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The supply chain implications of industrial symbiosis

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Abstract

This paper proposes an enterprise input-output model to assess the impacts created by industrial symbiosis (IS) on traditional supply chains for production inputs, triggered by resource use change. The model is capable of measuring a variety of sustainability indicators such as resource and waste savings, total energy use reduction, employment creation, reduction in greenhouse gas emissions. Furthermore, the model can be used to analyze IS exchanges from a dynamic perspective, since it is able to take into account dynamic scenarios in wastes production and inputs requirement. A numerical example is presented to show how the model works. This example shows how the impacts of IS strongly depend on the combined effects of upstream supply chains topology, waste treatment processes, and waste-input substitution rate.

Keywords: industrial symbiosis, circular economy, sustainability, input-output, supply chains.

1. Introduction

Industrial symbiosis (IS) is a subfield of industrial ecology that engages separate industries in a collective approach to competitive advantage, involving physical exchanges of materials, energy, and services (Chertow, 2000; Lombardi and Laybourn, 2012). In particular, companies can replace production inputs with wastes generated by other companies. Through IS, the amount of wastes disposed of in landfills and the amount of production inputs purchased from conventional suppliers can be reduced. Furthermore, by adopting the IS practice, companies can achieve economic benefits from reducing their waste disposal costs and input purchasing cost while creating environmental and social benefits for the collectivity simultaneously (e.g., Jacobsen, 2006). For this reason, the IS practice is expected to play a major role for the transition towards circular economy (e.g., Lüdeke-Freund et al., 2018; Saavedra et al., 2018).

Although IS takes place between production processes of several companies, it creates induced impacts on their traditional supply chains, triggered by resource use change. Hence, IS may be responsible for creating indirect impacts from the environmental, economic, and employment perspective. However, so far the literature focused on assessing the direct effects of IS, i.e., the physical and monetary flows generated between the production processes exchanging wastes and the new jobs created by the symbiotic exchanges (e.g., Bain et al., 2010; Sendra et al., 2007), while less attention has been devoted to analyze the above-mentioned indirect effects. The assessment of such effects is fundamental to fully understand the overall impact of IS on productive systems. Furthermore, the models so far proposed to quantify the effects are not dynamic, i.e., they are able to analyze the effect of the IS relationship only in a specific scenario, defined *a priori*. However, since companies are involved in a dynamic business environment, the effectiveness of the above-mentioned models might be limited.

In order to fill both these gaps, we design a Dynamic Enterprise Input-Output (EIO) model (Grubbstrom and Tang, 2000) for analyzing the changes in physical flows of resources in the upstream supply chains of companies involved in IS synergies. The proposed model is able to analyze IS exchanges from a dynamic perspective, since it is able to take into account changes in waste production and input requirement. A numerical example is used to show how the model works.

The paper is organized as follows: Section 2 presents the EIO model, Section 3 shows the numerical example, and Section 4 is devoted to discussion and conclusions.

2. The Enterprise Input-Output model

This section is divided into three subsections. Section 2.1 presents the dynamic EIO model for IS relationships, which allows to take into account all the flows of waste and resources directly created by the symbiotic practice. In Section 2.2, a generic upstream supply chain is modeled according to the EIO approach.

Finally, Section 2.3 models the effects of IS on the upstream supply chains of the waste treatment company and of the company using wastes to replace production inputs.

2.1 Dynamic EIO model for IS relationships

According to the EIO approach, companies are modeled as black boxes transforming inputs purchased from their suppliers into one main product, which is used by other companies as intermediate product or is sold on the market. As a result of this transformation, companies produce wastes, which need to be disposed of. Both inputs requirement and wastes production are driven by the amount of main output produced and the production technology.

