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Economic sustainability under supply chain and eco-industrial park concurrent design

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ABSTRACT

From a systemic point of view, the environmental efforts of single companies to achieve sustainable economic and environmental development are not enough because of the economic difficulty of reaching both zero-waste production state and high level of resource efficiency. This work focuses on payback period as a commitment keeping mechanism to ensure network stability at least until the recovery of the investment made for value creation from waste. A scenario analysis is proposed to investigate how the characteristics of each stakeholder within a network can affect the economic sustainability of the others.

1. Introduction

In the last decades, companies, belonging to all the economic sectors, are increasing the efforts to improve their environmental performances. Beyond the ethical reasons to reduce the environmental impacts, also the economic ones, due to the institutional lobbying for a sustainable development, must be considered (European Commission, 2015; United Nations, 2015). By-products and waste from manufacturing, stocking and delivering activities, but also the increasing cost of purchasing raw materials, threaten the profits, indeed (Ball et al., 2009). Even though new technologies are available to increase resource efficiency and reduce waste and by-products production, they are not economically affordable for all the companies. Furthermore, a complete conversion of all the raw materials in finished products is not achievable. Hence, the technological innovation must be coupled with a strategy of relationship development to find other stakeholders capable of giving value to every single waste (in the broadest sense of the term) of business activities.

Several paradigms addressed the key principles for dealing with the increase of environmental performances through the development of relationships among companies. Circular Economy (CE) is mainly focused on the potential value that the waste of a company could assume for another, taking into consideration several elements such as prices, resource consumption and using a holistic perspective of business instead of an intra-company one (Ellen MacArthur Foundation, 2013).

Cyclic Industrial Ecology Model (CIEM) is a more technical paradigm than CE because of its specific focus on exchanges among companies. In fact, the Industrial Ecology Models ("Cyclic", "Quasi-Cyclic", and "Linear") describe the exchanges of materials and resources between the environmental ecosystem and the industrial one (Graedel, 1994). In this framework, waste is intended as the object of an exchange that does not add value to the receiver, rather it harms her. In CIEM, the industrial ecosystem needs to exchange its process waste and by-products among its members until all the products (harmful for the environment) are converted in not dangerous materials. Industrial Symbiosis (IS) is the relationship of waste and by-products exchange among at least three stakeholders, to foster the reuse of waste as raw material, instead of its disposal. A network of stakeholders linked by ISs is an Eco-Industrial Park (EIP).

Waste is a product for which there are no customers (Chertow and Ehrenfeld, 2012), so that investments of some kind are required to find it. Investments must be economically sustainable along the time, at least until their payback. Hence, EIPs design has to be coupled with the design of a proper Supply Chain (SC) in order to deliver the new products (derived from waste) to the final customer (Castiglione and Alfieri, 2019).

The network structure is strategically relevant for the companies, since each company has the role of waste provider and/or waste transformer and is asked to make investments for the sake

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of the whole network. For a company, understanding how the operational processes and the product design (of companies in the network) affect its own economic sustainability, achievable joining the EIP and the related SC, is fundamental to maximize the leverages. Furthermore, this analysis can lead to strategical insights from (i) operational, and (ii) product life-cycle and design points of view.

Section 2 discusses the relevance. The importance of commitment keeping mechanisms and similar approaches is especially addressed. Section 3 provides the mathematical representation of the addressed problem, while Section 4 discusses the experiments settings. Finally, Section 5 presents and discusses the results, and Section 6 concludes this work summing up obtained results and future research.

