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Abstract

Industrial symbiosis (IS) is cooperation between companies to achieve collective benefits by supplying and reusing industrial waste to substitute virgin resources in production. In this paper, we investigate the IS phenomenon from a supply chain management perspective. We propose a collaborative planning model to coordinate master planning of operations of waste suppliers and buyers. Furthermore, we analyze planning decisions related to IS when waste exchange is combined with virgin resource procurement. We demonstrate that conditions of virgin resource procurement affect the economic feasibility and waste utilization potential of IS.

Keywords: industrial symbiosis, operations, collaborative planning

Introduction

Resource efficiency is a key aspect in relation to the economic and environmental dimensions in sustainable supply chain management. A well-known way to improve resource efficiency of operations is reusing waste (Gupta, 1994). In industrial symbiosis (IS) one company's industrial waste (e.g., by-products, excess energy, and residual resources) substitutes virgin resources in another company's production process (Chertow, 2000). IS typically involves previously economically unrelated companies and manifests in close geographical proximity, for example, in industrial parks or within geographical regions. Companies in IS leverage synergies between each other by simultaneously reducing waste disposal costs and virgin resource needs. Besides these economic benefits, the general environmental contributions of IS are resource savings and reductions in pollution emission (Mirata, 2004).

From a supply chain perspective, IS is in contrast with traditional forward and reverse supply chains (Bansal and McKnight, 2009). While the supply network of an industry delivers and recycles certain types of end-products, IS connects different industries through their waste streams that would otherwise end up in landfills, water, or air. There are several examples of IS all over the world (e.g., Chertow, 2000; Heeres et al., 2004; Gibbs and Deutz, 2007; Behera et al., 2012). For example, in Kalundborg, Denmark, in the best-known and most studied example of IS, eleven companies from different industries utilize synergies through 7 energy and 12 waste streams, and form an inter-organizational unit of the local industries for collective benefits. Although in many cases IS refers to a network of companies, the synergies do however operate independently from each other. In other words, an IS network consists of individual bilateral relationships and each of these manifests a symbiosis. The goal of this paper is to analyze the coordination of these individual operations.

The academic literature mostly discusses IS from an industrial ecology perspective, focusing on e.g. the organizational framework (Behera et al., 2012), evolution and development (Gibbs and Deutz, 2007; Chertow, 2007), and innovation capability and organizational learning (Baas and Boons, 2004; Sterr and Ott, 2004). Furthermore, the literature recognizes the coordination challenges of organizing IS between previously unrelated companies and their willingness to collaborate (Mirata, 2004; Bansal and McKnight, 2009). In contrast, there is not much literature related to supply chain coordination and operations management in IS networks, even though the waste exchanges are a kind of buyer-supplier relationship. Some previous work has however been done, but mainly related to strategic planning. Cimren et al. (2011) proposed a mathematical model for optimal network design of IS considering annual production volumes in a set of potential companies that need to decide whether to participate in IS or not. More recently, Lee (2012) analyzed different market conditions for determining profit-maximizing operating strategies for a company that wants to implement industrial waste reuse inside their own organization.

In this paper, we focus on tactical level planning of operations in bilateral IS. On this planning level, the emphasis is on the master planning of operations in and outside IS. In most waste reuse scenarios, some storage or waste treatment is required, or additional procurement of virgin resources is necessary. These activities obviously increase overall costs of the waste exchange and influence the economic feasibility of IS.

In the following sections, first we discuss the relevance of collaborative planning of operations in IS. Then we propose a collaborative planning model for IS to analyze its additional economic costs and benefits. To demonstrate our decision model, we present an analysis of resource procurement costs in IS. The decision model includes resource procurement in and outside IS. The goal of the model is to capture the economic and environmental aspects (i.e. waste utilization) related the supply-demand interactions, to (i) increase the understanding of IS and (ii) support price setting for companies involved in IS, or considering to become involved. As such, we identify trade-offs for companies when operating in IS under different scenarios.