Let us consider two firms, A and B, and let us suppose that one waste generated by A can replace one input required by B. In this regard, let $w_A(t)$ and $r_B(t)$ be the amount of waste produced by A and the amount of input required by B at the generic time *t*, respectively. They can be computed as follows:

$$w_A(t) = W_A \cdot x_A(t) \quad (1)$$

$$r_B(t) = R_B \cdot x_B(t) \quad (2)$$

where $x_A(t)$ and $x_B(t)$ stand for the amount of output produced by A and B at time *t*, respectively, W_A stands for the amount of waste generated by A to produce one unit of output, and R_B stands for the amount of input required by B to produce one unit of output. The values of W_A and R_B depend on the production technologies adopted by companies and therefore they cannot be changed in the short period[1] (Sonis and Hewings, 2007).

When companies establish an IS relationship at time *t*, $e_{AB}(t) = \min\left\{ w_A(t); \frac{r_B(t)}{s_{AB}} \right\}$ units of waste are exchanged between them, where s_{AB} stands for a technical substitution coefficient, i.e., how many units of input can be replaced by one unit of waste. As a result, firm A does not discharge $e_{AB}(t)$ units of waste and firm B does not purchase $s_{AB} \cdot e_{AB}(t)$ units of input from conventional suppliers. However, it may happen that the waste needs a treatment process (e.g., grounding, filtration) before it can be used as input (e.g., Aviso, 2014; Yune et al., 2016). The generic waste treatment process can require *n* additional inputs and generate *m* additional wastes. In this regard, let $\vec{r}_T(t)$ be the $n\times1$ vector of the additional inputs required by the waste treatment process at time *t* and let $\vec{w}_T(t)$ be the $m\times1$ vector of additional wastes generated by the waste treatment at time *t*. These vectors can be computed as follows:

$$\vec{r}_T(t) = \vec{R}_T \cdot e_{AB}(t) \quad (3)$$

$$\vec{w}_T(t) = \vec{W}_T \cdot e_{AB}(t) \quad (4)$$

where $\vec{R}_T$ is the $n\times1$ vector whose generic *i*-th element denotes how many units of input *i* are required for the treatment of one unit of waste and $\vec{W}_T$ is the $m\times1$ whose generic *j*-th element denotes how many units of waste *j* are produced for the treatment of one unit of waste. Fig. 1 shows all the physical flows of inputs and wastes created by the IS relationship as well as two upstream supply chains: (1) the chain supplying the input required by B (highlighted in blue); (2) the chain supplying the inputs required by the waste treatment process (highlighted in orange).

2.2 The upstream supply chains

In this section, we model the above-mentioned upstream supply chains. According to the EIO approach, each chain is modeled as a network of firms, each of them requiring primary inputs from outside the chain and intermediate products from other companies belonging to the chain, transforming them into one output, and producing wastes (Albino et al., 2003). Fig. 2 shows a generic supply chain for the generic *p*-th input. Let us consider the supply chain of the generic focal company (fc) and let us suppose that *n* firms belong to this chain. Let $\vec{x}^{fc}(t)$ be the $n\times1$ vector whose generic *i*-th element denotes the amount of output produced by firm *i* at time *t*. This vector can be computed as follows:

$$\vec{x}^{fc}(t) = (I^{fc} - A^{fc})^{-1} \cdot \vec{f}^{fc}(t) \quad (5)$$

[1] This is the reason why W_A and R_B are not function of the time.

