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The impact of Information Sharing and Waste Treatment Lead Time in Symbiotic Supply Chains: a Simulation study

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Abstract

Symbiotic supply chains offer companies a valuable opportunity to embrace the Circular Economy model, which aims to effectively utilize waste. Despite growing interest in this area, there exists research lacks on the dynamic behavior of symbiotic supply chains, a crucial aspect in traditional supply chains. This study seeks to fill this gap by analyzing the dynamics of two supply chains that implement a symbiotic exchange of waste at the manufacturer level. We focus on evaluating their performance based on two key factors: (1) information sharing between the supply chains and the (2) waste treatment lead time. Using agent-based modeling simulation, through a full-factorial design of experiments, we assess performance in various scenarios. The results highlight the significant impact of symbiotic flows on the dynamics of the participating supply chain member.

Keywords: Symbiotic Supply Chains; Circular Economy; Agent-based Modeling Simulation

1. Introduction

To meet economic, environmental, and social needs, traditional Supply Chains (SCs) need to overcome the linear "take-make-dispose" economy and embrace the transition to a more sustainable approach proposed by the Circular Economy (CE) (Foundation, 2013; Batista et al., 2023). CE promotes collaborative mechanisms that transform waste or secondary outputs into resources for other processes or for other SCs (Howard et al., 2019). Industrial Symbiosis (IS) aligns with the CE, fostering relationships and exchanges among different entities to convert waste materials into value for other firms (Chertow et al., 2021). IS aims to reduce by-products and negative environmental impact, making it conducive to CE development. It involves material, energy, and information flows among firms, introducing new relationships between previously unrelated companies that form Symbiotic SCs (SSCs) (Turken and Geda, 2020; Turken et al., 2020), in contrast to traditional Forward SCs (FSCs) where interactions are typically limited to upstream and downstream entities. Understanding the dynamics of SSCs is crucial due to their potential impact on operational performance. However, limited research has explored the role of IS in SCs, necessitating a consolidation of the current state of the art. Notably, the Bullwhip Effect (BE), a widely investigated phenomenon in SC research, that pertains to order and inventory fluctuations (Papanagnou, 2021; Moritz et al., 2022), has not yet explored in the context of SSCs. The BE occurs in about two-thirds of firms, and it may impact their profitability up to the 30% due to increased on inventory costs, deteriorates customer service level, and logistics and transportation inefficiency (Braz et al., 2018; Framinan, 2022). Thus, is it essential to manage this detrimental effect on SC performance, and several authors have investigated it in FSCs (Yang et al., 2021).

Motivated by the aforementioned considerations, our objective is to address the existing research gap and contribute to the understanding of SSC dynamics by investigating their dynamic performance and the influence of symbiotic mechanisms on the BE. Specifically, through the Agent-based Modeling Simulation (ABMS) technique we study the BE in a SSC that represents two traditional SCs implementing IS mechanisms. In this model, we integrate the conventional inputs from the forward flow for one member, known as the Waste User, with the waste flow provided by another member, the Waste Producer, belonging to a different SC. Our focus is on examining the inter-SC information sharing policies within SSCs and the impact of the waste treatment lead time, which refers to the time required to process waste into suitable inputs for the member receiving them in place of new virgin resources. Using a Design of Experiments (DoE) approach, we compare scenarios involving symbiotic exchange with a baseline scenario without any IS implementation. We evaluate the performance of the Waste User through commonly used metrics to detect the BE. By doing so, we highlight the significance of studying the dynamics of these SCs, as their operational performance is influenced by the presence of IS.

The rest of the paper is structured as follows. Section 2 exposes a summary of the current state of the art for IS and SSCs. Section 3 describes the SSC model, the assumptions and the methodological approach, together with the experimental design and the metrics. Then, Section 4 discusses on the obtained results from the simulations. Finally, Section 5 provides the conclusions and future research directions.

2. State of the art

Initially defined by Chertow (2000), IS involves the exchange of materials, energy, water, and/or by-products between separate firms in a collective approach. The purpose of IS is to substitute primary inputs, such as virgin resources, in production processes with wastes from other processes. This reduces the need to purchase resources from traditional suppliers, thus raw material extraction. Indeed, IS has gained attention for its potential in sustainable development, offering cost reductions, increased revenues, and competitive advantages (Fraccascia, 2019).

