternative modelling approach is necessary to model such multi-agent behaviour. Game theory has long been used as a mathematical framework to model the behaviour of multiple agents with potentially conflicting interests in various domains (von Neumann and Morgenstern, 1944). Game theory based approaches have also been developed within the context of IS and IE. The earliest reported work used a matrix game representation using emergy as a measure of sustainability (Lou et al., 2004). Chew et al. (2009) later proposed a matrix game approach for the establishment of water networks in an EIP. A static Stackelberg game model was formulated as a bi-level Mathematical Programming model for government-industry interactions in EIPs using both direct exchanges among plants (Aviso et al., 2010) and intermediate hubs through which exchanges are channelled (Tan et al., 2011). The latter models were solved heuristically via fuzzy optimization. An alternative approach based on inverse optimization was also proposed by Tan and Aviso (2012). Later work recognized the natural significance of cooperation among partners in an IS scheme (Piluso et al., 2009). For instance, Chew et al. (2011) demonstrated how incentives can be used to induce cooperation to yield Pareto optimal solutions in an EIP. On the other hand, an alternative approach is to pool total profits or savings arising from an IS program, and subsequently allocating the benefits among the partners in the EIP. A good example is the interplant Heat Integration case described by Hiete et al. (2012), who proposed the use of the Shapley value (Shapley, 1953) as a rational basis for profit-sharing.

In this work, we propose an alternative approach based on the cooperative game approach developed by Maali (2009). This approach uses an elegant Linear Programming (LP) formulation to derive appropriate shares for partners in an IS coalition, and ensures that the resulting allocation is rational from the perspective of each member as well as the entire coalition. The rest of the paper is organized as follows. Section 2 gives the formal problem statement, while Section 3 describes the model formulation. A case study based on the Heat Integration example of Hiete et al. (2012) is then solved in Section 4. Results of derived are compared with alternative solutions described previously in the literature. Finally conclusions and prospects for future work are given in Section 5.

2. Problem Statement

Let $\aleph$ be the set of all players/companies and S is a coalition of player/company i. The characteristics function value $v(S)$ can be referred as the summation of all payoffs of players/companies (x_i) to form a coalition. For instance, there are three companies (A, B and C) that interested to form a coalition, the characteristics function value will be written as $v(A \cup B \cup C)$.

Given the total benefits that accrue for every possible sub-coalition, including the grand coalition that involves all partners, the problem is to determine a rational allocation of the benefits among the partners.

3. Maali's Method

The optimization-based cooperative game model with the max-min method (Maali, 2009) is stated as follows. The optimization objective is set to maximize the independent continuous variable λ, which is given as:

$$\text{Max } \lambda \tag{1}$$

The model is subject to the following constraints:

$$\frac{1}{C_i} x_i \geq \lambda \qquad \forall i \tag{2}$$

$$x_i \geq v(\{i\}) \qquad \forall i \tag{3}$$

$$\sum_i x_i = v(\aleph) \qquad \forall i \tag{4}$$

where C_i is Maali's variable, which can be determined as:

$$C_i = \sum_S [v(S) - v(S - \{i\})] / v(\aleph) \qquad \forall i \tag{5}$$

4. Case Study

A case study from literature example (Hiete et al., 2012) is resolved to demonstrate the proposed approach. Four companies (A = pulp production, B = bio-oil production, C = fibreboard and D = torrefaction) are located in an industrial cluster. Three of them (A, B and C) are interested in forming an EIP to promote heat integration within the industrial cluster. They tried to encourage company D to join the EIP. In this case study, two scenarios are considered to determine the allocation of savings via proposed approach. In Scenario 1, company D is not included in the optimization whereas Scenario 2 presents the allocation of savings for all companies. Table 1 tabulates the potential savings from different coalitions as compared to individual process integration. Note that the values are obtained from Thermal Pinch Analysis, including calculation of capital costs, piping system and necessary backup utilities investments as performed by Hiete et al. (2012).

Table 1: Comparison of savings arising from different coalitions (Hiete et al., 2012)

Coalition $v(S)$	Potential savings compared to individual process integration (in 1,000 US$)
{A}	–
{B}	–
{C}	–
{D}	–
{A,B}	13
{A,C}	18
{A.D}	129
{B,C}	121
{B,D}	0
{C,D}	0
{A,B,C}	130
{A,B,D}	142
{A,C,D}	146
{B,C,D}	121
{A,B,C,D}	259

The allocation of savings for companies A, B and C is performed in Scenario 1. First, the value of Maali's variable, C_i is determined from Eq(5).

