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Estimating the Circularity Performance of an Emerging Industrial Symbiosis Network: The Case of Recycled Plastic Fibers in Reinforced Concrete

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Abstract: In recent times, the construction industry has been handling circular economy strategies in order to face the most important challenges in the sector, namely the lack of raw materials and the environmental impacts derived from all the processes linked to the entire supply chain. The industrial symbiosis approach represents an effective strategy to improve the circularity of the construction industry. This study analyses the circularity performance of an emerging industrial symbiosis network derived from the production of a cement mortar reinforced with recycled synthetic fibers coming from artificial turf carpets. From the collection of artificial turf carpets at the end-of-life stage it is possible to recover several materials, leading to potential unusual interactions between industries belonging to different sectors. A suitable indicator, retrieved from the literature, the Industrial Symbiosis Indicator (ISI), has been used to estimate the level of industrial symbiosis associated with increasing materials recirculation inside the network. Four scenarios—ranging from perfect linearity to perfect circularity—representing growing circularity were tested. Findings demonstrate that the development of an effective industrial symbiosis network can contribute to improving the circular approach within the construction sector, reducing environmental and economic pressures.

Keywords: sustainable construction material; fiber-reinforced concrete; recycled aggregate; circular economy; industrial symbiosis

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1. Introduction

The construction industry is one of the most environmentally damaging, responsible for consuming over 32% of the world's natural resources [1]. The annual global extraction of materials has grown from 22 billion to 70 billion tons from 2002 to 2017 [2]. Particularly, the fine aggregate amount has increased by 70% from 2005 to 2015 [3], while river sand, the most convenient source worldwide, is currently being exploited at an annual rate of 750 MT for construction activities, seriously threatening the environment [4]. However, this is not only a natural resource-related issue. Environmental impact is also linked to material production that includes transport and manufacturing processes related to the construction industry [5]. Raw material supply is a dominant phase for the entire life-cycle environmental impact of the most-used construction materials (e.g., concrete and steel), accounting in 2018 for about 80% of related global warming potential (GWP) [6].

In this critical context, the European Union (EU) has assumed a lead role towards a more sustainable future. One of the main EU instruments for the promotion of environmental policies is the Green Public Procurement (GPP) [7], defined as "a process whereby public authorities seek to procure goods, services and works with a reduced environmental impact throughout their life cycle when compared to goods, services and works with the same primary function that would otherwise be procured" [8]. Italy implemented the GPP with several policies. As article 18 of the law entered into force on 2 February 2016 [9], it has become mandatory for all Italian public institutions to include minimum environmental criteria in their public procurement actions. This requirement guarantees that the national policy on green public procurement is incisive not only in reducing environmental impacts but also for achieving the objective of promoting circular production and consumption models, as well as sustainable employment. One of the criteria is the requirement for a minimum recycled content in several construction products, e.g., concrete and cement mortars. This led to the spread of technological innovation and circular economy (CE) strategies inside construction sector-related products, services, and works.

Although no standards exist for the application of CE practices in the construction industry, guidelines can be grouped depending on the life cycle stage of application [10]. The main circular relates to raw material and component production, design phase, and end-of-life concerns; they include, among others, the disassembly and management of demolition waste, take-back schemes, the reuse of building materials in new constructions, the change of use of materials, and the reuse of secondary materials in the production of building materials. More complete guidelines on CE practices regarding industrial waste can be found in [11].

The transition of the construction industry towards circularity involves the creation of networks that should include all the actors belonging to the supply chain, from design and raw material suppliers to end-users, service providers, and recyclers, as well as associated information flows. This kind of network implies an exchange of knowledge and requires collaboration and trust among partners [12,13]. In short, the creation of industrial symbiosis (IS) networks may provide the supporting framework for the transition towards circularity.