2. Literature review

2.1. In product centered environment

Life cycle engineering has an important role in waste identification and value creation thanks to its attention to the product life cycle. Its focus over each phase of product life, identifying the required input and the produced output, and this makes it a powerful approach for identifying potential sources of value (Bilge et al., 2017). The importance of identifying unexploited outcomes from each life cycle phase is at the basis of costing models as Total Life Cycle Cost Model, which highlights the achievable value creation hidden in waste. However, it is focused on a company level perspective, e.g., one of its practical application is for material selection in CE perspective and it does not actually consider the presence of other stakeholders but it is mainly product characteristic oriented (Bradley et al., 2016; 2018). Even though life cycle approach supports the idea that reducing waste within a company is fundamental, since producing waste is unavoidable (Pauli, 1997), it is also focusing on inter-company approaches. In fact, Material Flow Cost Analysis (Prox, 2015) and big data approaches (Bin et al., 2015) can be used to identify and design how to exploit the overall waste along the whole supply chain, both optimizing processes and developing new partnerships with companies that could use the produced waste. However, these collaborations among companies, according to CE and CIEM paradigms, usually base their success on the exploitation of the previous inefficiencies, and completely neglect the careful selection of the network of stakeholders. Among the most important selection criteria, there should be also both the economic effort and the investment period required to each stakeholder for joining the network. In fact, even if the arising partnerships are promising, most of them depend on the local industrial context (e.g., Toxopeus et al., 2017), and they cannot be exported in different regions with different partners. Partners, and probably also the other sites of the current company (if any), have different cost structures that require different agreements on the basis of the required investments and their returns. Economic indicators are largely used also in Life Cycle Engineering to compare different investment possibilities (Pechmann and Zarte, 2017), or flow optimization for multi-product cycle (Hauschild et al., 2017) but they have never been used as a mechanism to keep the commitment of the partners, and to assess how much this mechanism costs to the companies.

2.2. In system centered environment

SC-EIP concurrent design allows to increase the maximum exploitable value, but stakeholders' commitment becomes critical in order to ensure to the network the right resilience, stability and reliability. However, both in the CE literature and in Industrial Ecology (IE) one, the main focus is on the optimization of material flows, network design, and quantity of recycled waste. It stands out the lack of tools for evaluating the economic impact of the strategies to achieve reliable network (Boix et al., 2015; Lieder and Rashid, 2016), the so called "commitment keeping mechanisms". This lack is reflected also in the indicators usually adopted to evaluate EIP performances, even if the importance of stakeholders' keeping commitment is largely recognized (Valenzuela-Venegas et al., 2016). The most similar approach from literature is used for measuring the network stability. It is often based on Social Network Analysis to identify the most critical nodes (Song et al., 2018) and Food Web Analysis for prey-predator relations among species (Genc et al., 2019), without considering any kind of economic and operational information. The concept of commitment keeping mechanism is applied in decentralized systems, like in this case, while, when an institutional anchor tenant is present (e.g., governmental institutions), it is supposed to be capable to keep the commitment of the other tenant stakeholders (e.g. Liu et al., 2015).

2.3. Common field

One or more manufacturers could look for tight relationships with local companies in order to use their waste as raw materials for new products. This approach is fostered by governments for exploiting local resources, creating value and reducing waste (Allais et al., 2015). In this case, the nature of the synergies is an IS exchanges, because a customer is found for something that before was a waste. EIPs have temporary nature, at the beginning they are based on ISs exchanges, but after a certain period, when investments will be recovered, those relationships become just trading relationships. Hence, EIPs could be originated by manufacturers during their product development processes. The involvement of suppliers in the product development phase (Dombrowski and Karl, 2016) is becoming a widespread practice, also because it has practical benefits from the new product sustainability point of view. However, it could lead to negative implications since product development is one of the most critical activities for companies. While there is a lack of commitment keeping mechanisms also for the product development process, several factors are largely studied to identify different scenarios of supplier selection from costing and environmental impact point of view (Schöggl et al., 2017), and these factors could be leveraged in such keeping mechanism.

3. Problem description

A major problem related to the EIPs is that they are untrustworthy and not resilient structures as their members' main focus is their own business. Hence, infrastructural, manufacturing, economic, logistic, and managerial efforts in EIP activities mostly come from residual resources. To avoid this behavior, a commitment keeping mechanism has been designed to equalize the payback periods of the investments done by all the stakeholders (Castiglione and Alfieri, 2019). Equalization of payback is based on a positive redistribution of resources from EIP to the stakeholders who made larger investments with longer payback period (i.e., the time to get the investment back). This positive redistribution is supported by a negative contribution, a sort of fee, for those who are obtaining an immediate larger leverage from EIP after a small capital expenditure. Since all the EIPs are different one from the other, due to the involved companies, their profitability, the final products sold, and the available infrastructures, also the EIP positive redistribution can be performed in different manners. For this reason, the role of the same company sharing the same waste and/or the same infrastructures for waste enhancement, changes depending on the EIP.