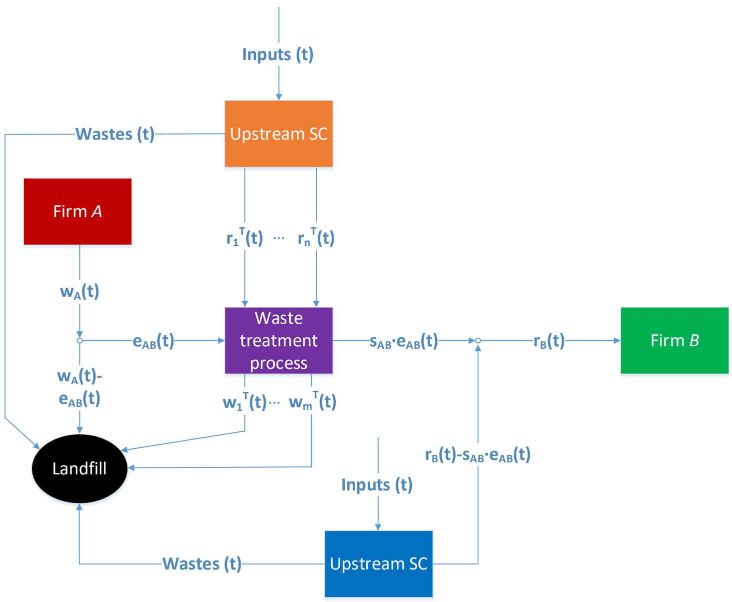

Fig. 1. Physical flows of inputs and wastes generated by IS.

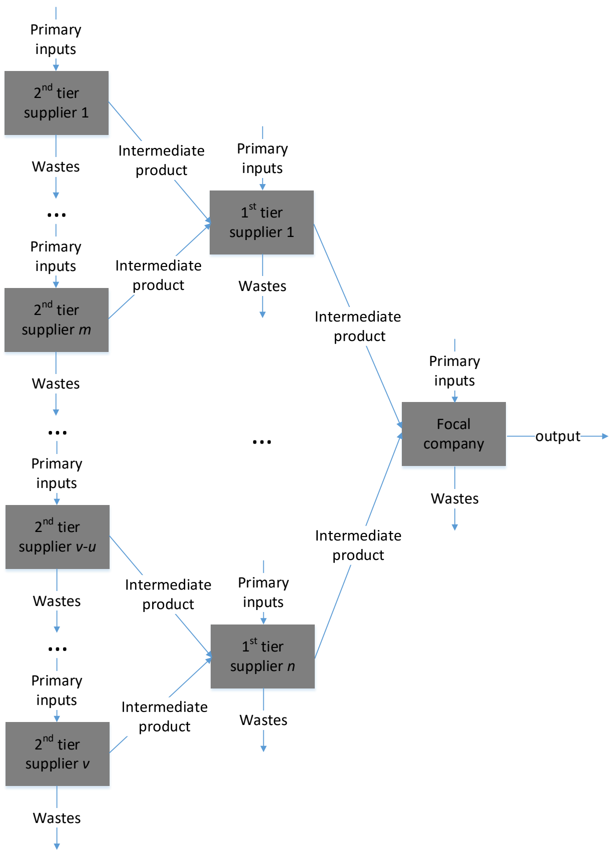

Fig. 2. Scheme of a generic supply chain for the *p*-th input.

where I^{fc} is the $n\times n$ identity matrix, A^{fc} is the $n\times n$ matrix whose generic element A_{ij}^{fc} denotes how many units of output produced by firm *i* are used as intermediate product by firm *j* to produce one unit of output, and $\vec{f}^{fc}(t)$ is the $n\times 1$ vector whose generic *i*-th element denotes how many units of output are demanded to the firm *i* by the focal company at time *t*.

Let us suppose that companies belonging to the chain overall require *n(p)* primary inputs and produce *n(w)* wastes. In this regard, let $\vec{p}^{fc}(t)$ be the $n(p)\times 1$ vector whose generic *i*-th element denotes the amount of primary input *i* required by the firms belonging to the chain and let $\vec{w}^{fc}(t)$ be the *n(w)*×1 vector whose generic *j*-th element denotes the amount of waste *j* required by the firms belonging to the chain. These vectors can be computed as follows:

$$\vec{p}^{fc}(t) = P^{fc} \cdot \vec{x}^{fc}(t) \quad (6)$$

$$\vec{w}^{fc}(t) = W^{fc} \cdot \vec{x}^{fc}(t) \quad (7)$$

where P^{fc} is the *n(p)*×*n* matrix whose generic element *ij* denotes how many units of primary input *i* are required by firm *j* to produce one unit of output and W^{fc} is the *n(w)*×*n* matrix whose generic element *ij* denotes how many units of waste *i* are generated by firm *j* to produce one unit of output.