Related literature

Collaborative relations build on trust and expectations of long-term business relationships (Hoyt and Huq, 2000). Supply chain collaboration assumes close co-operation and coordination between business partners on aspects like information sharing and joint planning of operations (de Leeuw and Fransoo, 2009). Coordination of operations requires supply chain members to include each other's plans at different levels of the planning hierarchy resulting in joint decision making, to improve the overall economic, operational and environmental performance. Although collaboration develops with information sharing, at different planning levels companies might be reluctant to share specific information resulting in information asymmetry. Collaborative planning is a joint decision making procedure for aligning plans of individual supply chain members assuming information asymmetry (Stadtler, 2009).

In general, supply chain planning is often divided over three levels: strategic, tactical and operational (Fleischmann et al., 2008). Typically, master planning of operations on the tactical level considers a planning horizon of 3-12 months and consists of procurement, production, and distribution decisions. Collaborative planning on the tactical level coordinates these domains between supply chain members. Collaborative planning, unlike central planning, often assumes an iterative negotiation procedure where conflicting objectives need to be considered (Stadtler, 2009). For instance, Dudek and Stadtler (2004) suggested a procedure in which the optimization models of individual planning domains are extended to include each other's preferences. Although the partners' proposals usually cause deviations from the locally optimal plans, the overall performance of the supply chain is improved.

IS relates to an industrial community that seeks enhanced economic and environmental performance through collaboration (Lowe, 1997). Nonetheless, a sustainable business model, which offers collective and fair benefits, is the most important enabler of IS (Behera et al., 2012). Furthermore, trust and willingness to co-operate also have significant importance in IS relationships (Gibbs and Deutz, 2007). In fact, IS often facilitated by the underlying community that shares information (Baas and Boons 2004). The collaborative behavior during the development phase shows in information sharing about the waste streams and resource demands as well as methods of recycling (Sterr and Ott, 2004; Grant et al., 2010). The collaboration often starts with negotiation to ensure a fair sharing of benefits (Behera et al., 2012). Furthermore, collaboration in IS is often coordinated by a central organizational unit, which has a central focus on developing synergies (Mirata, 2004). The most important role of the central coordination is to find partners whose supply and demand of waste streams match. This kind of "match-making" often focuses on a certain industrial area but can also take place on a national level, such as in the case of the National Industrial Symbiosis Program in the UK (Mirata, 2004).

The greatest economic benefit attributed to IS is the geographic proximity between the partners, and the resulting low transportation costs. Nevertheless, focusing on a larger scale obviously offers more potential relationships (Sterr and Ott, 2004), even though the increased distances might reduce its attractiveness. Moreover, waste disposal costs and virgin resource prices are also important enablers for IS (Lee, 2012).

As mentioned earlier, some work has been done on the strategic planning level, studying the aggregate match of waste supply and demand (Cimren et al., 2011), and on the development of production strategies when adding a waste stream to a product portfolio (Lee, 2012). On the other hand, IS has not been previously investigated on tactical level. The effect of industrial waste reuse on production and inventories has however been discussed in Ferdows and Carabetta (2006), but this work focuses on highly integrated production systems. Companies in IS are not integrated in terms of production and they operate their individual supply chains. Our work contributes to the literature by discussing master planning of waste supply and reuse in IS where suppliers and buyers are economically independent.

Considering the collaborative nature of companies in IS, some level of collaboration in planning can also be expected, and a collaborative planning model can be developed to support this activity and provide a sound basis for the sharing of costs and benefits. Such a collaborative planning model also allows improving waste utilization and resource efficiency.

Collaborative planning model for industrial symbiosis

This section follows Stadtler's (2009) work on collaborative planning model development, whose general framework translates into the following three steps in the IS setting: (1) the structure of IS and the relationship among its members (2) the decision situation facing each member and (3) the characteristic of the collaborative planning procedure.