This work aims to investigate the implications of the used commitment keeping mechanism (i.e., stakeholders' payback periods equalization) for four possible kinds of stakeholder, which are introduced in the following section. For each one of them, the strengths and weaknesses of entering the specific EIP with the other three types of companies, and the best network in which she should enter are highlighted

3.1. Experimental parameters

The EIP and the related SC are described as a unique network of N companies that are represented through a set of parameters. The first set of parameters represents the initial investment made by each stakeholder i: IS_i initial investment for stocking infrastructures, IT_i initial investment for transportation infrastructures (e.g., pipelines, new roads, or warehouse docks), and IP_i initial investment for productive capacity. The aggregated initial investment I_i required to every stakeholder i is defined in (1).

$$I_i = IS_i + IT_i + IP_i \tag{1}$$

Together with investment parameters, parameters to define operational performances of stakeholders are also considered. The network is assumed already designed so that the exchanged quantities among stakeholders can be considered as given. Given the unit cost for transportation tc_i, production pc_i and stocking ic_i, the operative cost OC_i for company i is defined as follow:

$$OC_i = tc_i + ic_i + pc_i \tag{2}$$

Market prices (for each company i of the network) mp_i for products sold to customers not belonging to the network are considered fixed (they do not depend on the involved stakeholders). Within the EIP, stakeholders can decide to offer their products to the other stakeholders, at a lower price than the market one. Hence, saved unit costs ac_i buying resources within the network instead of from the market, and internal network price np_i have to been considered. The profit P_i of company i is defined in (3), and it summarizes all the source of benefits due to the EIP membership:

$$P_i = ac_i + np_i + mp_i \tag{3}$$

4. Methodology

Payback period (PbP) is the number of periods required to company i to recover the investment I_i given its expected cash flow. The expected cash flow CF_i is assumed to be the average cash flow obtained during all the T periods following the investment. It is defined as follows:

$$CF_i = \frac{\sum_{t=1}^{T} P_{it} - OC_{it}}{T} \tag{4}$$

The expected cash flow CF_i of company i is modified through the keeping mechanism by the addition (subtraction) of positive (negative) contribution to reduce (increase) its own. The cash flow modifications reduce the differences among the stakeholders' payback periods reducing the cash flow of those that are better performing for the benefit of the ones with less performance due to different type of investment or less profitable role within the EIP.

4.1. Design of experiment

To understand the implications of the adopted commitment keeping mechanism on stakeholder's economic sustainability, different types of stakeholder are defined varying the initial investment and the cash flow. Four types are identified:

- Low initial investment I_i, high cash flow CF_i;
- Low initial investment I_i, low cash flow CF_i;
- High initial investment I_i, high cash flow CF_i;
- High initial investment I_i, low cash flow CF_i;

Table 1
Experimental plan for 4 stakeholders, four different scenarios, each one repeated for every T between T_{min} and T_{max} plus the aggregated minimum PbP $\widehat{T}^*$.

Stakeholder type	I_i (M€)	Scenarios (4 different scenarios)		
		1. All short PbP		
		Single PbP	CF_i	$T_{min} - T_{max}$ ($\widehat{T}^*$)
I.low-CF.high	30	3,00	10,00	
I.low-CF.low	10	5,00	2,00	6–
I.high-CF.low	110	7,00	15,71	7
I.high-CF.high	100	6,00	16,67	(5.6334*)
		2. All high PbP		
I.low-CF.high	30	12,00	2,50	
I.low-CF.low	10	15,00	0,67	15–
I.high-CF.low	110	16,00	6,87	16
I.high-CF.high	100	15,00	6,67	(14.963*)
		3. 3 out of 4 short PbP		
I.low-CF.high	30	3,00	10,00	
I.low-CF.low	10	15,00	0,67	6–
I.high-CF.low	110	7,00	15,71	15
I.high-CF.high	100	6,00	16,67	(5.8078*)
		4. 3 out of 4 long PbP		
I.low-CF.high	30	4,00	7,50	
I.low-CF.low	10	15,00	0,67	12–
I.high-CF.low	110	16,00	6,87	16
I.high-CF.high	100	15,00	6,67	(11.526*)

Initial investment is given and it is assigned in a random manner with the assumption that low initial investment is from three to ten time less than the one identified as high investment. Stakeholders' cash flow CF_i is varied in order to obtain 4 different scenarios of initial payback period distributions:

1. each stakeholder has a short payback period (from 3 to 7 years);
2. each stakeholder has a long payback period (from 12 to 16 years);
3. three stakeholders out of four have a short payback period (from 3 to 7 years) while one has a longer one (from 12 to 16 years);
4. three stakeholders out of four have a long payback period (from 12 to 16 years) while one has a shorter one (from 3 to 7 years);