2.3 The effects of industrial symbiosis on the upstream supply chains

In this section, we model the effect of the IS relationship described in the previous section on the two supply chains mentioned in Section 2.1: (1) the supply chain of the input required by firm B; (2) the supply chain of the inputs required by the waste treatment process.

When $e_{AB}(t)$ units of wastes are used by firm B, the company does not purchase $s_{AB} \cdot e_{AB}(t)$ units of input from the conventional supplier, which will reduce the amount of output produced. As a consequence, all the companies involved in the upstream supply chain will reduce their production levels. Let us suppose that *nB* companies belong to the chain. Let $\Delta\vec{x}^B$ be the *nB*×1 vector whose generic element *i*-th element denotes the reduction in the amount of output produced by firm *i*. Such a vector can be computed as follows:

$$\Delta\vec{x}^B(t) = (I^B - A^B)^{-1} \cdot \begin{bmatrix} 0 \\ 0 \\ \ldots \\ -s_{AB} \cdot e_{AB}(t) \end{bmatrix} \quad (8)$$

where I^B and A^B are *nB*×*nB* matrices (see Eq. 5). According to Eq. 6 and Eq. 7, the amount of the *nB(p)* primary inputs required and the amount of *nB(w)* wastes produced by the companies belonging to the chain will be reduced. Let $\Delta\vec{p}^B(t)$ the *nB(p)*×1 vector whose generic *j*-th element denotes the reduction in the amount of primary input *j* required by the companies and let $\Delta\vec{w}^B(t)$ be the *nB(w)* ×1 vector whose generic *q*-th element denotes the reduction in the amount of waste *q* produced by the companies. These vectors can be computed as follows:

$$\Delta\vec{p}^B(t) = P^B \cdot \Delta\vec{x}^B(t) \quad (9)$$

$$\Delta\vec{w}^B(t) = W^B \cdot \Delta\vec{x}^B(t) \quad (10)$$

where P^B is a *nB(p)*×*nB* matrix and W^B is a *nB(w)*×*nB* matrix (see Eq. 6 and Eq. 7).

When the waste needs a treatment process before being used as input, such a process requires *n* additional inputs (see Eq. 3 for the amounts of these *n* inputs). As a consequence, all the companies involved in the upstream supply chain of the waste treatment company will increase their production levels. Let us suppose that *nT* companies belong to this chain. Let $\Delta\vec{x}^T$ be the *nT*×1 vector whose generic element *i*-th element denotes the increase in the amount of output produced by firm *i*, which can be computed as follows:

$$\Delta\vec{x}^T(t) = (I^T - A^T)^{-1} \cdot \begin{bmatrix} 0 \\ 0 \\ \ldots \\ \vec{R}_T \cdot e_{AB}(t) \end{bmatrix} \quad (11)$$

where I^T and A^T are *nT*×*nT* matrices (see Eq. 5). According to Eq. 6 and Eq. 7, the amount of the *nT(p)* primary inputs required and the amount of *nT(w)* wastes produced by the companies belonging to the chain will increase. Let $\Delta\vec{p}^T(t)$ the *nT(p)*×1 vector whose generic *j*-th element denotes the increase in the amount of primary input *j* required by the companies and let $\Delta\vec{w}^T(t)$ be the *nT(w)* ×1 vector whose generic *q*-th element denotes the increase in the amount of waste *q* produced by the companies. These vectors can be computed as follows:

$$\Delta\vec{r}^{T}(t) = R^{T} \cdot \Delta\vec{x}^{T}(t) \quad (12)$$

$$\Delta\vec{w}^{T}(t) = W^{T} \cdot \Delta\vec{x}^{T}(t) \quad (13)$$

where P^T is a $nT(p)\times nT$ matrix and W^T is a $nT(w)\times nT$ matrix (see Eq. 6 and Eq. 7).