In its Workshop Agreement CWA 17354:2018, the European Committee for Standardization defines IS as "the use by one company or sector of underutilized resources broadly defined (including waste, by-products, residues, energy, water, logistics, capacity, expertise, equipment, and materials) from another, with the result of keeping resources in productive use for longer. It presents a systems approach to a more sustainable and integrated industrial economy that identifies business opportunities to improve resource utilization and productivity" [14]. Therefore, IS is recognized to be an effective approach to sustainability and CE in the industry sector, promoting the optimization of the materials cycle, increasing resource efficiency, reducing waste and pollution, and bringing about economic benefits. In the construction sector, IS project assessment demonstrated the reduction of environmental impacts (mainly waste and polluting emissions reduction), economic benefits deriving from logistic costs reduction and new revenue streams, and social benefits due to job creation, mainly in vulnerable communities [15].

The present study aims at evaluating the circularity performance of an emerging symbiosis network including six companies belonging to different sectors. The origin of the network derives from the production of a cement mortar reinforced with recycled synthetic fibers, coming from artificial turf carpets at the end-of-life stage. Since the IS approach is an evolving process aiming at continuous improvement in terms of sustainability and circularity goals, the dynamic behavior of IS can be evaluated through the use of performance indicators measuring the symbiotic level of activity. The study focuses on circularity performances and potential CE-related implications representative of the market, such as the regulation of inert waste recovery [16], and environmental and human health risks related to the treatment of waste materials and their reuse inside construction products [17].

The study employs a suitable IS indicator retrieved from the literature. Different scenarios are compared: the absence of symbiosis (Scenario 0), the initial situation created from real data (Scenario 1), and a theoretically improved situation (Scenario 2), up to a so-called "perfect symbiosis" (Scenario 3). The IS indicator returns a dynamic systemic evaluation that allows for the continuous assessment and monitoring of IS evolution, considering the potential changing of parameters such as time, new company links, amount of material, changes in the market and legislation conditions, and environment-related issues—therefore facilitating the decision-making process [18]. The findings may support company managers, practitioners, and local authorities during the implementation of the network and are expected to be useful in maintaining or improving the IS and the related circularity performance over time.

The remainder of the article is organized as follows: Section 2 reveals the case study, showing the circularity options. Section 3 presents the literature overview and explains the adopted indicator. Section 4 shows the results obtained for different scenarios. Finally, Section 5 discusses the main features of the study and its limitations.

2. Case Study

In the framework of the IMPReSA Project, funded by the Emilia Romagna Region, an innovative cementitious material that uses synthetic fibers as reinforcement has been developed; non-recyclable plastic particles are retrieved from artificial turf carpets from soccer pitches at the end-of-life stage. From artificial turf carpets at the end-of-life stage, it is possible to recover additional raw materials in different percentages to use as by-products, stimulating the emergence of a supply chain network between industries based on the exchange of materials and by-products, according to the industrial symbiosis approach. Table 1 lists the recoverable materials.

Table 1. By-products recoverable from artificial turf carpets at the end-of-life stage.

By-Products	Percentage [%]	Total Amount per Year [tons]
PE-PP fibers	12.5	173.15
Rubber	34.5	699.53
Silica sand	50.5	477.90
Bituminous membrane	2.5	34.63

According to IS taxonomy [19], the network, built up around an anchor company and involving at least three actors, can be considered and treated as an evolving self-organized IS system. Figure 1 shows the network.

