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Towards Circular Economy through Industrial Symbiosis in the Dutch construction industry: A case of recycled concrete aggregates

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ABSTRACT

Since 95% of the Construction and Demolition Waste (CDW) is down-cycled and the material value is not effectively recovered, the Dutch construction industry strives for implementing Circular Economy (CE). From the recycling/reusing perspective, a key enabler towards CE is Industrial Symbiosis (IS). Although IS has been widely applied in manufacturing industries, its implementation is unclear in the construction industry. Particularly, the potential IS economic convenience is hard to predict in the highly fragmented construction supply chain. This study explores the IS based on the Recycled Concrete Aggregates (RCA) in the context of a concrete waste supply chain in the Twente region of the Netherlands. The research tackles with the CE challenge of lacking economic incentives by investigating the Industrial Symbiosis Network (ISN) emerged by replacing Primary Concrete Aggregates (PCA) with RCA. An Agent-Based Modelling (ABM) approach is proposed by integrating Geographic Information Systems (GIS) to present the dynamic supply-demand of RCA. Besides, supply chain actors are simulated as negotiable agents in a platform model to reveal the IS collaboration dynamics under different economic scenarios. It is found that the IS exists in the construction industry but only in an implicit manner because the RCA treatment requires the collaboration of multiple actors across substantial temporal and spatial differences. The study enriches the IS taxonomy by defining Implicit IS and provides instruments to support the decision-making of business collaborations and policy-making for a circular construction industry.

1. Introduction

The construction industry has a high resource intensity. It consumes primary materials between 1.2 and 1.8 million tons annually in Europe (WEF 2015). In the Netherlands, for example, the construction industry accounts for around 50% of the total material consumption (Rijkswaterstaat 2016). Meanwhile, Construction and Demolition Waste (CDW) generated in the Dutch construction sector is approximately 25 million tonnes per year and occupies around 46% of the total amount of waste in the whole country (Eurostat 2017). In particular, a considerable amount of concrete has been used and takes up to 85% of the total CDW (Bossink and Brouwers 1996; Rijkswaterstaat 2016; Pacheco-Torgal et al., 2013). The production of concrete brings a huge amount of CO_2 emissions while concrete waste cannot be decomposed naturally or utilized directly (De Brito and Saikia 2013). The amount of demolition concrete waste is expected to increase dramatically in Europe since the majority of concrete structures built from the 1950s, after World War II, are approaching to the end of their lives (Lotfi et al., 2015). Thus, it is almost impossible to avoid concrete waste in the coming decade. On the other hand, concrete waste could offer new business opportunities for the construction industry on the way towards Circular Economy (CE) (De Brito and Saikia 2013; Pacheco-Torgal et al., 2013). This article explores the implementation of such opportunities with a focus on the recycled concrete supply chain design based on Geographic Information Systems (GIS) and proposes an Information Technology (IT) platform where the involved actors can perform negotiations to implement CE businesses.

CE provides new business opportunities by overturning the traditional linear material usage pattern to a more sustainable, efficient and circular one (Lieder and Rashid 2016; Andrews 2015). It is a sustainable concept that focuses on maintaining the material value to the maximum extent by implementing the practices of reducing, reusing and recycling, and benefits the society in the aspects of both economy and environment without aggravating the

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burden of extracting the primary natural resources (Geissdoerfer et al., 2017; Ghisellini et al., 2018). Defined by the Ellen MacArthur Foundation (EMF), who created the *Circular Butterfly Diagram*, three basic CE principles are: 1) preserve and enhance natural capital, 2) optimize yields from resources in use, and 3) foster system effectiveness (EMF 2015).

To realize the transition towards CE, not only industrial actors, but also the government should participate and take action (Schult et al., 2015; Rijkswaterstaat 2016; Abreu and Ceglia 2018; Schraven et al., 2019). The government consciously formulates strategies and implement economic policies that support and coordinate the CE transition by providing external forces (Boons et al., 2017). Countries with massive industrial demands, like Germany and China, regard CE as a prominent part of the sustainable policy agenda since decades ago (McDowall et al., 2017). In the Netherlands, the government is exploring feasible normative measurements together with the industry.

The Dutch national call of realizing CE by 2050 forms tremendous pressures on construction industrial actors. Although the Dutch construction sector minimized the irresponsible waste disposal by recycling more than 95% of CDW (Schult et al., 2015), only less than 3% of the recycled materials are returned to the construction usage while the majority of them serve as foundation components of the road infrastructure. In other words, most concrete waste is down-cycled and its value is not effectively recovered, which failed to meet the CE requirement (Ghisellini et al., 2018). This current situation cannot be maintained since the demand for constructing the road foundation with concrete waste is expected to decrease because of: 1) the alternative residual materials from other sources, such as asphalt and plastic (Schult et al., 2015), and 2) the lower net growth rate of road infrastructure (Lotfi et al., 2015). Thus, efforts are required to increase the up-cycling rate of concrete waste.

1.1. Recycled concrete aggregates supply chain & circular business barriers

One of the most effective up-cycling strategies for CDW is replacing Primary Concrete Aggregates (PCA) with Recycled Concrete Aggregates (RCA) in the production stage of construction concrete elements (De Brito and Saikia 2013; Alnahhal et al., 2018; Rijkswaterstaat 2016). Apart from minimizing the waste disposal, the implementation of RCA prevents primary resource depletion. It is a significant CE practice that contributes to closing the material loop by reducing the dependency on primary resources and increasing the efficiency of material consumption (De Brito and Saikia 2013; Gálvez-Martos et al., 2018; Pacheco-Torgal et al., 2013). Therefore, the successful implementation of RCA supply chain is vital to achieving a circular built environment.