The existing literature primarily consists of case studies with diverse objectives (Neves et al., 2020). Jacobsen (2006) focused on the understanding of economic and environmental performances connected to the Kaludnbung case in Denmark. Morales et al. (2019) analyzed the industrial ecosystem evolution of the Altamira symbiosis in Mexico. Biava et al. (2023) proposed a strategy for managing industrial waste and reducing the use of virgin raw materials for the Bergamo–Brescia case in Italy. In addition, various studies have highlighted the challenges and sources of uncertainty in IS, such as supply/demand tradeoffs and understanding the collaboration in IS networks (Guedes et al., 2019). For instance, Albino et al. (2016) analyzed the efficacy of contractual mechanisms for IS networks characterized by diverse levels of uncertainty and turbulence. Fraccascia and Yazan (2018) assessed the role of online information-sharing platforms in supporting IS relationships. Neves et al. (2020) provided a comprehensive review of previous studies on IS. Demartini et al. (2022) carried a systematic literature review on the modeling approaches used in the IS design and analysis. Zhang et al. (2021) carried a comparative review on the state-of-the-art practices and research in circular SC chain and find out that SC researchers have not conducted much research on IS and its associated open-loop circularity archetype. Moreover, the need for standardization has been recognized as a main issue that need to be resolved to appropriately manage IS settings (Guedes et al., 2019; Neves et al., 2020).

Table 1. Acronyms and Notation

Notation	Description
CE	Circular Economy
SC	Supply Chain
FSC	Forward Supply Chain
IS	Industrial Symbiosis
SSC	Symbiotic Supply Chain
BE	Bullwhip Effect
ABMS	Agent-based Modeling Simulation
DoE	Design of Experiments
OUT	Order up to
WIP	Work in process
ε	Inter-Supply Chain Information Sharing
TP	Waste Treatment Process
μ_{L_t}	Mean Waste Treatment Lead Time
k	Supply Chain index
i	Supply Chain echelon index
L_{ki}	Lead time of echelon *i* in Supply Chain *k*
L_T	Treatment Lead time
$\mu_{D_{C_k}}$	Mean customer demand of Supply Chain *k*
$\sigma^2_{D_{C_k}}$	Variance of customer demand of Supply Chain *k*
O_{ki}	Order placed by echelon *i* in Supply Chain *k*
I_{ki}	Inventory of echelon *i* in Supply Chain *k*
WIP_{ki}	Work in process of echelon *i* in Supply Chain *k*
B_{ki}	Backlog of echelon *i* in Supply Chain *k*
W	Waste generated by the Waste Producer

From the SC perspective, by expanding traditional FSCs to include symbiotic members and resource and information sharing, IS contributes to the development of what Turken and Geda (2020) refer to as SSCs. SSCs combine the goals of customer satisfaction, minimizing non-product output disposal, and improving resource efficiency. However, just few authors have focused on SSCs specifically from the operational point of view. Che et al. (2021) developed a game model to study the influence of the degree of symbiosis. Daquin et al. (2023) presented a mixed-integer linear model with the aim of optimizing the production planning of SSCs. Yang et al. (2023) derived the analytical forms of the equilibrium solution for order quantities and the wholesale prices of recycled materials.

3. Materials and Methods

To analyze the SSCs dynamics, we utilize the structure illustrated in Figure 1. In general, SSCs face greater uncertainty regarding the quantity and quality of materials compared to traditional FSCs due to the complex and adaptive nature of IS, which makes simulation a suitable solution to study this kind of SCs. Thus, as methodological approach for our SC model, we selected the ABMS, which is particularly implemented in modeling complex phenomena and is increasingly recognized in scientific disciplines (Abar et al., 2017; Innocenti et al., 2022). Specifically, it is widely used in the SC dynamics literature, see e.g. Dominguez et al. (2021) and Naghavi et al. (2020). In addition, it has been recently also adopted to advance the knowledge in the IS field (Demartini et al., 2022; Wang et al., 2022), see e.g. Yazan and Fraccascia (2020) and Yu et al. (2021). Hence, such a method is appropriate to study SSCs dynamics. The ABMS ha been carried with the software AnyLogic.