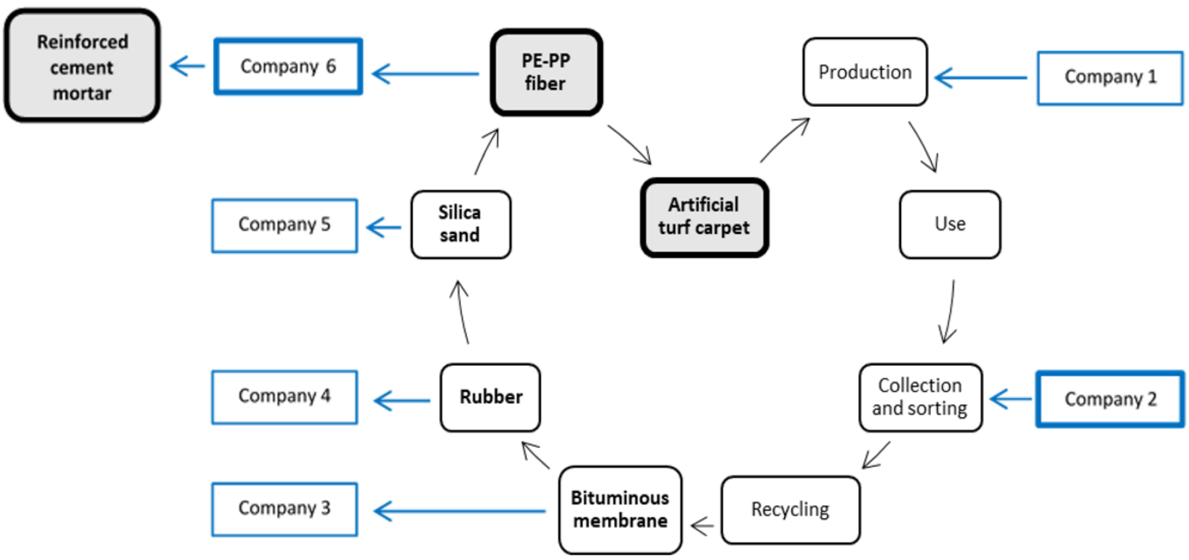

Figure 1. Schematic diagram showing the industrial network and circularity interactions among companies.

Company 1 is an industrial actor that collects and treats waste, and can exchange both by-products and raw materials with other actors. Company 2 collects and treats artificial turf carpets by mechanical sorting to wash and separate all the materials. Company 3 could adopt the bituminous membrane scraps for road asphalt mixtures while Company 4 could recycle the rubber to produce playground surfaces. Company 5 uses silica sand in general construction activities. Company 6 aims to use PE-PP fibers as dispersed reinforcement in a cementitious matrix to innovate and make their flagship products greener. Closing the loop, Company 1 produces artificial turf carpets, using recovered sand and rubber.

3. Literature Overview and Indicator Selection

3.1. Literature Overview

Various indicators have been proposed in the literature for measuring circular economies at three levels: macro (global, national, regional, city), meso (industrial symbiosis, eco-industrial parks), and micro (single firm, product) [19–21]. This study focuses on meso-level indicators that “focus on the industry, consumption activity or particular material level helping to detect waste of materials, pollution sources and opportunities for efficiency gains in specific sectors or consumption domains” [22].

A review by De Pascale et al. [23] retrieved a comprehensive set of 61 circularity indicators at the three levels. Several meso-level indicators have been developed to assess economic and environmental performance connected to existing industrial parks, such as the one in Kalundborg (Denmark) [24], or the five located in the Jiangsu province (China) [25]. On the other hand, qualitative and quantitative methods are used by scholars to evaluate IS impact on the companies involved and surrounding communities in terms of enhanced sustainability [26]. Many authors have suggested IS performance indicators with different properties and relations to business and sustainability goals; Mantese and Amaral [27] identified eight studies presenting indicators or sets of indicators. The main purposes of the indicators are to evaluate the level, or density, of symbiotic relationships within industrial areas, the degree of waste recycling or reuse as raw material (including hazardous materials), and the reduced environmental impact. A wider IS indicator taxonomy [28] shows that indicators investigating environmental and economic benefits are the most used, while social issues are still poorly considered; other indicators consider the structural characteristics of IS, such as network properties or the spatial scale of IS relationships.