3. Numerical example

In this section, a numerical example is presented to show how the model works. Let us consider the case whose data are reported in Table 1.

Table 1. Numerical data for the considered example.

Firm A	***Firm B***
$x_A(t) = 100$	$x_B(t) = 20$
$W_A = 0.1$	$R_B = 2.5$
$w_A(t) = 10$	$r_B(t) = 50$

Under the hypothesis that $s_{AB} = 1$, ten units of waste can be exchanged between Firm A and Firm B at time *t*, i.e., $e_{AB}(t) = 10$. Hence, Firm A does not dispose any units of waste of in the landfill whereas Firm B reduces the amount of input purchased from conventional suppliers by 10 units. Section 3.1 addresses the impact of IS on the upstream supply chain of Firm B. Section 3.2 addresses the impact of IS on the upstream supply chain of the waste treatment process. Finally, Section 3.3 shows a dynamic application of the EIO model.

3.1 The effects of industrial symbiosis on upstream supply chain of Firm B

Let us consider the supply chain shown in Fig. 3, composed of six companies, where Firm B6 provides Firm B with the input replaced by waste.

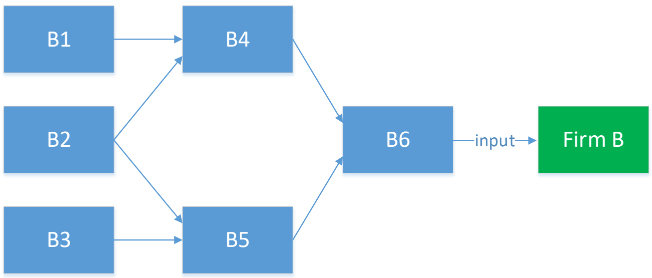

Fig. 3. Upstream supply chain of the Firm B.

The matrix A^B that describes the structure of the supply chain is shown as follows:

$$A^B = \begin{bmatrix} 0 & 0 & 0 & 10 & 0 & 0 \\ 0 & 0 & 0 & 2 & 4 & 0 \\ 0 & 0 & 0 & 0 & 3 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 2 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Accordingly, Firm B4 needs ten units of output from Firm B1 ($A_{14}^B = 10$) and two units from Firm B2 ($A_{24}^B = 2$) per unit of produced output. Firm B5 needs four units of output from Firm B2 ($A_{25}^B = 4$) and three units from Firm B3 ($A_{35}^B = 3$) per unit of produced output. Finally, Firm B6 needs one unit of output from Firm B4 ($A_{46}^B = 1$) and two units from Firm B5 ($A_{56}^B = 2$) per unit of produced output. Let us suppose that companies overall require two inputs (e.g., energy and workforce) and produce three wastes (e.g., wastewater, metal scraps, and plastic wastes). Matrices P^B and W^B are shown as follows:

$$P^B = \begin{bmatrix} 2 & 5 & 3 & 1 & 4 & 3 \\ 0.1 & 0.2 & 0.15 & 0.5 & 0.3 & 0.1 \end{bmatrix} \qquad W^B = \begin{bmatrix} 1 & 0 & 5 & 3 & 0 & 0 \\ 0 & 2 & 2 & 0 & 0.5 & 1 \\ 5 & 5 & 0 & 0 & 0 & 0 \end{bmatrix}$$