The LP model is:

$$\text{Max } \lambda \tag{6}$$

Subject to

$$3.2500x_A \geq \lambda \tag{7}$$

$$0.5285x_B \geq \lambda \tag{8}$$

$$0.5078x_C \geq \lambda \tag{9}$$

$$x_A,\ x_B,x_C,\ \lambda \geq 0 \tag{10}$$

$$x_A + x_B + x_C = 130{,}000 \tag{11}$$

The linear programming model is solved via LINGO v13.0. The savings of companies A, B and C are approximately US$10,000, US$59, 000 and US$61,000 in this scenario.

In Scenario 2, the steps presented previously are repeated by including company D in the coalition in this scenario. Since more savings can be obtained with the participation of company D in the EIP, the approximate savings of US$73,000, US$60,000, US$63,000 and US$63,000 for each company are calculated in this scenario. The results for both scenarios are tabulated in Table 2.

Table 2: Detailed saving allocation of both scenarios (in 1,000 US$)

Company	Scenario 1	Scenario 2
A	9.60	72.90
B	59.00	60.40
C	61.40	62.60
D	-	63.10
Total	130	259

An alternative cooperative game technique – Shapley value which introduced by Shapley (1953) is used to compare with the results obtained from Maali's method in this work. The formula of Shapley value is given as:

$$x_i = \sum_{S \subseteq N\setminus\{i\}} \frac{|S|!(n-|S|-1)!}{n!}\left[v(S \cup \{i\}) - v(S)\right] \qquad \forall i \tag{12}$$

Figures 1 and 2 shows the comparison of the proposed method and Shapley value for both Scenario 1 and 2.

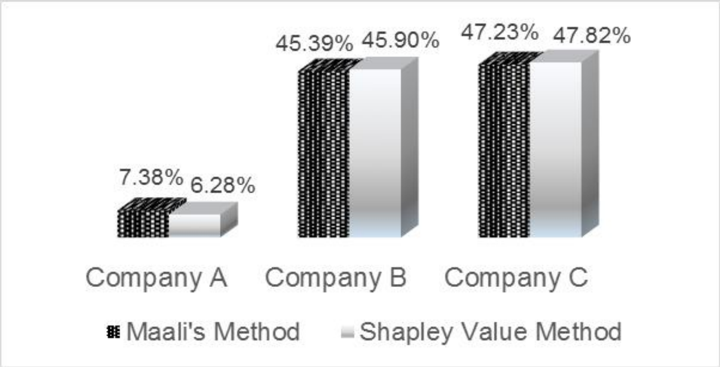

Figure 1: Comparison of Maali's method and Shapley value for Scenario 1

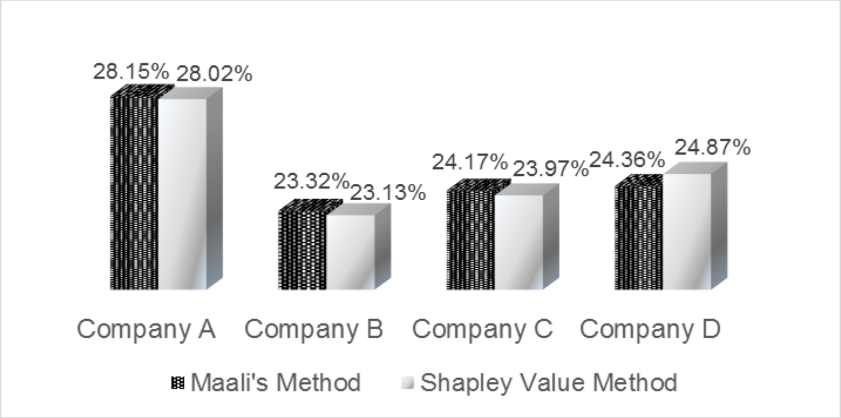

Figure 2: Comparison of Maali's method and Shapley value for Scenario 2

5. Conclusions

In this work, an approach towards optimal allocation of costs and benefits in cooperative interplant Process Integration in EIPs has been demonstrated. This approach is based on the cooperative game approach developed by Maali (2009), which uses an LP formulation to determine the appropriate shares, given the potential benefit determined for every possible sub-coalition. This method has been applied in this paper to a case of Thermal Integration among multiple industrial plants, where pooled net savings that accrue from reduced energy consumption are shared among the partners. Future work will focus on extending the proposed approach by integrating the game theoretic model within a disjunctive programming Network Synthesis model.

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