Some hybrid indicators integrating more than one sustainability and/or structural dimension have also been developed. Park and Behera (2014) [29] use a hybrid indicator, composed of one economic and three environmental indicators, based on the eco-efficiency concept introduced by the World Business Council for Sustainable Development; eco-efficiency considers the relationship between the value of the output obtained (product or service) and the environmental impact generated. An ecosystem approach is adopted by Fraccascia et al. [19], who designed five classes of indicators to assess the effectiveness of waste exchanges and quantify the specific contributions of individual firms/waste exchanges to network operations. Felicio et al. [18] developed an Industrial Symbiosis Indicator (ISI) for monitoring the evolution of IS networking within an eco-industrial park, intending to provide a decision-making tool for IS stakeholders. The combination of qualitative and quantitative indicators to evaluate the technical feasibility, economic viability, and environmental benefits of potential resource exchanges are proposed by Kosmol et al. [20]. The key performance quantitative indicator system set up by Lutjie and Wolgemuth [30] consists of four subsystems including economic, environmental, and social indicators, and a general indicator system considering IS structure, activity, knowledge transfer, resilience, and adaptability issues.

3.2. Indicator Selection

Among the meso-level CE and IS indicators retrieved from the literature, the hybrid ISI indicator proposed by Felicio et al. [18] meets the requirements for achieving the study objectives. It estimates the dynamic behavior of a symbiotic industrial network by measuring the symbiotic level of activity and combines both quantitative CE criteria, such as the amounts of materials exchanged, and qualitative ones (e.g., legislation and environmental and human health related risks), allowing a wide perspective on the creation of circular exchanges.

The methodology is based on the Environmental Impact Momentum (EIM) index number that considers by-product flow and environmental impact—combining material flow analysis (MFA), environmental impacts assessment (LCA), and dynamic decision support system (DSS) theories.

MFA is a proven method that allows tracking of the flow of materials throughout their entire lifecycle (production, use, and end-of-life) towards environmental compartments (air, water, and soil) [31]. LCA is also a widely accepted technique to assess environmental impacts associated with all the stages of a product's life, from raw material extraction through to materials processing, manufacture, distribution, use, and end-of-life [32]. Previous research confirms that both methods are mostly applied in CE and IS contexts to unveil circular and symbiotic opportunities and analyze the state of industrial networks [28,30,33].

The combination of MFA and LCA with dynamic DSS [34] supports the ISI indicator, a real and infinite number that measures the level of symbiosis, considering environmental impacts and amount of reused materials on a scale that increases continually as the level of symbiosis increases and new organizations are added to the park.

Changes in the symbiotic level within a network could be used to support practitioner decisions about processes, for instance. By-product flow depends on the amount of exchanged material within an EIP, called inbound by-product (AiP), and the amount of material that is not re-used and leaves the park, called outbound by-product (AoP). The higher the internal flow of the inbound by-product and the lower the external flow of by-product, the higher is the value of the symbiosis indicator (i.e., most of the by-products generated in the EIP are reused within the park itself and little by-product leaves the park). Conversely, if the external flow of by-products is high, the level of symbiosis will be lower. Figure 2 outlines the rationale of the indicator.