For example, to produce one unit of output, Firm 2 requires five units of energy ($P_{12}^B = 5$) and 0.2 units of workforce ($P_{22}^B = 0.2$) and produces two units of metal scraps ($W_{22}^B = 2$) and five units of plastic wastes ($W_{32}^B = 5$). According to Eq. 8, the impact of IS on the amount of output produced by the companies can be computed as follows:

$$\Delta\vec{x}^B(t) = \left\{ \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} - \begin{bmatrix} 0 & 0 & 0 & 10 & 0 & 0 \\ 0 & 0 & 0 & 2 & 4 & 0 \\ 0 & 0 & 0 & 0 & 3 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 2 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \right\}^{-1} \cdot \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ -10 \end{bmatrix} = \begin{bmatrix} -100 \\ -100 \\ -60 \\ -10 \\ -20 \\ -10 \end{bmatrix}$$

For example, the amount of output produced by Firm B1 is reduced by 100 units whereas the amount of output produced by Firm B4 is reduced by 10 units. The impact of IS on the amount of inputs required and wastes produced can be computed as follows, according to Eq. 9 and Eq. 10:

$$\Delta\vec{p}^B(t) = \begin{bmatrix} 2 & 5 & 3 & 1 & 4 & 3 \\ 0.1 & 0.2 & 0.15 & 0.5 & 0.3 & 0.1 \end{bmatrix} \cdot \begin{bmatrix} -100 \\ -100 \\ -60 \\ -10 \\ -20 \\ -10 \end{bmatrix} = \begin{bmatrix} -1000 \\ -51 \end{bmatrix}$$

$$\Delta\vec{w}^B(t) = \begin{bmatrix} 1 & 0 & 5 & 3 & 0 & 0 \\ 0 & 2 & 2 & 0 & 0.5 & 1 \\ 5 & 5 & 0 & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} -100 \\ -100 \\ -60 \\ -10 \\ -20 \\ -10 \end{bmatrix} = \begin{bmatrix} -430 \\ -340 \\ -1000 \end{bmatrix}$$

Hence, the energy and workforce required are reduced by 1000 and 51 units, respectively. As a consequence of IS, the production of wastewater is reduced by 430 units, the production of metal scraps by 340 units, and the production of plastic wastes by 1000 units.

3.2 The effects of industrial symbiosis on upstream supply chain of waste treatment process

Let us consider the supply chain shown in Fig. 4, composed of four companies, where Firm T3 and Firm T4 provide the waste treatment process with two additional inputs.

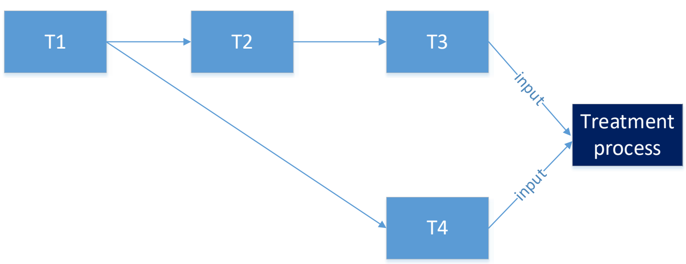

Fig. 4. Upstream supply chain of waste treatment process.

The matrix A^T that describes the structure of the supply chain is shown as follows:

$$A^T = \begin{bmatrix} 0 & 0.25 & 0 & 1 \\ 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

Accordingly, 0.25 units of Firm T1 output are required by Firm T2 per unit of produced output. To produce one unit of output, Firm T3 requires two units of Firm T2 output. Finally, one unit of Firm T1 is required by Firm T4 per unit of produced output. Let us suppose that companies overall require two inputs (e.g., energy and workforce) and produce four wastes (e.g., waste heat, waste oil, fly ash, and wastewater). Matrices P^T and W^T are shown as follows:

$$P^T = \begin{bmatrix} 2 & 1 & 2 & 1.5 \\ 0.2 & 0.1 & 0.1 & 2 \end{bmatrix} \qquad W^T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 2 & 3 & 1 & 2 \\ 0 & 3 & 0 & 0 \\ 1 & 2 & 5 & 0.5 \end{bmatrix}$$