However, Construction Supply Chain Management (CSCM) has been scattered and underdeveloped because of high fragmentation and project-based characteristics of the construction industry (Nam and Tatum 1988; Vrijhoef and Koskela 2000; Adriaanse 2014; Deng et al., 2019). A massive amount of waste generated in the built environment results from the poor coordination of multiple stakeholders among the supply chain across huge spatial and temporal differences (Omar and Ballal 2009). Many scholars provided innovative approaches to implement CE in CSCM. For instance, some proposed principle frameworks to facilitate the CE implementation (Mendoza et al., 2017; Gálvez-Martos et al., 2018) while others provided technical solutions by applying Building Information Modelling (Akinade et al., 2018; Deng et al., 2019). Although there are fruitful results on the design, implementation, and evaluation of sustainable construction supply chains, the previous research focus is limited to the waste minimization within the traditional supply chain structure. Concerning massive concrete waste streams in the coming decade, scant attention has been devoted to the extension of the traditional supply chain structure and integrate the recovery mechanisms for materials. Hence, a holistic approach is required to integrate the RCA with PCA material flows as a whole and to further develop a closed-loop supply chain structure towards CE (Lieder and Rashid 2016; Schult et al., 2015). One of such a structure is known as Industrial Symbiosis.

1.2. The role of Industrial Symbiosis

Industrial Symbiosis (IS) is one of the most effective enablers for the transition towards successful CE by recovering the value of by-products and waste (Abreu and Ceglia 2018; Saavedra et al., 2018; Yazan and Fraccascia 2019). Originating from a prominent example of industrial facilities in Kalundborg, Denmark, IS refers to synergistic interactions between companies where one's waste(s) can be used as input(s) of another, including materials, energy, services and facilities (Jacobsen 2006; Lombardi et al., 2012; Baldassarre et al., 2019). IS falls under the CE principles and aims to convert negative impacts resulted from the conventional linear model into the positive environmental and economic benefits (Chertow and Ehrenfeld 2012; Fraccascia and Yazan 2018).

Fig. 1 schematizes the conceptual relationships among IS and CE. Based on the *Circular Butterfly Diagram* proposed by EMF (2015), an extra circle of IS is added next to the recycling flow in the manufacturing stage. This circle entails the IS philosophy that A cooperates with B by forming up-cycling material flows (Abreu and Ceglia 2018; Ghisellini et al., 2018; Mendoza et al., 2017). Fundamentally, IS can be considered as a mechanism to develop CE from the perspectives of reusing and recycling, and to be more than merely an external driver. Depending on various factors, such as natural characteristics of materials, typologies of actors and the market seasonality, IS practices may not be limited to only direct exchanges between resource providers and consumers, but also involve intermediaries and coordinators who provide services such as recycling treatments and business relationship management (Chertow and Ehrenfeld 2012). The recycling factory is a vital third-party in the recycled concrete aggregates supply chain (Pacheco-Torgal et al., 2013), however, such a supply chain has not been investigated systematically from the perspectives of IS. In general, the IS implementation is unclear in the construction industry though it is proved as a promising strategy to support the CE transition.

1.3. Problem statement

The implementation of IS, independently from the application sector, requires economic motivations for involved actors. In fact, among various factors that may affect the IS initiation, such as technical, political, economic, informational and organizational factors, economic benefits are the main driver for companies to involve into a potential IS cooperation (Esty and Porter 1998; Mirata 2004; Yazdanpanah and Yazan 2017). The establishment of such cooperation could be vulnerable and dynamic because there is no standard recipe for a successful IS while it is closely related to mutual economic and environmental benefits (Mirata 2004; Chopra and Khanna 2017). Specifically, the economic benefits obtained from IS should fulfil the desired economic expectation of any actor, and a fair benefit-sharing mechanism is essential to motivate the collaborative behaviours (Mirata 2004). It confirms the current situation in the RCA supply chain where it is technologically feasible to deliver more RCA but actors are not motivated for circular businesses as a matter of unpredictable economic convenience (Gálvez-Martos et al., 2018).

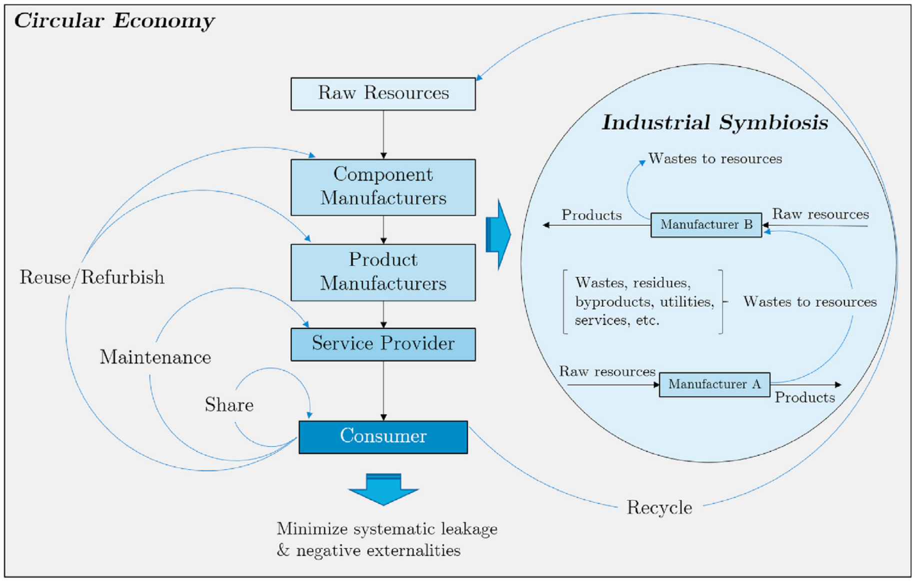

Fig. 1. Conceptual diagram of Industrial Symbiosis and Circular Economy, adapted from (EMF 2015; Abreu and Ceglia 2018).