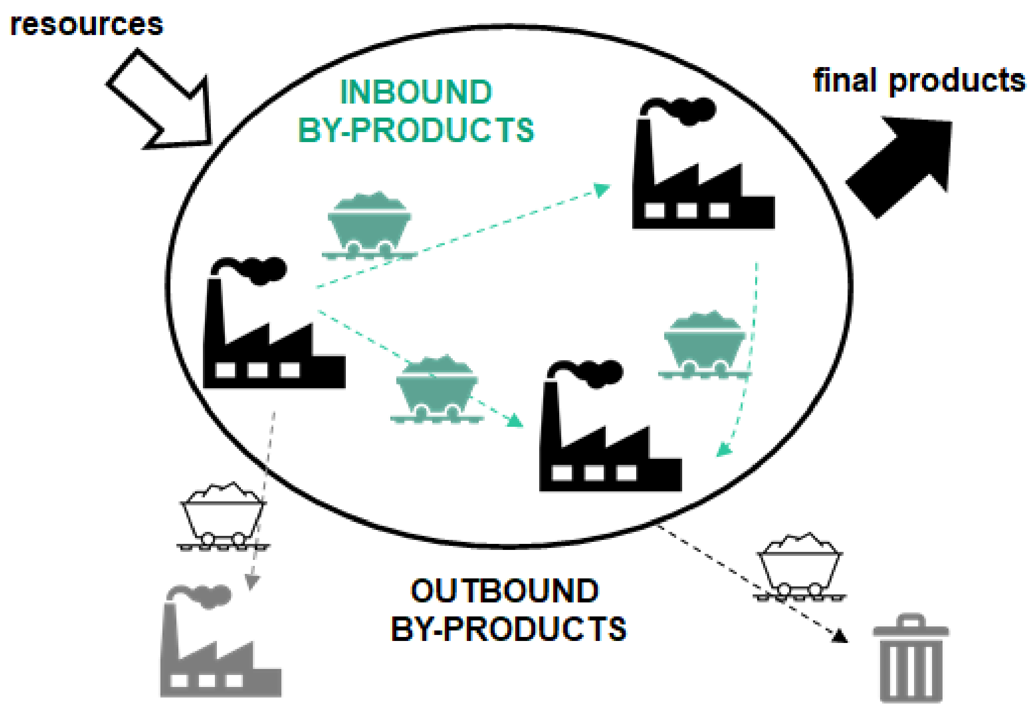

Figure 2. Inbound (AiP) and outbound by-products (AoP). Adaptation from Felicio et al. [18].

3.3. Criteria

To each by-product is associated a value, according to the assessment of 5 criteria [18]:

1. Legislation, for both inbound and outbound by-products;
2. Class of by-product, for both inbound and outbound by-products;
3. Use of by-product, for inbound by-products;
4. Destination of by-product, for outbound by-products;
5. Problems/risks, for both inbound and outbound by-products.

The legislation criteria consider the requirements needed for each by-product, when recovered, recycled, and re-used, mainly according to the EU Construction and Demolition waste protocol [21]. The class of by-products is evaluated in line with the D.M. 27/09/2010 that implements the EU Waste Framework Directive [22], regulating hazardous and non-hazardous inert and non-inert waste; values are assigned accordingly. Criteria use and destination of by-products are determined according to the characteristics of each material and the potential practical applications, taking into account the need for pretreatment operations. The use criterion is evaluated according to the following options: (i) by-product is treated by both the donor and recipient company; (ii) by-product is treated by the recipient company; and (iii) by-product treatment is not required by either of the companies. The destination criterion considers (i) the industrial landfill; (ii) the need for pretreatment; and (iii) the absence of pretreatment [35]. Finally, the problem/risk category takes into account the frequency of occurrence of potential barriers or difficulties related to waste management and business operation deriving from drastic changes in industry and society [36,37].

The evaluation assumes three discrete values: one, three, or five. The analytical hierarchy process (AHP) supported the evaluation of weights for criteria following the methodology proposed by Goepel [37]. AHP allows the assigning of a priority to a series of decision-making alternatives, or comparative evaluation of criteria which is both qualitative and quantitative, and therefore not directly comparable, by combining multidimensional scales into a single priority scale. To assure a consistent outcome, AHP requires calculation of the consistent ratio CR—namely, the probability that the final result comes from a rational, consistent process that respects transitivity among criteria. Proponents of AHP state that a CR higher than 10% does not assure sufficient transitivity [38]; if a final CR does not reach such a threshold, inconsistencies must be identified and the judgment reviewed. A consistent review may achieve a CR of around 1% [39]. Our evaluation process achieved a CR = 1.3%, which is widely satisfactory. The procedure proposed by Goepel [37] also informs confidence intervals (95%) for the evaluation.

Five representative stakeholders have been asked to give their judgment on the selected criteria: the managers of two of the companies involved in the IS (Company 2 and Company 6), two scholars, and a legislator. Table 2 shows the outcomes of the judgment as well as the evaluation criteria.

Table 2. Weight, evaluation, and values of the selected criteria.