Every scenario is evaluated several time, each time increasing the time period $\widehat{T}$, from the lowest one (i.e., the aggregated minimum payback period $\widehat{T}^*$ obtained dividing the total initial investment by the sum of all the stakeholders' cash flows) to the longest payback period of the stakeholders. In each evaluation, the positive and negative contributions of all the stakeholders and how their Return On Investment (ROI) changes are observed and compared to the ROI they would get if the commitment keeping mechanism were not applied. Table 1 shows the complete set of analyzed scenarios. The problem introduced in the Section 3 is represented through the solution of the following Mixed Integer Linear Programming (MILP) model. The goal of the optimization model is leading the stakeholders' payback periods to the same target period (which is given) and not to completely redistribute the profit generated through the EIP. Hence, the sum of all the positive (negative) contributions pc_{ij} (nc_{ij}) received (paid) by company i from (to) company j cannot exceed the amount necessary to each stakeholder to recover her investment. When the number of periods (fixed in the experiment) for the complete investment recovery is too short to be reached also through the redistribution, the optimization model does not find any feasible solution. The main stakeholder appointed for providing contributions to the others is the one with the highest ROI. However, when other stakeholders exceed the main contributor's ROI, they will contribute in turn. Considering the ROI weighted by the invested amount I_i is important to measure the profitability reachable by the stakeholders. Hence, in (5) y represents the maximum ROI. It is bounded from below by constraints (6), where the cash flow CF_i introduced in (4) is modified by the addition (subtraction) of all the positive (negative) contributions pc_{ij} (nc_{ij}) received (paid) by company i from (to) company j, and it is weighted by the investment made I_i. Payback period of each stakeholder, taking into consideration positive pc_{ij} and negative contributions nc_{ij}, can be reduced to the target payback period only if constraints (7) holds. The average cash flow CF_i, multiplied by the given target payback period, $\widehat{T}$ minus the investment made I_i and EIP contributions, has to be greater than 0 (it is equal to 0 if the $\widehat{T}$ is exactly the payback period of the investment). Constraints (8) and (9) ensure that to every positive contribution pc_{ij} provided to i by j corresponds a negative contribution nc_{ij} paid by j for i. When a stakeholder i receives positive contributions the boolean variable $x_{0,i}$ is equal to 1 thanks to the big M constraint (10), while $x_{1,i}$ is equal 1 when stakeholder i provides negative contribution towards other stakeholders (constraints (11)). Constraints (12) forbids stakeholder i to provide and receive contributions within the same time horizon ($\widehat{T}$). Positive pc_{ij} and negative nc_{ij} contributions are continuous variables greater or equal to 0 (constraints (13)).

$$\min y \qquad (5)$$

$$y \geq \frac{CF_i * \hat{T}}{I_i} + \frac{\sum_{j\in N} pc_{ij}}{I_i} - \frac{\sum_{j\in N} nc_{ij}}{I_i} - 1 \qquad \forall i \in N \qquad (6)$$

$$CF_i * \hat{T} - I_i + \sum_{j\in N} pc_{ij} - \sum_{j\in N} nc_{ij} \geq 0 \qquad \forall i \in N \qquad (7)$$

$$nc_{ij} \geq pc_{ji} \qquad \forall i, j \in N \qquad (8)$$

$$nc_{ij} \leq pc_{ji} \qquad \forall i, j \in N \qquad (9)$$

$$\sum_{j\in N} pc_{ij} \leq Mx_{0,i} \qquad \forall i \in N \qquad (10)$$

$$\sum_{j\in N} nc_{ij} \leq Mx_{1,i} \qquad \forall i \in N \qquad (11)$$

$$x_{0,i} + x_{1,i} \leq 1 \qquad \forall i \in N \qquad (12)$$

$$nc_{ij}, pc_{ij} \in \Re^+ \qquad \forall i, j \in N \qquad (13)$$

$$x_{0,i}, x_{1,i} \in K = \{0, 1\} \qquad \forall i \in N \qquad (14)$$

5. Results

The model, solved using ILOG CPLEX version 12.9.0, returns all the contributions among actors. The scenarios where all the stakeholders have similarly short or long payback periods, represent the extreme cases where everyone is in the same situation. In the first case, everyone agrees that joining EIP is profitable, but the contributions exchanged are not so relevant because profits are fairly distributed. In the other case, joining the EIP is not a good deal because it has low profitability for everybody. More interesting are the cases in which the distribution of well performing and low performing stakeholders is varied, and the higher the number of companies, the greater the number of different situations. The most relevant scenarios in the figures go deep the case of a single well performing company (the anchor tenant), which has two different representative set of partners to deal with. In the "3 out of 4 long PbP" case the other three stakeholders have a low profitability, while in the "3 out of 4 short PbP" the anchor tenants adjunctive effort is almost completely dedicated only to support the less performing one.