One of the barriers against CE implementation in the construction supply chain is the lack of successful CE business models which ensure the economic benefit for all actors (Adams et al., 2017; Ghisellini et al., 2018). This is a challenge caused by the above-mentioned operational dynamics of RCA supply chains. Therefore, the actors are not able to foresee the economic benefits of implementing CE businesses. Hence, the RCA supply chains strive for instruments that provide industrial actors with real-time coordination based on operational and collaborative dynamics (Lieder and Rashid 2016; Geissdoerfer et al., 2018). This study investigates the potential of IS based on concrete waste in the Dutch construction industry via an innovative approach. The approach is proposed by integrating the Agent-Based Modeling (ABM) with Geographic Information Systems (GIS) within the concept of IS. The research would enrich the IS literature by exploring its implementation in a new context and provide strategical guidance with local supply chain actors and government bodies on the transition towards CE. The article is structured as follows: the next section introduces the methodological background and models applied in the approach. In Section 3, a case study of the RCA supply chain located in the Twente region of the eastern Netherlands is presented. Section 4 provides the result analysis, followed by the discussion in Section 5 and conclusions in Section 6.

2. Methodology

This research adopts a methodology that integrates ABM with the Enterprise Input-Output (EIO) computation analysis embedded in the GIS. In the first part of this section, the methodological background is provided. Then, two conceptual simulation models applied in the approach are developed.

2.1. Methodological background

2.1.1. Geographic Information Systems

The relevance of GIS is well-known regarding logistics optimization, environmental impact evaluation and cost-benefit analysis (Delivand et al., 2015; Kleemann et al., 2017; Lemire et al., 2019). The geospatial condition, which is also known as proximity, is one of the key facilitators of IS (Chertow 2000). The geographic dimension is naturally embedded within the IS assessment because it influences not only the transportation cost but also social dynamics among industrial actors (Sterr and Ott 2004). The GIS serves as a digital tool that articulates the complex spatial relationships of industrial actors and delivers a visual framework for conceptualizing, understanding and prescribing decisions regarding the emergence of IS agglomerations (Massard and Erkman 2009). Beyond the conventional quantitative analysis, it shows great potential to support efficient communication among different parties by providing dynamic spatial information in a cartographic manner.

Specifically, GIS helps to manage the dynamics of construction supply chains by combining accurate spatial information with onsite data retrieved from Building Information Modelling (BIM) technologies (Deng et al., 2019; Xu et al., 2019). GIS also provides a comprehensive overview of the supply chain to optimize transportation and inventory performance (Deng et al., 2019; Thöni and Tjoa 2017). It is important to take the locations of supply chain actors into account from the spatial point of view when investigating IS because it may influence the investment decisions and regulatory planning (Albino et al., 2002; Hiete et al., 2011).

2.1.2. Agent-based modelling & Collaboration Platform

IS in a larger context with multiple actors is known as Industrial Symbiosis Network (ISN) (Chertow and Ehrenfeld 2012). It is essentially a Complex Adaptive System (CAS) where a number of entities interact with each other and their environment by exchanging information simultaneously (Holland 2006; Heckbert et al., 2010). The theory of CAS is applied extensively to tackle with the challenges in dynamic supply chains (Holland 2006). It emphasizes a bottom-up approach that analyses the system from the individual perspective as the complex and often non-linear interactions at the micro-level lead to the unpredictability and adaptability of the macro performance of the entire system (Paulin et al., 2018).

In particular, Agent-Based Modeling (ABM) is one of the most suitable instruments to investigate dynamic interactions within such a system (Batten 2009; Wilensky and Rand 2015; Paulin et al., 2018; Yazan et al., 2018). The basic individuals are programmed as intelligent agents that behave based on certain routines and value propositions (Heckbert et al., 2010). Compared to traditional simulation approaches, ABM enriches our understanding of the entire system with basic interaction principles at the bottom level (Ahrweiler 2017). It echoes the theory of CAS and provides visionary insight into the system's future development. For instance, the policy-making indirectly implies prediction because real-world tests would be risky and costly (Ahrweiler 2017). Therefore, ABM is also regarded as a preferred approach to facilitate the policy-making (Zhang and Lin 2016; Luo et al., 2019).

Many studies applied ABM to investigate IS in the form of Collaboration Platform. The significant role of the online information platform for IS has been recognized by many scholars. Halstenberg et al. (2017) confirmed that the platform facilitated the exchange of by-products and allowed businesses a safe and common environment for discussing synergies through IS. Fraccascia and Yazan (2018) agreed that such a platform was useful to reduce uncertainties and implement a trustful business. Also, its direct network effect was quantified by Fraccascia (2020) supporting the emergence of IS. Furthermore, multiple types of platform architectures were developed regarding by-products exchange recognition, waste quantity matchmaking and detecting IS based on a web-GIS tool (Massard and Erkman 2009; Raabe et al., 2017; Low et al., 2018).

2.1.3. Enterprise Input-Output analysis

Scholars provide various measurements to analyse the IS collaborations by Enterprise Input-Output (EIO). The EIO analysis is defined as a mathematical description of production processes, which includes the input-output structure of a company or a network of companies that records material flows and financial transactions among various units (Lin and Polenske 1998; Grubbstrom and Tang 2000). The physical and monetary flows can be expressed explicitly by applying the EIO analysis within a company, between different companies and the overall market (Lin and Polenske 1998). The EIO approach is valuable to analyse the IS cooperation in terms of economic profits as well as environmental impacts because the costs generated from primary production inputs, by-products and waste during the entire process are taken into account in the analysis (Yazan et al., 2017; Fraccascia and Yazan 2018). Previous studies developed models of supply chains to compute product outputs, materials and waste flows and provided insights into resources consumption and environmental impacts accordingly (Albino et al., 2002; Zhang et al., 2018).

2.2. Model development

2.2.1. GIS supply chain model

The GIS supply chain model presents an overview of supply-demand dynamics throughout the RCA/PCA supply chain in a virtual environment with geographical traffic information. The initial step is to establish a traffic environment by integrating the traffic system with the global coordinates system. The traffic system is imported from the OpenStreetMap Foundation (OSMF) that provides traffic information on different types of roads and waterways. By integrating the traffic information into the global coordinates system, the transportation distances among different destinations are obtained. The second step is to define agents. Two types of agents are defined to represent the RCA supply chain structure: destinations and vehicles (Fig. 2). *Destinations* are static agents that symbolize supply chain actors by loading global coordinates on the GIS map. They store and supply materials at different geographic locations. *Vehicles*, in contrast, are mobile agents that link destinations by loading, transporting and dumping materials. They are heterogeneous agents with different routines and parameters. Destinations are linked by arrows of different colours in Fig. 2. These arrows represent a possible routine setup. However, the vehicle routines may differ from case to case, and its specific application is explained in the case study section.