Structure and relationships in industrial symbiosis

Although the IS phenomenon is used to describe an entire system of supplier-buyer connections, the bilateral synergies create a network of two-tier supply chains. The two tiers may however involve several suppliers and buyers as well as different waste streams. If a supplier provides more than one type of waste stream, we assume in this paper that these are coordinated separately. For example, the power plant in Kalundborg provides gypsum and excess heat as two separately coordinated waste streams. However, if a supplier provides the same type of waste stream to more than one buyer then they need to be coordinated simultaneously. For example, the excess heat provided by the power plant is utilized in several other factories. On the other hand, a buyer may procure more than one type of waste stream or the same type from different sources and utilize it in one production process. For example, the bioethanol factory in Kalundborg often procures different types of biomass residue (e.g. wheat straw and corn stover) from farmers. Considering the different types of structures between two tiers, the smallest building block in IS is the bilateral relationship. Depending on the number of suppliers and buyers on the tiers these relationships based on one waste stream type need to be coordinated either separately (1-1) or simultaneously (1-*n*; *n*-1).

In this paper we focus on IS between two or more production companies. Furthermore, we assume these production companies operate on separate markets and thus have individual supply chains. Therefore, it is important to point out that coordinating IS does not necessarily mean the coordination of production on either side. We assume here that changing the actual production plans in IS to improve the waste exchange would either result in increased inventories or in backorders or lost sales. We note that this kind of coordination of waste streams is not unseen, but it assumes a more integrated production (Ferdows and Carabetta, 2006). Due to the fact that companies in IS are not integrated, we assume fixed production quantities, which determine the quality and temporal distribution of waste supply and demand. The operations related to IS are the treatment, storage, distribution, and procurement of the waste stream.

It is important to note that both supplier and buyer participate in IS because they capitalize and reduce cost, respectively. In other words, if IS did not provide economic benefits for both of its tiers then it would not work. Instead of IS both tiers would operate with the original form of disposal and procurement. For example, the power plant in Kalundborg could discharge its excess steam in the sea; or the cardboard manufacturer may procure only mined gypsum. Depending on treatment, storage, and additional procurement costs, as well as the way these are shared, companies might find IS economically infeasible. Therefore, “sustainable” IS coordination needs to provide a solution that is economically feasible for both tiers and it also maximizes waste utilization. From an economic perspective, IS competes against waste disposal and virgin resource procurement costs and the negation power of the two tiers regarding the price of waste depends on the relative costs of original operations compared to the IS alternative. If the disposal of a certain type of waste is costly then the buyer of the waste has more power to set the price. On the other hand, when there is no disposal fee, for example due to a lack of environmental regulation, or the supplier has more buyers to choose from, or the buyer has high virgin resource procurement costs, then the supplier has more negotiation power.

Decision situations in industrial symbiosis

In the following, we elaborate on the decision context that IS encompasses and adds to the original supply chain operations. We focus on the tactical level master planning of operations in a two tier IS. According to Stadler's (2009) framework we answer the following questions: when and which decisions take place with which objectives and what kind of information is exchanged.

In general, collaboration between two parties starts with determining the conditions of collaboration, which often incurs negotiating the terms of a contract that is valid over a certain period of time (Stadler, 2009). Similarly, one of the most important steps prior to implementation of IS is negotiation (Behera et al. 2012). To come to an agreement the two tiers need to consider their waste supply and demand quantities, as well as their individual master plans for the upcoming planning period (i.e., 3-12 months), to take into account possible temporal mismatches. Before the two tiers come to an agreement they need to know how IS would affect their disposal and procurement costs, which basically determines the economic feasibility of IS and consequently the agreed price of the waste. Note that the economic feasibility of IS based on tactical level considerations can also be used to support strategic decisions, for example, whether or not to participate in IS or to find out the most efficient *1-n* network structure.

With IS, the supplier avoids disposal fees. For example, the pharmaceutical company in Kalundborg avoids disposal fees by selling its biomass residue to farmers instead of landfilling it. Moreover, the supplier expects to earn profit from selling its waste. Consequently, the supplier wants to allocate its waste stream between potential buyers in the most profitable way. On the other hand, while disposal is an on-demand option in IS, the waste supply is subject to the demand that has restriction on quality and quantity. Consequently, the supplier needs additional treatment and storage operations, which incur costs. Therefore, before setting a waste price the supplier needs to know how its total costs would change with respect to a certain demand on its waste.