Criteria	Weight/ Confidence Intervals	Evaluation	Value
Legislation	17.4% (±3.0 pp)	Good practices	1
		General requirement	3
		Specific legal requirement	5
Class of by-product	19.8% (±3.0 pp)	Non-hazardous—inert	1
		Non-hazardous—non-inert	3
		Hazardous	5
Use of by-product	18.6% (±4.4 pp)	Treatment by both the giving and receiving company	1
		Treatment by the giving company	3
		Treatment not required	5

Table 2. *Cont.*

Criteria	Weight/ Confidence Intervals	Evaluation	Value
Destination of by-product	25.1% (±5.0 pp)	Another network, with pretreatment	1
		Another network, without pretreatment	3
		Landfill or incineration	5
Problems/ Risks	18.2% (±1.6 pp)	Rare	1
		Possible	3
		Frequent	5

pp = percentage points.

4. Results

Tables A1 and A2 show the evaluations of the criteria for each by-product with their respective weights, used for the calculation of the degree of inbound (DiP) and outbound (DoP) by-products (Equation (A1)). Results are listed in Tables A3 and A4. Equations (A2)–(A4) produce the ISI indicator.

Four scenarios were depicted, ranging from perfect linearity to perfect circularity. The various scenarios include the actual situation (Scenario 1), where only sand and rubber are recovered, and an improved situation that considers the reuse of PE-PP fibers (Scenario 2). Moreover, two extreme cases are also investigated: one with the absence of materials exchange (Scenario 0) and one that simulates the complete reuse of by-products (Scenario 3). Such scenarios illustrate the dynamics of the symbiosis network—the more ISI approaches 5, the higher the symbiotic level; the more ISI approaches 0, the lower the symbiotic level.

Scenario 0 represents a conventional linear economy, where artificial turf carpets at the end-of-life stage route to landfill and no raw materials return for secondary uses. Without any material exchange or recycling, the ISI indicator's value is 0. Results of Scenario 0 are listed in Table A5.

Scenario 1 represents the actual situation, in which company 2 sells 100% of the sand and rubber to two of the partners included in the network. The sand is reused without any pretreatment processes by company 4 for construction activities, while the rubber is recycled by company 5 to produce surface systems for playground environments. PE-PP fibers and bituminous membrane scraps exit the network to be landfilled. In this case, the total of in-bound by-products is 43% and ISI = 0.272. Results of Scenario 1 are listed in Table A6.

The value of ISI calculated in Scenario 1 can be considered as the minimum threshold value for the case under study. The involved actors can use it as the minimum reference value to evolve the network, improving circularity performances.

Scenario 2 assumes the reuse of PE-PP fibers as reinforcement in cementitious matrices according to the IMPReSA project results [40]. In this scenario, 100% of sand and rubber still routes to companies 4 and 5, and 100% of bituminous membrane scraps is landfilled, while 80% of PE-PP fibers route to company 6, helping it to innovate and make its flagship products greener. The remaining 20% of plastic routes to landfills during cleaning and shredding operations. In this case, with 98% of inbound by-products, ISI = 0.537. Results of Scenario 2 are listed in Table A7.

Scenario 3 represents the perfect circular economy, considering that all the recovered amount of raw materials is destined for secondary uses, with the introduction of company 3 that reuses the bituminous membrane scraps to produce asphalt mixtures. In this scenario, the ISI value is 3238—the maximum level of the other scenarios. Results of Scenario 3 are listed in Table A8.

5. Discussion

The results are summarized in Figure 3. When there is not an exchange of materials (corresponding to null AiP) the value of ISI is 0, while when all the recovered material is exchanged and recycled or reused by the companies (corresponding to AiP = 100%), the value of ISI increases (dashed line), serving as a piece of feedback information concerning the level of circularity achieved by the symbiotic network. The solid line points out the ISI reference level, corresponding to the current situation, that can be improved. The ISI indicator doubles its value when most of the available plastic fibers are used, showing an improved circularity performance of the symbiotic network.