2.2.1.1. GIS model interaction mechanism. Based on predefined routines, vehicle agents move and interact with destination agents to realize the processes of loading and dumping materials. The main task of agents is to realize material transferring. They have to collaboratively establish connections between their *tanks* (virtual resource containers) by exchanging messages. These messages indicate their current states and tentative requests for others. A sample of the interaction mechanism is illustrated on the right side of Fig. 2. In this sample, the destination and the vehicle are both autonomous agents that execute a set of routines by updating their states. These states are updated when certain conditions are fulfilled. For instance, trucks shall not leave the destination unless they are fully loaded, or the material will only be transferred when a targeted vehicle that arrives at the assigned location and is available to load materials. This process of recognizing each other and confirming that both are in ready-states of transferring materials is called *synchronization* (Fig. 2). It ensures the connections are correct among a number of heterogeneous agents in a complex system. The interaction mechanisms between all agents share the same primary concept with the one explained above. When interactions occur simultaneously and repeatedly, the network starts to operate as a whole and circular material flows emerge.

2.2.1.2. GIS model parameters & stochasticity. The overall material flow can not be manipulated directly since it is a phenomenon without any central control. But it can be affected by the change of individual parameters which are:

- For destination agents: agent quantity, location, storage capacity, material flow rate and up-cycling efficiency;
- For vehicle agents: agent quantity, hauling speed, vehicle capacity, loading/unloading rate, and the priority of choosing a destination.

By changing these parameters at the basic agent level under different circumstances, different systematic phenomenons can be observed in consequence. Although their changes would not fully be applied in this research, it is valuable to equip the model with these basic parameters for future operations. It contributes to further optimizing the real-time logistics and operations of circular supply chains by avoiding the disruptions triggered by a supply-demand mismatch or delivery gaps.

The model is stochastic to show the uncertainties of the waste supply at the regional level. The waste supply is inherently uncertain because waste is not produced upon demand (Yazan and Fraccascia 2019). Thus, the consistency of waste delivery is difficult to achieve when waste emerges as incidental material flows. Besides, several additional factors may influence the waste delivery, such as project phases, locations, weather and traffic conditions. The stochasticity of this model is reflected on the decision-making process of how a vehicle determines which site to proceed. During this process, each site is encoded as a unique digit while each vehicle randomly chooses a digit/site to deliver materials. The digit is restored randomly for each new round of the vehicle's routine.

2.2.2. Collaboration Platform model

Focusing on the IS cooperation between two actors from the economic perspective, an ABM Collaboration Platform (CP) model is developed. It simulates whether and how an IS cooperation would be developed under different circumstances. There are three types of interactive agents in this model, namely, two company agents

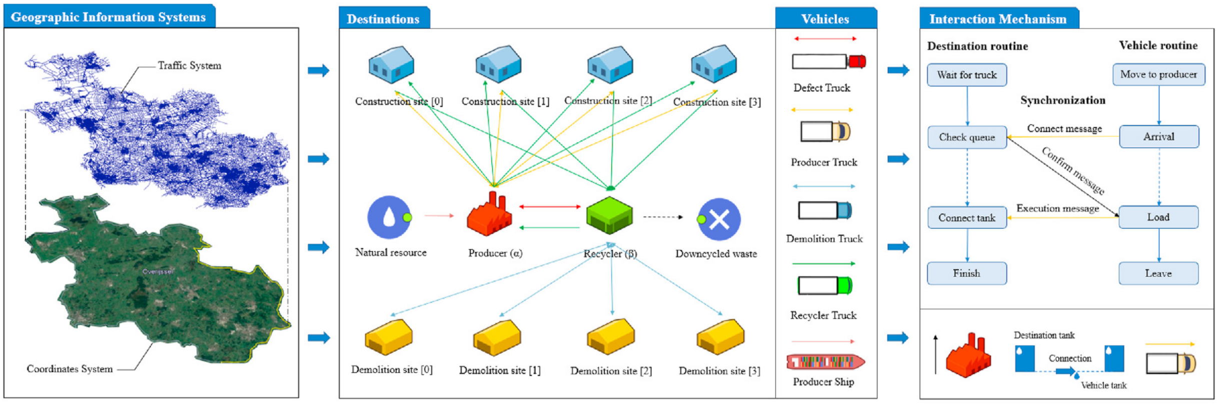

Fig. 2. Agent definition of GIS model.

and one platform agent. Fig. 3 illustrates the agent definition and the model architecture.

The company agents, A and B, are designed for modelling companies involved in an IS cooperation. They make decisions in favour of their interests. The agent architecture consists of *parameter, state, message* and *action*. A and B make decisions on whether to participate in the collaboration by comparing received benefits and their benefit expectations. Based on this comparison, the corresponding actions are executed, such as sending their decisions to the platform agent C. In this model, C serves as a mediator that ensures the information exchange between A and B. Its function is to moderate the cooperation by detecting and reacting to the responses from company agents.