The buyer expects to reduce its resource procurement costs in IS. On the one hand, this depends on delivery distance between supplier and buyer in IS. On the other hand, it depends on the relative price of the waste compared to the virgin resource. In fact, when the IS alternative is closer and waste is cheaper and the supply can cover all the demand then the buyer clearly reduces its procurement costs. However, when the buyer needs to combine the IS alternative with its original virgin resource supplier then the economic feasibility of IS might change. When the buyer procures fewer resources from its original supplier than it previously did, we assume that the buyer enters to a different contract with the supplier and faces with a higher virgin resource price per unit. Consequently, before participating in IS the buyer needs to know how its total costs would change with a certain waste supply.

In this system the decision domains, which can be represented with interconnected optimization-based decision models, have conflicting objectives: the supplier tier aims to maximize profit while the buyer tier aims to minimize costs. The agreed waste price should somehow balance these aims. Using collaborative planning, the supplier and buyer tier could negotiate on a (fair) price that makes IS economically feasible for both of them. The resulting conditions of collaboration determine the master plan of the IS for the following planning horizon that changes the original waste disposal and procurement plans.

In collaborative planning, information asymmetry exists during the negation process. This means that some information (e.g., related costs) might be hidden from the negotiation partner. For example, in IS it is possible that the buyer is reluctant to share the virgin resource price(s) with the supplier in order to keep its bargaining position. Similarly, the supplier might be reluctant to share its disposal, treatment and storage costs with the buyer for the same reason. On the other hand, in a collaborative "match-making" event, potential IS participants share their (expected) amount of waste that will

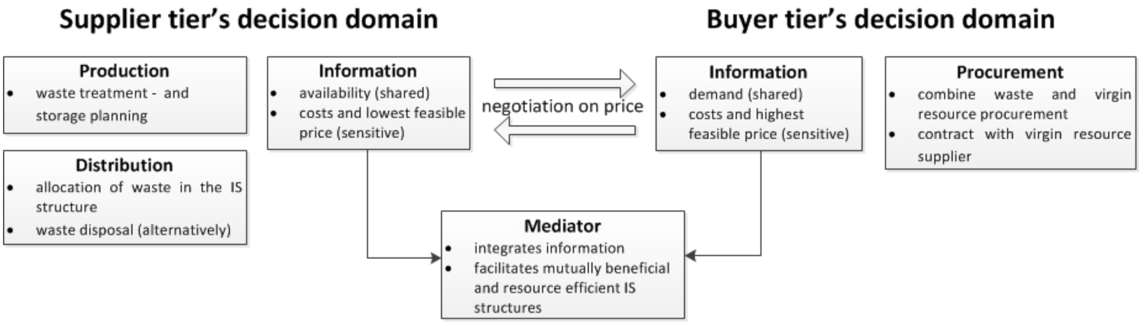

Figure 1 - Collaborative model for master planning in industrial symbiosis.

occur in production during the planning period; and similarly, they share their (expected) resource requirements. Figure 1 depicts the structure of the proposed collaborative planning model, including the procurement, production, and distribution decisions, as well as the information used in the negotiation process.

A collaborative planning procedure for industrial symbiosis

The collaborative planning procedure governs the negotiation between the tiers. The procedure often uses a mediator (an "interface") for facilitating communication and the procedure's goal is to provide a solution that both tiers accept (Stadler, 2009).

In collaborative planning terms the central organizational unit of IS is a mediator, who is supporting the interactions among members (see Figure 1). During the development of IS the mediator keeps track of available waste streams in the region and facilitates businesses between suppliers and buyers. To identify and assess opportunities during this procedure information and communication technology tools integrate information related to waste generations and reuse opportunities in a database (Sterr and Ott, 2004, Grant et al., 2010). During the collaborative planning procedure the mediator of IS might play the role of an honest broker that is familiar with data (e.g., lowest and highest feasible waste price) that members are reluctant to share with each other. Thereby, the mediator is able to support the negotiation on a fair price for example in a *1-n* IS. Moreover, the mediator has its own objective: maximizing waste utilization. The mediator has overall picture of all supply and demand in a given region, therefore, it is able to estimate and facilitate the most resource efficient IS networks.