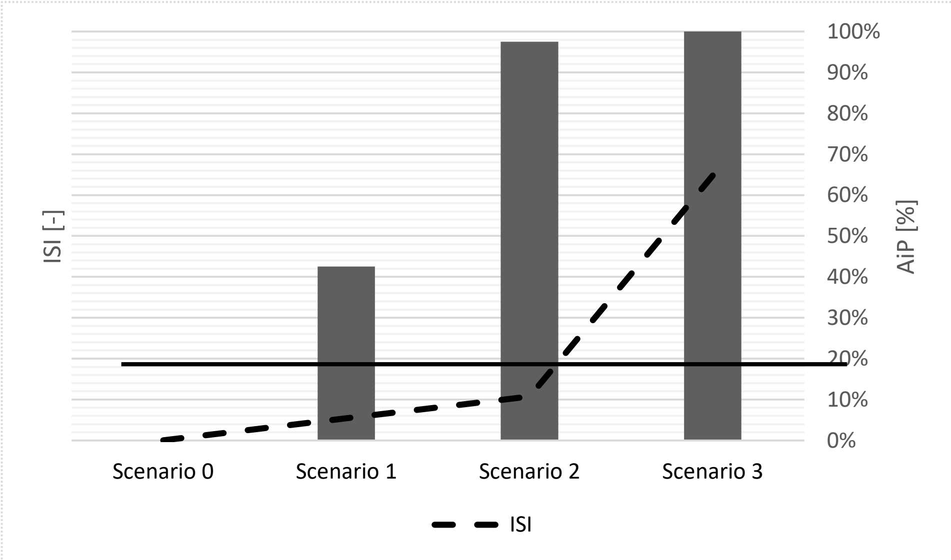

Figure 3. Summary of results: relationship between the ISI indicator and the AiP (chart out of scale).

The ISI indicator, as demonstrated by Felicio et al. [18], can identify distinct levels of symbiosis. The ISI calculation methodology is easy and does not require a large amount of input data, which is usually difficult to obtain. Other indicators, such as those based on the eco-efficiency concept or those used within environmental impact assessment methods (LCA) and material flows (MFA), require specific data and long processing times, as well as expertise often not available in the companies.

Even though the ISI indicator is not comparable with other indicators, its application could serve in attracting companies to apply symbiotic raw material exchanges and also in persuading decision-makers of development through IS and CE initiatives. In our study, the use of the ISI indicator allowed us to make both the anchor company (company 1) and the partners belonging to the network aware of the potential benefits of implementing growing levels of symbiosis, and circularity.

Further research should address the limitations of this study. Firstly, additional evaluation of the level of circularity under different scenarios are needed, considering the inclusion of other companies or stakeholders and the changes in the amount of by-product. Moreover, comprehension and comparability of the indicator could be increased by adding an environmental indicator, such as the ecoefficiency of the entire network.

6. Conclusions

The production of innovative concrete reinforced with recycled synthetic fibers returned from artificial turf carpets has contributed to increasing secondary material exchanges and the level of symbiotic activity in a network of companies.

The present study evaluated the circular performance of the emerging network through the application of an indicator retrieved from the literature. The indicator is used to calculate the level of symbiosis for different scenarios, considering material flow and environmental impacts. Since a growing level of symbiosis corresponds to a higher level of circularity, we showed that the industrial symbiosis approach can contribute to promoting circular economy practices within the construction sector.

This evaluation would be especially important during implementation of the network and would be expected to help decision-makers to maintain its performance over time, or even to improve performance over time.

Further studies should focus on more in-depth case studies as well as a survey of the entire Italian cement industry. Other industries should also be addressed in further studies, such as the steelmaking industries. A typical steelmaking plant generates about 0.6 tons of waste for each ton of finished product, which represents a huge amount of secondary material to be converted into a usable by-product. Other activities, such as food supply chains, that intensively exploit the environment, should also be investigated.