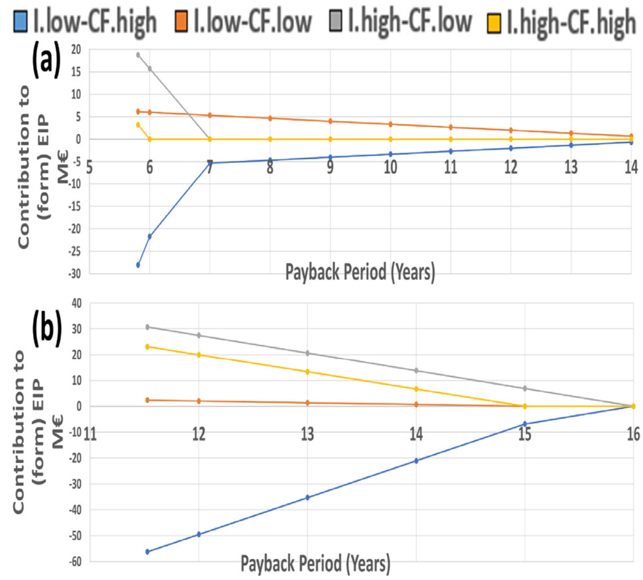

Fig. 1. (a) 3 out of 4 short Payback Period; (b) 3 out of 4 long Payback Period.

In the experiment, the changes in the contributions provided by the most performing stakeholders to the fewer performing ones are observed for different target payback period. The results are highlighted in Fig. 1, which shows the contribution changes in scenarios "3 out of 4 short PbB" (a) and "3 out of 4 long PbB" (b). In each point of both figures, all the stakeholders have reached their payback period, or, when they are able to distribute contributions, they earn more than the initial investment. The most performing stakeholder (Investment low-Cash Flow high), in both cases, provides contributions to the others (blue line always negative). In scenario (a), other two companies are well performing (yellow and gray lines), so stakeholders would need just little more time to reach their payback period by themselves. Conversely, in scenario (b), also pushing forward the target payback period, all the less performing stakeholders need to receive a positive contribution to almost recover the entire investment as the worst performing company does. Payback period is critical for two main reasons: (i) shortening the payback period to the less performing stakeholders means increasing their ROI within the 16-years period, letting them to recover earlier the investment, while ensuring their commitment; (ii) shorter equalized target payback period for the less performing companies means receiving more contributions, making profitable to join the EIP. For example, a company with high investment and low cash flow in Fig. 1(b), without contributions, will recover its investment in 16 years, which is too much considering that it is the maximum duration of an environmental governmental authorization. Hence, if the equalized payback period is not reduced, such company will not join the EIP.

In Fig. 2, it is shown how the four stakeholders' ROI changes when reducing the target payback period in the four scenarios. Comparing 2(c) and (d), it emerges that a company capable to have a high ROI from ISs relationships, i.e., capable to create large value from waste, will prefer having the most of the partners at its same level of ROI. The reason is the fact that a reduced effort allows to reduce the payback period of all the partners, making the EIP an affordable investment for all the companies. Indeed, comparing 2(c) and 2(d) emerges that in scenario (c) a limited percentage of anchor tenant's (blue bar) ROI is able to take the other stakeholders (orange and grey bars) to the complete recover of the initial investment (horizontal 100,00% black line). The other stakeholders, both the well performing (but lower than the best one) ones and those with fewer incomes (compared to the initial in-