In collaborative planning it is important to select who starts the negotiation (Stadtler, 2009). In IS waste availability (e.g., time and quantity) is the bottleneck of collaboration. Therefore, collaborative planning has to start downstream, with a proposal of availability from the supplier. In this first iteration the proposal contains the quantity and the temporal distribution of the waste and the unit price that would cover the planned costs as well as the supplier's expected profit. Next, the buyer either accepts the proposal or suggests a counter-proposal with different delivery times and quantities at perhaps a lower price that makes IS economically (more) beneficial. In the next iteration the supplier takes this proposal and calculates the resulting storage, treatment and additional disposal costs and decides whether or not to accept the buyer's proposal. If the conditions are not acceptable the supplier suggests a counter-proposal with different conditions. This iterative procedure continues until the IS members come to an agreement or reject the idea of IS due to economic infeasibility. Ideally, the procedure will result in a situation where all members of the IS leverage fair economic benefits. However, win-win situations might still differ in terms of waste utilization. For example, a buyer in IS will choose to procure less waste and obtain virgin resources at a cheaper price if that reduces its procurement costs. On the other hand, the mediator is able to

Table 1 – Virgin resource supply with 5 contract types for 0-12000 units

Contract type	**1**	**2**	**3**	**4**	**5**
Price (per unit)	2.00	1.75	1.50	1.25	1.00
Volume range (units)	0-2400	2400-4800	4800-7200	7200-9600	9600-12000

improve overall resource efficiency by facilitating those potential and mutually beneficial IS relationships structures that result in better waste utilization.

Preliminary findings – the buyer's perspective

In this section we discuss the buyer's economic preferences in IS in some theoretical scenarios. We consider one supplier with a specific and limited waste stream that is provided according to the supplier's main production plan. The buyer tier consists of one buyer, who is able to use the waste to substitute virgin resources in its production. Besides the IS alternative the buyer also has an original supplier. We assume that the supplier outside IS offers virgin resources at different prices (monetary unit (MU)/unit), such that for lower amounts the corresponding price is higher. The resulting pricing function is a step function, which means that each price corresponds to a range of amounts, following the commonly used all-units quantity discount (e.g. Dolan, 1987). In the following we refer to these ranges as contract types (see Table 1 for an example). Note that the virgin resource supplier is indifferent to the quantity within a contract, which gives flexibility to the buyer. On the other hand, this price structure also limits the buyer because it is not able to choose price in-between two contract offers.

From the buyer's perspective, when a limited amount of waste is available, it will need to choose a contract with its virgin resource supplier to cover its production. We created an optimization model that models the buyer's cost minimizing decision. The model was used in experiments with potential waste supply/demand coverage ratios (1-90%), which represent the available waste quantity, and different waste unit prices considered between 0.05-0.95 MU/unit. In each experiment, the buyer needs to decide which contract it chooses and how much waste it procures. The buyer faces a trade-off between these two options: the more waste it procures, the higher the unit price in the contract with the original supplier becomes. Different parameter combinations not only result in different optimal costs, but also result in different waste utilizations and different feasible waste unit prices that allow maximum utilization.