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Appendix A

Equations

$$\text{DP} = \text{evaluation of the criterion} \times \text{weight of the criterion} \tag{A1}$$

$$\text{EIMi} = \sum_{w=1}^{n} \text{AiP} \times \text{DiPw} \tag{A2}$$

$$\text{EIMo} = \sum_{w=1}^{n} \text{AoP} \times \text{DoPw} \tag{A3}$$

n = number and type of by-products involved in the calculation; w = type of by-product

$$\text{ISI} = \text{EIMi}/(1 + \text{EIMo}) \tag{A4}$$

Table A1. Criteria for inbound by-product (AiP).

By-Products	Legislation	Class of By-Product	Use of By-Product	Problems/Risks
PE-PP fibers	5	3	1	1
Sand	5	1	5	1
Rubber	5	3	5	1
Bituminous membrane	5	5	5	1

Table A2. Criteria for outbound by-product (AoP).

By-Products	Legislation	Class of By-Product	Use of By-Product	Problems/Risks
PE-PP fibers	5	3	1	1
Sand	5	1	3	1
Rubber	5	3	3	1
Bituminous membrane	5	5	3	1

Table A3. Calculated values of the degree of inbound by-product (DiP).

By-Products	Legislation	Class of By-Product	Destination of By-Product	Problems/Risks	DiP
PE-PP fibers	0.870	0.594	0.196	0.182	1.842
Sand	0.870	0.198	0.980	0.182	2.23
Rubber	0.870	0.594	0.980	0.182	2.626
Bituminous membrane	0.870	0.990	0.980	0.182	3.022

Table A4. Calculated values of the degree of inbound by-product (DoP).

By-Products	Legislation	Class of By-Product	Destination of By-Product	Problems/Risks	DoP
PE-PP fibers	0.870	0.594	5.000	0.182	6.646
Sand	0.870	0.198	5.000	0.182	6.250
Rubber	0.870	0.594	5.000	0.182	6.646
Bituminous membrane	0.870	0.990	5.000	0.182	7.042

Table A5. Results of ISI calculations for Scenario 0. Absence of industrial symbiosis.

By-Products	AiP	DiP	AiP × DiP	AoP	DoP	AoP × DoP
PE-PP fibers	0.000	1.842	0.000	173.153	6.646	1150.772
Sand	0.000	2.230	0.000	699.536	6.250	4372.101
Rubber	0.000	2.626	0.000	477.901	6.646	3176.129
Bituminous membrane	0.000	3.022	0.000	34.631	7.042	243.868
		EIMi	0		EiMo	8942.870
					ISI	0

Table A6. Results of ISI calculations for Scenario 1. Initial situation.

By-Products	AiP	DiP	AiP × DiP	AoP	DoP	AoP × DoP
PE-PP fibers	0.000	1.842	0.000	173.153	6.646	1150.772
Sand	349.768	2.230	779.983	349.768	6.250	2186.050
Rubber	238.950	2.626	627.484	238.950	6.646	1588.065
Bituminous membrane	0.000	3.022	0.000	34.631	7.042	243.868
		EIMi	1935.428		EiMo	5168.754
					ISI	0.272

Table A7. Results of ISI calculations for Scenario 2. Improved situation.

By-Products	AiP	DiP	AiP × DiP	AoP	DoP	AoP × DoP
PE-PP fibers	138.522	1.842	255.158	34.631	6.646	230.154
Sand	699.536	0.000	0.000	0.000	6.250	0.000
Rubber	477.901	0.000	0.000	0.000	6.646	0.000
Bituminous membrane	34.631	0.000	0.000	34.631	7.042	243.868
		EIMi	233.281		EiMo	474.022
					ISI	0.537

Table A8. Results of ISI calculations for Scenario 3. Perfect symbiosis.

By-Products	AiP	DiP	AiP × DiP	AoP	DoP	AoP × DoP
PE-PP fibers	173.153	1.842	318.947	0.000	6.646	0.000
Sand	699.536	2.230	1559.966	0.000	6.250	0.000
Rubber	477.901	2.626	1254.968	0.000	6.646	0.000
Bituminous membrane	34.631	3.022	104.653	0.000	7.042	0.000
		EIMi	4289.767		EiMo	0
					ISI	3238.534

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