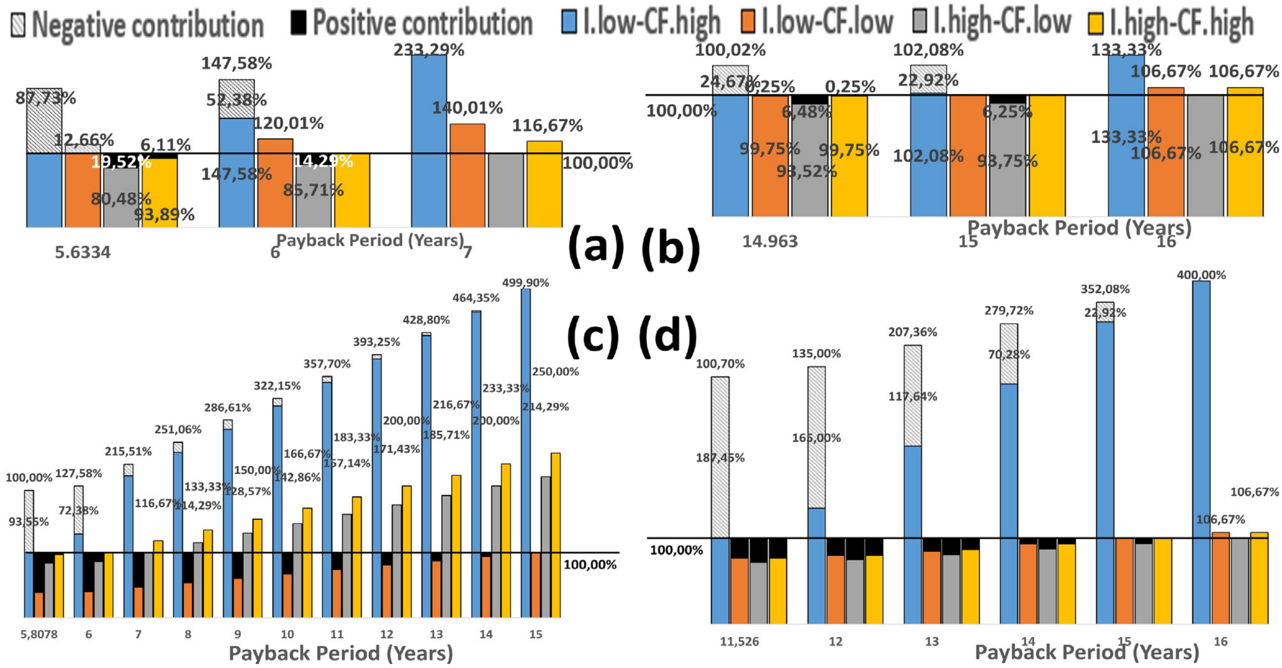

Fig. 2. (a) All short PbP; (b) All long PbP; (c) 3 out of 4 short PbP; (d) 3 out of 4 long PbP.

vestment), will prefer scenario (c). When the investment size made by the low performing companies increases, the most performing ones will pay higher contributions; however, the less performing companies will hardly reach a good ROI that makes joining the EIP convenient, without receiving a positive contribution.

6. Conclusion

To the authors' knowledge, this is the first work considering the influences that the use of the payback period as a commitment keeping mechanism has over network compositions, under SC-EIP concurrent design. Networks of companies are the main element for fostering circular economy, creating value from waste, reducing the environmental impacts, and exploiting environmental performances for gaining competitive advantages. Co-design (with supplier) of new products is becoming a widespread practice also for exploiting the above-mentioned network benefits, beyond a better control on the final product sustainability, planning also their End-Of-Life. Even though economic performances related to belonging to a network, its resilience and its stability are recognized as relevant factors, current literature in circular economy, industrial ecology and life-cycle engineering has not properly addressed the topic till now. In this work, a scenario analysis is performed to obtain evidence about the operation of payback equalization, varying the target payback period in four different scenarios. The results show the importance of a main tenant of the network, capable to support the investment in technologies and infrastructures for waste transformation, stocking and delivery. Without its role, most of the investments will not be possible due to the high payback period (i.e., low ROI) companies have to face. However, the results described so far have to be deepened. Hence, future research has to address more in details how the stakeholders can be partitioned in different classes of profitability, looking for patterns in EIP development case studies. Several stakeholder strategies are still unexplored, for example about the leverages of the purchasing reduced costs for raw material within the EIP, or policy prices during the product life-cycle. Future researches will provide tools to companies and designers to compare, at strategic level, different alternatives for product development, also considering the economic and environmental performances in their local area. This work is the first step for making these two different kinds of performances closer.

CRediT authorship contribution statement

Claudio Castiglione: Conceptualization, Methodology, Software, Validation, Visualization, Investigation, Writing - original draft, Writing - review & editing. **Arianna Alfieri:** Supervision, Conceptualization, Methodology, Writing - review & editing.

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