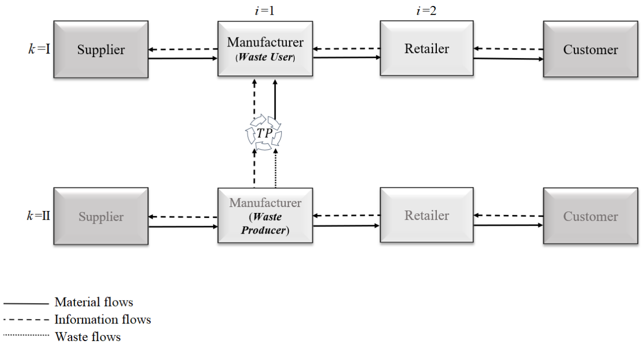

Figure 1. Symbiotic Supply Chain structure

Our model comprises two conventional FSCs (k=I, II). Each FSC consists of a manufacturer (i=1) and a retailer (i=2), with external supplier and customer. The manufacturer in the k=II SC, referred to as the Waste Producer, in the process of addressing its incoming demand generates waste. After undergoing a treatment process, the waste is sent to the manufacturer of the k=I SC, known as the Waste User, which utilizes this waste as new inputs.

3.1. Modelling Assumptions

Our model employs a number of assumptions derived from the SC dynamics literature and adapted to the SSCs setting, e.g. Chatfield and Pritchard (2013), Cannella et al. (2021) and Corsini et al. (2023). Customers demands, D_{C_k}, and lead times for the forward flows, L_{ik}, are assumed to be stochastic, independent and identically distributed (i.i.d.) variables. We assume that an Order-Up-To (OUT) periodic-review policy is adopted by each member of both SCs, as shown in Equation 1.

$$O_{ik}(t) = S_{ik}(t) - I_{ik}(t) - WIP_{ik}(t) + B_{ik}(t) \tag{1}$$

Here $S_{ik}(t)$ it the OUT level, $I_{ik}(t)$ is the current inventory, $WIP_{ik}(t)$ the inventory on order but not yet arrived (or work-in-progress) and $B_{ik}(t)$ the backlog. The volume of waste produced by the Waste Producer, $W(t)$, is a function of the volume of output produced at time t, i.e. the satisfied demand of its downstream member. We assume that a waste treatment process *TP* is required to make the waste usable as input by the Waste User, i.e. homologous with products coming from the forward flow (Fraccascia, 2019). A deterministic lead time, known as waste treatment lead time and denoted by μ_{L_T}, is assigned to *TP*. It follows that both flows are used to satisfy incoming demands by the Waste User. We assume that the symbiotic flow is governed by a push policy, i.e. as soon as waste are done with the treatment process, they are sent to the Waste User. Thus, waste is always prioritized as in line with the CE principles.

As cooperation is key of IS (Chertow, 2000), in this work we study the information sharing between members of different SCs, i.e. inter-SC information sharing. Moreover, as together with forecasting and ordering policy, the information sharing ones are characteristic elements in bullwhip modeling (Wang and Disney, 2016), we study three possible inter-SC information sharing policies, (ε) between the two SCs (Dominguez et al., 2021).

- *Absence of inter-SC information sharing* (ε=NO). In this scenario, we assume that there is no inter-SC information sharing, i.e. there is no exchange of information between the two SCs and the symbiotic flow is ignored in the computation of the base stock. The Waste User receives a volume of products from the Waste Producer that automatically increases its inventory.
- *Estimation for net demand* (ε=EST). Now, we assume that there is still no information sharing between the two SC, i.e. between the Waste Producer and the Waste User. However, the Waste User uses the only information available, that is the volume of products received at each time unit, to estimate a new net demand.
- *Presence of Inter-SC information sharing* (ε=YES). Finally, information on the treatment process is available for the Waste User that uses them to improve the estimation of the OUT level. Specifically, the waste work-in-progress for the waste and the waste treatment lead time are assumed to be known.