2.2.2.1. CP model parameters & stochasticity. In the CP model, both companies are motivated to cooperate once they can both achieve cost reductions. The total benefit (ΔC_i) is in the form of the overall cost reduction thanks to IS. It is calculated as the cost variations between the baseline and possible scenarios and i refers to the code of each scenario while C_0 stands for the baseline cost:

$$\Delta C_i = C_0 - C_i \tag{1}$$

A benefit-sharing factor λ is designed to moderate the cooperation by determining the percentage of ΔC_i received by each company. Specifically, the Received Benefit (RB) gained by A (Δ_α) and B (Δ_β) can be computed as follows:

$$\Delta_\alpha = \lambda \Delta C_i \tag{2}$$

$$\Delta_\beta = (1-\lambda)\Delta C_i \tag{3}$$

In this study, λ is generated by agent C as a stochastic value that follows the normal distribution of (0.5, 0.2) (Yazan and Fraccascia 2019). Meanwhile, the Expected Benefit (EB) of A (Δ_α^*) and B (Δ_β^*) are adaptive values that fluctuate according to a threshold factor η. The factor η is a stochastic value that ranges from 0.05 to 0.5 (Albino et al., 2016). It represents the minimum cost reduction expectation of each agent from the IS cooperation. The EB of two IS participants are computed as:

$$\Delta_\alpha^* = \eta_\alpha C_\alpha \tag{4}$$

$$\Delta_\beta^* = \eta_\beta C_\beta \tag{5}$$

where η_α and η_β are threshold factors of α and β. Besides, C_α and C_β are the total costs that A and B invest in the collaboration, respectively. As for other parameters, *State* indicates the extent to which the agent reaches in the whole cooperation process. The information is conveyed among agents by sending *Messages*. Stimulated by the message from another, agents take different *Actions*, such as changing colours and moving positions. These actions are captured and recorded by the central platform agent C. The interactive mechanism of the CP model is explained in Appendix A.

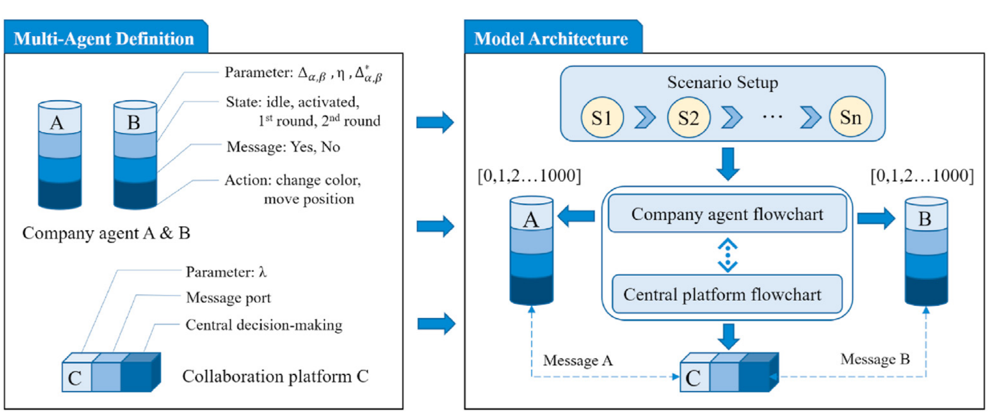

Fig. 3. Agent definition & Model architecture of CP Model.

3. Case study

In this section, a case study is performed to investigate the potential IS based on the RCA supply chain in the Twente region. It is the most urbanised region in the eastern Netherlands with intensive construction and demolition activities, which means a large amount of concrete waste needs to be up-cycled in this area. Meanwhile, the majority of construction actors in the Netherlands are involved in the Concrete Agreement (Betonakkoord 2018) to implement the Dutch national call of realizing CE by 2050. Many actors who reached the consensus of creating a circular concrete sector in this agreement are located in the Twente region, which formed a collaborative enterprise atmosphere (Schuttenbeld et al., 2019). In this case study, the local supply chain structure is clarified by interviewing the local actors firstly. Then, the economic analysis of the potential IS is carried out by applying the EIO computation method. Afterwards, the proposed simulation approach is implemented to demonstrate the supply-demand and collaboration dynamics.

3.1. RCA supply chain in Twente

The interview is an effective data collection method that helps to investigate practical situations by collecting quantitative and qualitative information (Sekaran and Bougie 2016). Seven interviews were conducted with local supply chain actors to investigate the current situation of the concrete waste supply chain in the Twente region. The aim of each interview is to find out actor's: 1) functions and responsibilities in the supply chain, 2) partners in its collaboration network, 3) specifications of concrete wastes management in terms of qualities, quantities and costs, and 4) expectations of strategic interventions from the government. The results of the first three topics are regarded as practical model inputs. The last one provides substantial local knowledge for the discussion.

3.1.1. Material flows

The interviews combined with literature and document analysis provided an overview of the concrete flows. The main actors in this supply chain are all Small-Medium Enterprises, which include the concrete production factory, the construction contractor, the demolition company, and the concrete waste recycling factory. This actor categorization is consistent with the finding of Schraven et al. (2019). To demonstrate the material and monetary flows among these actors, the material supply chains are schematized in Fig. 4.

The major concrete material supply flow consists of the following processes:

- Primary Concrete Aggregates (PCA) are extracted by the conventional aggregates supplier and delivered to the concrete production factory;
- Concrete elements are produced by the concrete production factory and delivered to construction sites;
- Defect concrete waste is generated during the concrete production process and transported to the recycling factory;
- Construction and demolition waste is generated from sites and transported to the recycling factory;
- Concrete waste is separated from other CDW and recycled by the recycling factory;
- Depending on the waste quality and recycling investment, three types of recycled materials are provided. The Recycled Concrete Aggregates (RCA) and extra processed RCA (RCA*) are purchased by the concrete production factory, while Down-Cycled Concrete (DCC) is delivered to the road construction as foundation fillers.

The recycling factory plays a significant role in this supply chain since it provides the technology of separating and recycling concrete waste. The entire recycling procedure starts by specifying concrete waste sources. Generally, the concrete waste is recognized mainly in two categories: 1) heterogeneous concrete waste, namely, the concrete waste mixed with other CDW, such as woods, plastics and steels; 2) homogeneous concrete waste, namely, the pure concrete waste without any other CDW (Schuttenbeld et al., 2019). Since recycling costs would result from switching the machine setups for heterogeneous waste, recycling costs are able to be reduced if more homogeneous waste is received (Biblus-net 2016). This indicates that the homogeneous concrete waste is more economically attractive to the recycling factory than the heterogeneous ones.