Due to its quantity flexibility, each contract normally allows the buyer to procure some waste (i.e. the difference between the total resource demand and the lowest amount that the contract allows). In the extreme case where there is only one contract, which is completely indifferent to the procured quantity, the buyer may utilize all the waste and procure the missing amount of virgin resources at the same price as without IS. As the number of contract offers increases, the buyer has less and less flexibility within each contract and it may utilize less waste instead of choosing a more expensive contract. In other words, each contract has a minimum waste supply/demand coverage above which it pays off to choose that contract and a maximum waste supply/demand coverage that the contract allows to fully utilize. These minimum and maximum amounts also depend on the waste unit price. To illustrate the above-mentioned behavior, consider that the buyer needs 1000 units of resources over 12 month and it can choose between five contracts offered in Table 1. Note that the price differences between the contracts and the quantity ranges are equal. When the potential waste supply/demand coverage is low (i.e. maximum 20%) the buyer is able to utilize all waste and stay with the cheapest virgin resource contract (i.e. 1 MU/unit). Above 20% coverage ratio, the waste utilization decreases to around 55% until the point (app. 37%

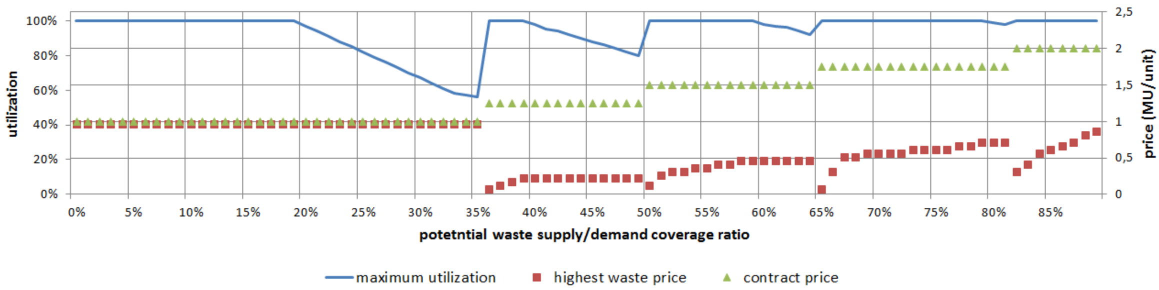

Figure 2 – Waste utilization and resource prices in IS.

coverage ratio) when it pays off to choose the second contract (i.e. 1,25 MU/unit). Above this point full utilization is again possible until the maximum coverage ratio (i.e. 40%) of the contract is reached.

According to Figure 2 this utilization pattern repeats along different coverage ratios. Note that the full utilization interval that a certain contract allows improves as the coverage ratio increases. In other words, as the potential waste supply increases, the earlier it becomes economically beneficial to choose a more expensive contract and utilize all waste. This is because the costs savings attributed to IS increase with the amount of waste procured.

Waste unit price also affects the buyer's choice and consequently maximum utilization. When the buyer chooses a more expensive contract first it can afford that only at a low waste unit price (see Figure 2). Above that price only partial utilization would be feasible. According to Figure 2, the highest affordable waste price within a given contract is reached with the maximum waste supply/demand coverage ratio that the contract allows. Furthermore, the highest affordable price depends on the cost saving attributed to IS. Therefore, the highest affordable waste unit price increases with the potential supply/demand coverage. For example the cardboard manufacturer in Kalundborg represents the beginning of the curves in Figure 2 because the gypsum waste, procured from the power plant, covers only a small part of their resource demand. The pharmaceutical company represents the other end because the excess heat from the power plant covers most of their steam requirement. However, note that real life contracts can be very different from ones we used in the experiments.

When there are more contracts to choose from the quantity range in each contract decreases. Consequently, the maximum utilization curve that corresponds to different waste supply/demand coverage ratios also changes (see Figure 3). When the coverage ratio is relatively low the maximum utilization decreases as the number of contracts increases because the quantity range of the contract is more limiting. However, as the potential coverage ratio increases maximum utilization becomes less and less sensitive to changing between different contracts. Note that the more contracts to choose from the earlier (i.e. the lower coverage ratio) this positive effect occurs and after a certain number of contracts the buyer will be able to choose a contract that allows maximum utilization regardless the coverage ratio (see Figure 3).