3.2. Design of Experiments and Performance indicators

We adopted a full factorial DoE approach for our simulations. The *inter-SC information sharing*, ε, for which we distinguish the three cases of ε=NO, ε=EST and ε=YES, as described in the previous section. The *mean treatment lead* *time*, μ_{L_T}, that we assume to be lower, equal, and higher than the mean forward lead time (μ_{L_T}=2, μ_{L_T}=4 and μ_{L_T}=8). Concerning the fixed parameters, the mean customer demands are $\mu_{D_{C_I}}$ = 50 and $\mu_{D_{C_I}I}$=25, and the coefficient of variation for customers demands is $D_{C_k}c.v.$=0.4. The mean forward lead time and the coefficient of variation for the forward lead times are $\mu_{L_{ik}}$= and $L_{ik}c.v.$ =0.25. We explore 9 different scenarios, plus the benchmark scenario, i.e. the traditional FSC. For each scenario, 20 replications have been performed, with a length of 3,500 periods with the first 200 removed as warm-up. The selected performance metrics that aim to detect the BE in our SSCs model are the order rate variance ratio, *OrVrR*, the inventory variance ratio, *InvVrR*, the wip variance ratio, *WipVrR*, and the average inventory *IA* as defines in Table 2.

Table 2. Performance Indicators

Name	Formula
Order rate variance ratio	$OrVrR_{ik} = \frac{\sigma^2_{O_{ik}} / \mu_{O_{ik}}}{\sigma^2_{D_{C_k}} / \mu_{D_{C_k}}}$
Inventory variance ratio	$InvVrR_{ik} = \frac{\sigma^2_{I_{ik}} / \mu_{I_{ik}}}{\sigma^2_{D_{C_k}} / \mu_{D_{C_k}}}$
WIP variance ratio	$WipVrR_{ik} = \frac{\sigma^2_{WIP_{ik}} / \mu_{WIP_{ik}}}{\sigma^2_{D_{C_k}} / \mu_{D_{C_k}}}$
Average inventory	$IA_{ik} = \frac{\sum_{t=1}^{T} I_{ik}(t)}{T}$

4. Results and Discussion

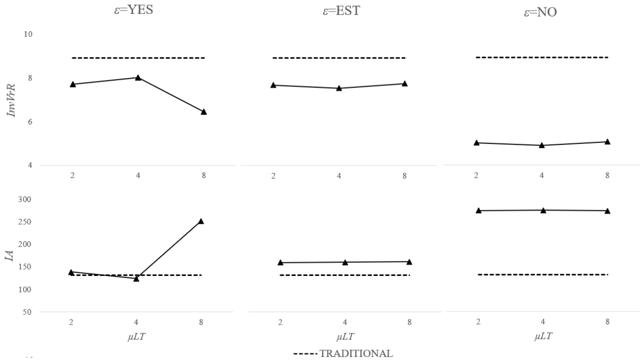

Figure 2. Interaction of ε and μ_{L_T} for the *InvVrR* and *IA* compared to the traditional FSC

In this section, we firsly present the numerical results obtained from the simulations according to the DoE described in the previous section, then we discuss on the arised insights. The following analysis focuses on the inter-SC information sharing policies policies and their impact on the BE metrics, i.e. referring to Figure 2 and 3. Starting from the *InvVrR*, results reveal that (for all ε) its values for the Waste User are lower compared to the *InvVrR* for the traditional scenario without the symbiotic exchange. In addition, when ε=NO, its value for the Waste User is the lowest. However, it happens because the *IA* is always higher than the traditional scenario. Therefore, when ε=NO the *IA* reaches the highest value compared to the other ε, i.e. due to the absence of any information in the inventory policy of the Waste User, while comparing ε=EST and ε=YES, we observe lower values of *IA* than when ε=NO. Concerning the *OrVrR*, similar results were obtained in the simulations between the three ε for this metric, i.e. the *OrVrR* is not affected by ε. A significant correlation was found between ε=YES and the *WipVrR*. We assume that when ε=YES, the Waste User updates its work-in-progress because the Waste Producer shares this information. This assumption entails a lower *WipVrR* when ε=YES compared to both the other ε and to the traditional scenario. Note that, for ε=NO and ε=EST the *WipVrR* show the same values. This results are consistent with the assumptions we made on the information shared between the Waste User and the Waste Producer.