On the other hand, instead of being used as concrete production inputs, heterogeneous concrete waste is roughly processed to be road foundation fillers, also known as DCC. Besides, it is also possible to up-cycle the heterogeneous waste into RCA, which is extra-processed RCA (RCA*) and often requires higher recycling costs (Schuttenbeld et al., 2019). Furthermore, the quality of RCA and RCA* are mainly assessed by considering grading size, particle roughness and general cleanliness (De Brito and Saikia 2013). The up-cycling efficiencies of RCA and RCA* of the recycling factory in this case study, as well as all other parameters collected from the interviews, are stated in Table 1.

3.2. EIO computation

In this case, the potential IS would occur when concrete waste is up-cycled into RCA to replace PCA. Therefore, the EIO computation focuses on the material flow between the concrete production factory (α) and the waste recycling factory (β). It is defined that α has two outputs: concrete products and defect concrete waste, as well as two inputs: PCA and RCA. The total demand for concrete aggregates X_α is:

$$X_\alpha = \gamma w_\alpha / W_\alpha \tag{6}$$

where W_α is the production efficiency of concrete product, and w_α is the annual amount of concrete product output. γ is the ingredient proportion of aggregates used in products. For the sake of simplification, the production processes of primary concrete and precast concrete are integrated.

Meanwhile, β has two inputs of construction and demolition concrete waste and defect concrete waste, as well as three outputs of RCA, RCA* and DCC. The supply amount of RCA and RCA*, i.e, X_β is:

$$X_\beta = (\delta + \delta^*)[w_\beta + (1 - W_\alpha)X_\alpha] \tag{7}$$

where w_β denotes the amount of concrete waste received by β from both demolition and construction contractors. $(1 - W_\alpha)X_\alpha$ indicates the amount of defect concrete. δ and δ^* are the technical ratios of recycling proportion of RCA and RCA*. It is assumed that construction and demolition waste is processed collectively and all RCA and RCA* up-cycled by β are purchased by α.

The quantities, such as w_α and w_β, are influenced by the construction market. Thus, they are inherently uncertain. Meanwhile, the technical coefficients, γ and δ, may change because of technological innovation. For instance, the novel concrete recycling technology presented by Lotfi et al. (2015) may result in a higher level of δ. To summarise, the computational material flows are schematized in Fig. 5:

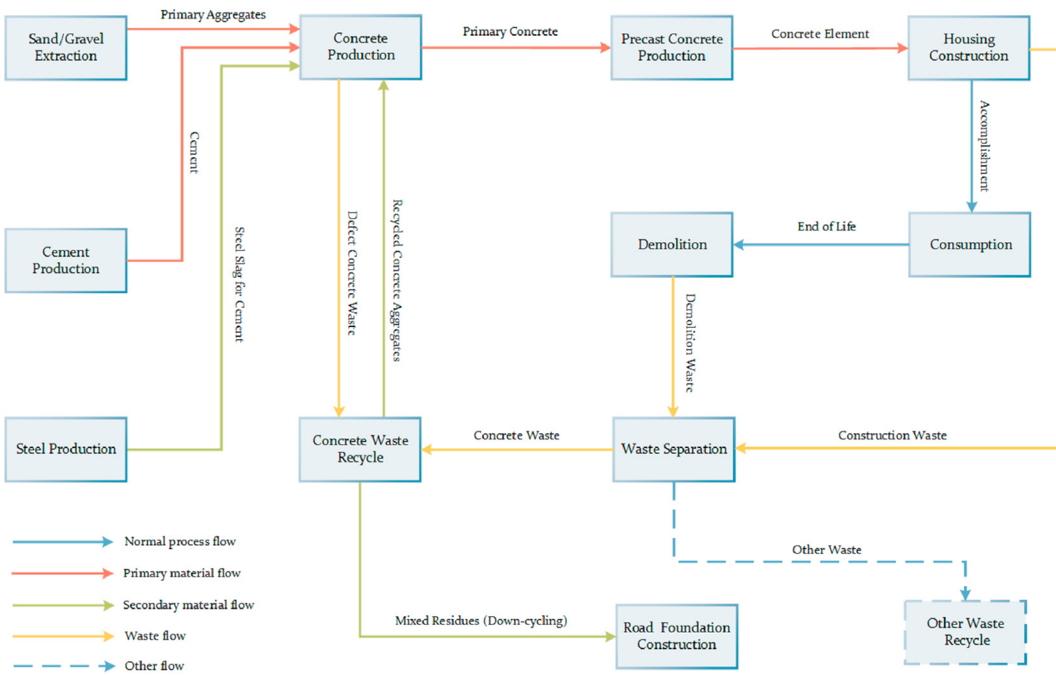

Fig. 4. Material flows of concrete aggregates supply chain.

Table 1
EIO model parameters.

Symbol	Description	Value	Unit
Technical coefficients & Quantities			
w_α	Annual output of concrete products	400,000	ton
γ	Ingredient proportion of aggregates	0.75	–
W_α	Production efficiency of concrete	0.95	–
δ	Recycling proportion of RCA	0.4	–
δ^*	Recycling proportion of RCA*	0.1	–
w_β	Annual input of concrete waste	100,000	ton
Basic unitary costs			
$C^P_{w_\alpha}$	Unit price of PCA	12	euro/ton
$C^R_{w_\beta}$	Unit price of RCA	12	euro/ton
C^T_α	Unit transportation cost of PCA	0.1	euro/km/ton
C^T_β	Unit transportation cost of RCA	0.2	euro/km/ton
D_α	PCA transportation distance	200	km
D_β	RCA transportation distance	40	km
C_{w_β}	Unit recycling cost of RCA	9	euro/ton
$C^*_{w_\beta}$	Unit recycling cost of RCA*	12	euro/ton
$C^D_{w_\beta}$	Unit recycling cost of DCC	7	euro/ton

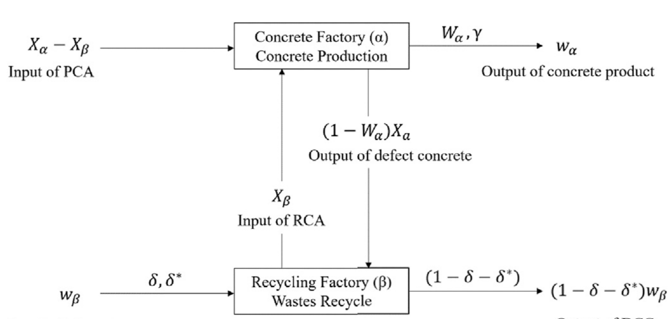

Fig. 5. Schematic material flow of EIO model.