Conclusion and future work

Based on our preliminary findings we conclude that the feasibility and resource efficiency of IS from the buyer's perspective depends on the potential waste supply/demand coverage ratio and on the relationship that the buyer has with its virgin resource supplier. We find that when the buyer needs to procure resources outside IS then the supply contracts offered by the virgin resource supplier limit the feasibility and resource efficiency of IS. Each contract allows the buyer to operate within a range of

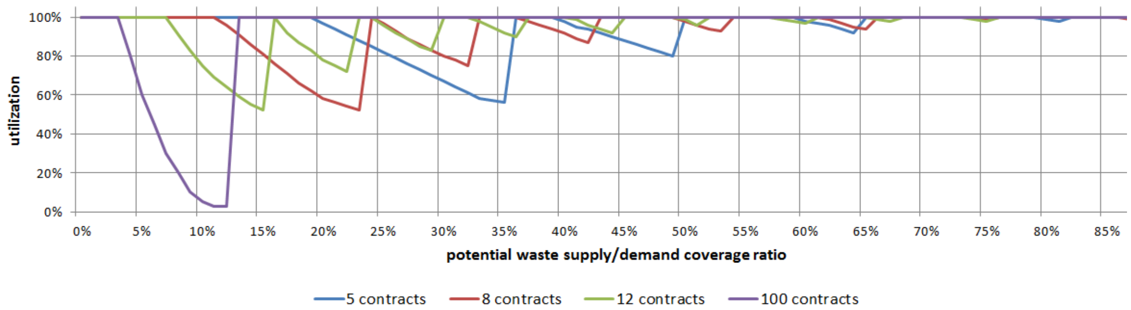

Figure 3 – Maximum waste utilization with different virgin resource contract numbers.

waste quantities. Cost savings in IS are maximized when the maximum amount of waste that the contract allows is procured. Also, this maximum waste utilization allows the highest affordable waste unit price. On the other hand, waste above the maximum utilization of a contract will not be procured. It is important to point out that in real life a buyer might have only a few choices regarding the number of contracts and the characteristic of contracts might not be that "equal" as the example in Table 1. Consequently, the curves that influence the buyer's decision are unique.

In this paper, we analyzed the buyer's perspective, and will focus more on the supplier's perspective and the overall IS perspective in future work. Based on the analysis in this paper, some statements on these perspectives can however already be made. Theoretically, from the supplier's perspective it might be more profitable to supply less waste to a buyer, who thus operates with a cheaper contract and can afford higher waste unit price. On the other hand, in this case the buyer has higher procurement costs and lower utilization is achieved. Nevertheless, the leftover waste can be supplied to another buyer if that is possible. In fact, when the supplier has more buyers to choose from (i.e. a 1-*n* IS structure), it faces a decision problem of how to allocate its waste in the most profitable way. Moreover, the supplier needs to consider the additional treatment and storage costs according to the individual demands. When the supplier has more potential buyers the supplier is better off to split its waste stream if this allows the buyers to operate with a cheaper virgin resource contract and pay higher waste unit price. Note that splitting the waste stream might lead to better utilization at a fixed waste price.

Normally, the supplier is not familiar with the buyers' contract types due to information asymmetry. Therefore, it would be difficult for the supplier to optimize waste allocation between the potential buyers. On the other hand, buyers are familiar with the available waste quantity, which is usually revealed before the negotiation. Consequently, each buyer is familiar with potential cost savings of IS that allows them to optimize their procurement plan. When the waste stream is split between more buyers there actual potential saving might be less than the expected. This can lead to further conflicts and reluctance to participate.

Collaborative planning usually resolves these conflicts. The mediator is able to facilitate the negotiation between a waste supplier and more buyers in a way that it improves waste utilization and offers fair benefits for every participant. Furthermore, the mediator in IS has a unique role in terms of resource efficiency in collaborative planning, which can be reflected in strategic decisions. Therefore, we believe that the role of collaborative planning increases with the number of potential buyers. In national industrial symbiosis programs where IS is considered in a geographical region it is likely that a supplier finds more potential buyers for its waste stream. Consequently, collaborative planning would support these national initiatives.

In the future we will extend the collaborative planning model with the supplier's decision model. After this, we will experiment with different potential IS structures in which we aim to improve waste utilization and also provide fair benefits for each member.

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