To sum up, from a managerial perspective, sharing is a pillar of IS applications. By definition, IS is based on sharing waste, by-products, services, and so on. However, within or between SCs, the problem of sharing information is still unresolved. Even if it has been widely demonstrated that, by implementing information sharing, firms in traditional FSC can benefit from BE reduction, they still ignore its adoption. As a consequence, implementing information sharing in SSCs is not that obvious. One interesting aspect that emerged from the analysis is that orders are not that influenced by the inter-SC information sharing as inventories are. Enabling inter-SC information sharing can make the system more stable, in terms of variability, compared to the other inter-SC information sharing policies. Moreover, as the only strategy that uses the information concerning the waste treatment lead times in the ordering policy is the enabled one, in these scenarios it is possible to observe its impact and observe that, increasing the waste treatment lead times, it also increases the BE in terms of orders, while it decreases in terms of inventory. Therefore, sharing information concerning the symbiotic exchange can help firms to appropriately choose the symbiotic partner according to the specific goal that they want to achieve, e.g. reduce orders or inventory variance. In other words, as we assume that the treatment lead time includes the transportation lead time, managers could easily deal with the geographical proximity problem that is still a discussion in the IS field, i.e. as the transportation lead time can be seen as a modeling for the geographical proximity or dispersion.

5. Conclusions

The field of IS is recognized as one of the most promising strategies to pursuit a CE and to achieve sustainable developments, however little IS research has penetrated the stream of SCs, indeed its impact on SCs dynamics is

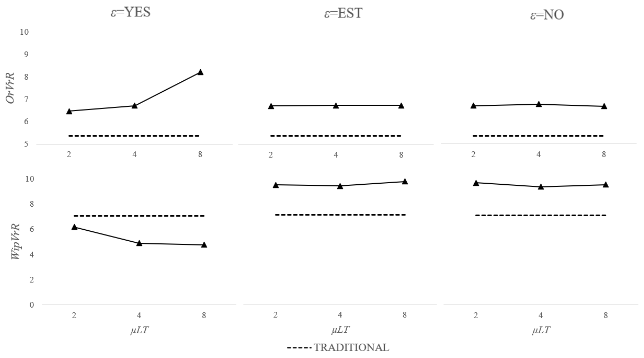

Figure 3. Interaction of ε and μ_{L_T} for *OrVrR* and *WipVrR* indicator compared to the traditional FSC

still unexplored. Therefore, in this work, we aim to explore the dynamics of SSCs. We analyze two identical FSCs, where, between the two manufacturers (a Waste User and a Waste Producer) exists a symbiotic exchange of waste. Adopting the ABMS technique and the DoE approach, we analyze the impact of different inter-SC information sharing policies that can be implemented and of different lead time for the treatment process of the waste. We evaluate the obtained scenarios through BE metrics and provide useful findings to help understand the operational behavior of SSCs. We state that the BE in SSCs, for the member involved in the symbiotic mechanism, differs compared to traditional FSCs. From the order variability perspective, it results higher, while from the inventory one, it results lower. From the analysis of inter-SC information sharing, we reassert its importance as in traditional FSCs. The member that uses the additional symbiotic flow as input, when the inter-SC information sharing is enabled, exploits at the best the symbiotic exchange compared to the other scenarios. Moreover, depending on the treatment lead time, it can benefit from orders, inventory or work-in-progress variability reduction. However, it should be noted that our research work is based on specific modeling assumptions which represent a limitation of this work. Thus, future research could analyze the BE in the SSCs under different assumptions. For instance, we suggest the comparison between the push policy and pull policy for the symbiotic flow Lin et al. (2022). To conclude, as the main goal of CE is to create systems that are self-contained, future studies could try to merge SSCs and CLSCs, then upgrade into Circular Supply Chains (Farooque et al., 2019; Zhang et al., 2023; Batista et al., 2023), where any both end-of-life waste and production waste are reduced. It follows that a new future direction could focus on how the members and overall operational performance of the SCs are affected by both IS e and closed-loops, i.e. CSC, thus, on studying the BE in the desired zero-waste systems.

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