According to Eq. 8, the impact of IS on the amount of output produced by the companies can be computed as follows:

$$\Delta\vec{x}^T(t) = \left\{ \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} - \begin{bmatrix} 0 & 0.25 & 0 & 1 \\ 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \right\}^{-1} \cdot \begin{bmatrix} 0 \\ 0 \\ 40 \\ 20 \end{bmatrix} = \begin{bmatrix} 40 \\ 80 \\ 40 \\ 20 \end{bmatrix}$$

The amount of output produced by Firm T1 and Firm T2 is increased by 40 units and by 80 units, respectively. The impact of IS on the amount of inputs required and wastes produced can be computed as follows, according to Eq. 9 and Eq. 10:

$$\Delta\vec{p}^T(t) = \begin{bmatrix} 2 & 1 & 2 & 1.5 \\ 0.2 & 0.1 & 0.1 & 2 \end{bmatrix} \cdot \begin{bmatrix} 40 \\ 80 \\ 40 \\ 20 \end{bmatrix} = \begin{bmatrix} 270 \\ 28 \end{bmatrix}$$

$$\Delta\vec{w}^T(t) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 2 & 3 & 1 & 2 \\ 0 & 3 & 0 & 0 \\ 1 & 2 & 5 & 0.5 \end{bmatrix} \cdot \begin{bmatrix} 40 \\ 80 \\ 40 \\ 20 \end{bmatrix} = \begin{bmatrix} 40 \\ 400 \\ 240 \\ 410 \end{bmatrix}$$

Hence, the energy and workforce required are increased by 270 and 28 units, respectively. As a consequence of IS, the production of waste heat is increased by 40 units, the production of waste oil by 400 units, the production of fly ash by 240 units, and the production of wastewater by 410 units.

3.3 Dynamic use of the EIO model

In this Section, a dynamic application of the EIO model is presented. In particular, this application shows how $e_{AB}(t)$, $\Delta\vec{x}^B(t)$, $\Delta\vec{p}^B(t)$, $\Delta\vec{w}^B(t)$, $\Delta\vec{x}^T(t)$, $\Delta\vec{p}^T(t)$, and $\Delta\vec{w}^T(t)$ can be easily and quickly computed in case of changes in the amount of main output produced, in the production technologies, and in technical substitution coefficient. Numerical values are shown in Table 2.

4. Discussion and Conclusion

While implementing IS, companies usually care about the direct economic impacts as well as their relationships with traditional suppliers. However, IS triggers a thorough change in the material and energy flows among the upstream supply chain actors. This paper investigates how such changes take place within the supply chain and allow further waste, material, and energy savings and consumptions. Input-output modeling is a strong tool to compute such effects as observed in the numerical example.

Table 2. Numerical results concerning the dynamic use of the EIO model.