3.2.1. Costs computation

In this section, the IS cost of each actor is computed based on the practical material quantities and prices information obtained from local actors. The monetary flow between α and β follows the basic rules: 1) The production factory purchases PCA from the conventional, but RCA and RCA* from the recycling factory; 2) The recycling company invests on the recycling equipment and labours.

It is assumed that one unit of PCA used in α is replaced by one unit of RCA from β with identical physical characteristics. In this case, the purchasing costs of PCA (C^1_α) and RCA (C^2_α) are:

$$C^1_\alpha = \left(C^P_{w_\alpha} + C^T_\alpha D_\alpha\right)(X_\alpha - X_\beta) \tag{8}$$

$$C^2_\alpha = \left(C^R_{w_\beta} + C^T_\beta D_\beta\right)X_\beta \tag{9}$$

where $C^P_{w_\alpha}$ and $C^R_{w_\beta}$ are unit prices (euro/ton) of PCA and RCA, respectively. $(X_\alpha - X_\beta)$ represents the PCA amount. C^T_α and C^T_β are unit transportation costs (euro/km/ton) for PCA and RCA. D_α is the transportation distance between the mining site in Nijmegen, the Netherlands and α, while D_β is the dynamic distance among α, β, and construction/demolition sites. The value of distance is determined by applying the simulation model, which is further explained in the section of Result. The cost of recycling CDW into RCA (C^1_β) and DCC (C^2_β) are:

$$C^1_\beta = \left(C_{w_\beta}\delta + C^*_{w_\beta}\delta^*\right)[w_\beta + (1 - W_\alpha)X_\alpha] \tag{10}$$

$$C^2_\beta = C^D_{w_\beta}(1 - \delta - \delta^*)[w_\beta + (1 - W_\alpha)X_\alpha] \tag{11}$$

where C_{w_β} and $C^*_{w_\beta}$ denote unit costs of recycling homogeneous and heterogeneous concrete waste into RCA. $C^D_{w_\beta}$ is the down-cycled unit cost of DCC. At last, the total cost (C_0) of the basic scenario of the IS cooperation is the sum of the costs paid by α and the costs paid by β (see Table 1 for the summary of all notations):

$$C_0 = \sum_{n=1}^{2} C_\alpha^n + \sum_{n=1}^{2} C_\beta^n \tag{12}$$

3.2.2. CO_2 Emission computation

CO_2 is the major noxious gas from the construction industry that pollutes the atmosphere and causes the greenhouse effect (De Brito and Saikia 2013). Therefore, the environmental benefit of replacing PCA with RCA is quantified as the reduction of CO_2 emissions. The computation of CO_2 emissions is carried out to estimate how much environmental benefits an IS cooperation would bring by replacing PCA with RCA. The key to CO_2 emission estimation is an appropriate emission factor (Alnahhal et al., 2018; Quattrone et al., 2014).

There are multiple measures to analyse the CO_2 emission of concrete since concrete contains different ingredients. For the sake of simplification, the computation elaborated in this study only takes into account the effects of implementing different coarse aggregates. The specifications of CO_2 emissions of recycling concrete aggregates are listed in Table 2.

Apart from aggregates, Ordinary Portland Cement (OPC) and sand also emit CO_2. In particular, OPC constitutes the largest proportion of CO_2 emission. According to Alnahhal et al. (2018), the replacement of PCA with RCA decreases the CO_2 emission by approximately 7% between Primary Concrete (PC) and Recycled Concrete (RC). This index covers the emission from transportation, grinding and recycling treatment processes. Based on Table 2, the total reduction of CO_2 emission (ΔE) due to the RCA can be computed by:

$$\Delta E = (e_P - e_R)(X_\beta W_\alpha / \gamma)*1000 / \rho \tag{13}$$

where e_P and e_R denote the total emission factors of PC (369 kg/m^3) and RC (342 kg/m^3) displayed in Table 2. The volume of RCA concrete product is calculated based on the mass of RCA, ingredient proportion and production efficiency. The concrete density (ρ) used in this research is 2,400 kg/m^3, even though it varies between the concrete of different strengths.

3.3. Model applications

Two simulation models were developed by the software, AnyLogic, a flexible simulation tool with Java language environment and powerful visualization functions (Borshchev et al., 2002). It has been applied widely by scholars in the field of supply chain management, industry operation and logistics monitoring (Ivanov 2017). The GIS supply chain model was implemented by adapting the logistic routine indicated in Fig. 4 as follows:

- Defect Truck: transfer defect concrete from α to β, and return RCA from β to α;
- Production Truck: transfer concrete elements from α to construction sites;
- Demolition Truck: transfer demolition waste from the demolition sites to β;
- Recycling Truck: transfer construction waste from the construction sites to β, and delivery RCA to α;
- Resource Ship: transfer PCA from the nature mining site to α.

For the sake of simplification, all vehicles were designed with the same virtual hauling speed. According to the information provided in Table 1, GIS simulation settings are listed in Table 3. The total capacity of construction sites and demolition sites were exactly 1000 times smaller than the practical inputs presented in Table 1, because this required less computing power of the program and effectively delivered the smooth simulation visualization with a concise geographic layout. Otherwise, a large number of destination sites were needed to represent the huge annual input-output amounts and the transportation network could be overwhelmingly intensive. Moreover, the global coordinates applied in the model are provided in Table 4.