	Changes in main output		***Changes in production technologies***		***Changes in technical substitution coefficient***
	$x_A(t) = 150$	$x_B(t) = 2$	$W_A = 0.08$	$R_B = 0.2$	$s_{AB} = 0.7$
$e_{AB}(t)$	15	5	8	4	10
$\Delta\vec{x}^B(t)$	$\begin{bmatrix}-150\\-150\\-90\\-15\\-30\\-15\end{bmatrix}$	$\begin{bmatrix}-50\\-50\\-30\\-5\\-10\\-5\end{bmatrix}$	$\begin{bmatrix}-80\\-80\\-48\\-8\\-16\\-8\end{bmatrix}$	$\begin{bmatrix}-40\\-40\\-24\\-4\\-8\\-4\end{bmatrix}$	$\begin{bmatrix}-80\\-80\\-48\\-8\\-16\\-8\end{bmatrix}$
$\Delta\vec{p}^B(t)$	$\begin{bmatrix}-1500\\-76.5\end{bmatrix}$	$\begin{bmatrix}-500\\-25.5\end{bmatrix}$	$\begin{bmatrix}-800\\-40.8\end{bmatrix}$	$\begin{bmatrix}-400\\-20.4\end{bmatrix}$	$\begin{bmatrix}-800\\-40.8\end{bmatrix}$
$\Delta\vec{w}^B(t)$	$\begin{bmatrix}-645\\-510\\-1500\end{bmatrix}$	$\begin{bmatrix}-215\\-170\\-500\end{bmatrix}$	$\begin{bmatrix}-344\\-272\\-800\end{bmatrix}$	$\begin{bmatrix}-172\\-136\\-400\end{bmatrix}$	$\begin{bmatrix}-344\\-272\\-800\end{bmatrix}$
$\Delta\vec{x}^T(t)$	$\begin{bmatrix}60\\120\\60\\30\end{bmatrix}$	$\begin{bmatrix}20\\40\\20\\10\end{bmatrix}$	$\begin{bmatrix}32\\64\\32\\16\end{bmatrix}$	$\begin{bmatrix}16\\32\\16\\8\end{bmatrix}$	$\begin{bmatrix}40\\80\\40\\20\end{bmatrix}$
$\Delta\vec{p}^T(t)$	$\begin{bmatrix}405\\42\end{bmatrix}$	$\begin{bmatrix}135\\14\end{bmatrix}$	$\begin{bmatrix}216\\22.4\end{bmatrix}$	$\begin{bmatrix}108\\11.2\end{bmatrix}$	$\begin{bmatrix}270\\28\end{bmatrix}$
$\Delta\vec{w}^T(t)$	$\begin{bmatrix}60\\600\\360\\615\end{bmatrix}$	$\begin{bmatrix}20\\200\\120\\205\end{bmatrix}$	$\begin{bmatrix}32\\320\\192\\328\end{bmatrix}$	$\begin{bmatrix}16\\160\\96\\164\end{bmatrix}$	$\begin{bmatrix}40\\400\\240\\410\end{bmatrix}$

The findings of the numerical case example indicate that the above-mentioned effects strongly depend on the topology of the supply chain under investigation. The total produced waste quantity (influenced by waste technical coefficient) as well as the total required primary input (influenced by primary input coefficient) are decisive for the total substitution quantity. Furthermore, the substitution rate between the waste and replaced primary input influences the total quantity of substitution, which is further influenced by the efficiency of waste treatment process. The topology of the supply chain is embedded in the A matrix, which gives a clue about the potential influence of the IS on the upstream flows, as it visualizes the interdependencies between production processes. While the above-mentioned parameters represent the technological efficiency of production processes and can be considered as internal factors, the total final demand for main products of the involved companies is an external factor shaped by the market conditions. Hence, all these parameters should be considered while computing the overall impacts of circular economic business implementation based on IS.

The model is capable of measuring a variety of sustainability indicators such as resource and waste savings, total energy use reduction, employment creation, which are shown in terms of units in the numerical example. Depending on the goal of the study, sustainability indicators such as GHG emissions, water consumption can also be computed. In addition, the model can be linked to a monetary input-output model to compute the economic impacts of implementing IS through the supply chain. Therefore, the model is useful for scenario analysis and may assist replying further questions, e.g.: (1) what would be the reaction of traditional suppliers to IS, such as increasing the prices of traditional primary inputs or trying to enter in the business of waste treatment? (2) How would the employment level of the sector producing traditional primary resources be influenced? (3) What if the energy consumption level of the waste treatment process is very high pushing the IS-based business through trade-offs between waste and primary resource savings and energy consumption increase? (4) How can such trade-offs be mitigated? The main shortcoming of the input-output model proposed in this paper is that it is a linear model, which cannot carefully reply to all of the above. Hence, there is a need for developing dynamic input-output models that consider day-to-day operational factors to better tackle with such questions. Thus, this paper can be considered as a seminal one for computing overall SC impacts of IS and for investigating the above-mentioned questions as future research.

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