The interface of the GIS supply chain model is captured in Fig. 6. The white truck hoppers are filled with colours if they are loaded with materials. Besides, the logistic routes follow the existing road infrastructure network and are generated automatically as the most efficient routes by the software. The quantity information of materials available at each destination is tracked in-time in the shape of circles with different radiuses. The more materials, the larger radius. In particular, yellow circles represent the quantity of demolition waste, green circles indicate the delivered concrete elements and red ones are the construction waste generated on-site.

As for the CP model, the simulation focuses on the IS between α and β based on the EIO computation. The interface of the CP model is demonstrated in Fig. 7. In the CP model, the company agents are simplified as *circles* and *squares*. For each simulation, the movement and colour of company agents are observed. The cooperation is successful when both agents turn to green (darker green means the case is only successful in the 2^{nd} round) and move to the zone of *Successful Zone*. And *Failed Zone* gathers the agents with the colour red (darker red means the case is also failed in the 2^{nd} round). Lastly, the yellow agents indicate that the negotiation proceeds into the 2^{nd} round but is not yet finished. For each case, the data of IS probability, λ value, EP, AP and threshold value are recorded in the data-monitoring windows. Models were uploaded and stored on AnyLogic Cloud. Click links to operate them: GIS Model and IS Model.

4. Results

This section presents the results of the case study. First, the GIS model was applied to demonstrate the supply-demand dynamics under different quantity-related scenarios. Second, the CP model investigates the IS cooperation space under different cost-related scenarios.

Table 2
CO_2 emission specifications (Alnahhal et al., 2018).

Type	CO_2 emission (kg CO_2/m^3)				
	OPC	PCA	RCA	Sand	Total
PC	311.6	46.8	0	10.43	**369**
RC	311.6	0	20	10.43	**342**

Table 3
GIS model basic scenario settings.

Agent Type	Agent No.	Material Type	Per Capacity	Unit
Construction site	4	Concrete element	100	ton
Demolition site	4	Concrete waste	25	ton
Defect truck	1	Concrete waste	5	ton
Production truck	4	Concrete element	5	ton
Demolition truck	2	Concrete waste	5	ton
Recycling truck	4	RCA & Concrete waste	5	ton
Resource ship	2	PCA	50	ton

Table 4
GIS model global coordinates.

Location	Coordinates	Location	Coordinates
Construction site [0]	52°12′52.5″N 6°53′15.3″E	Demolition site [0]	52°12′55.4″N 6°53′00.5″E
Construction site [1]	52°14′15.8″N 6°50′55.1″E	Demolition site [1]	52°14′15.8″N 6°50′55.1″E
Construction site [2]	52°18′02.7″N 6°50′13.1″E	Demolition site [2]	52°18′02.7″N 6°50′13.1″E
Construction site [3]	52°16′01.3″N 6°47′30.8″E	Demolition site [3]	52°16′01.3″N 6°47′30.8″E
Production factory [α]	52°13′49.0″N 6°50′47.3″E	Recycling Factory [β]	52°17′11.6″N 6°46′46.5″E

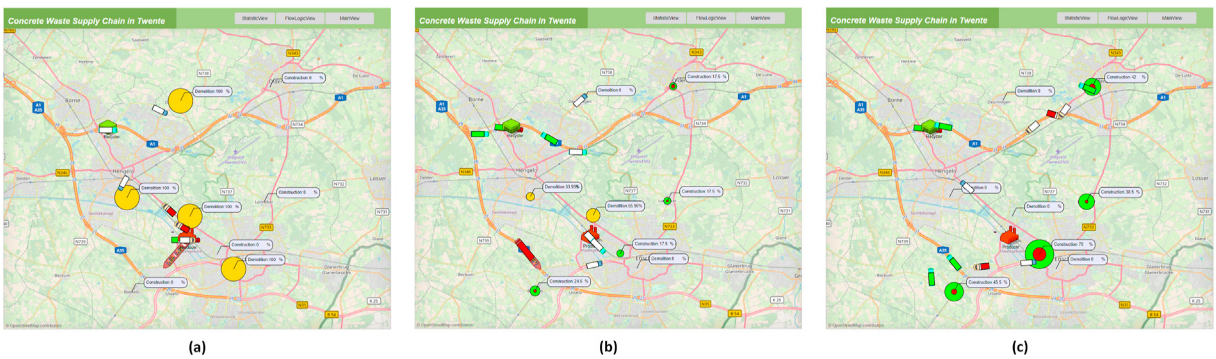

Fig. 6. GIS Model Simulation Interfaces: (a) Early stage; (b) Middle stage; (c) Late stage.

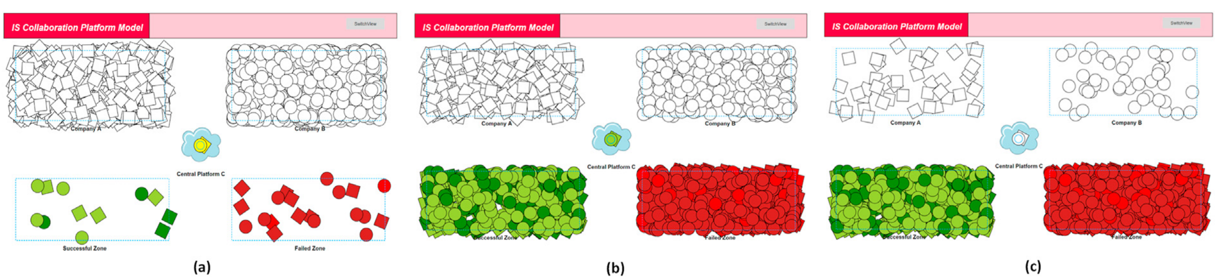

Fig. 7. CP Model Simulation Interfaces: (a) Early stage; (b) Middle stage; (c) Late stage.

4.1. GIS and EIO supply chain model result

The GIS model presents the variations of material quantities over time. To restore the simulation data and make it comparable to the EIO model's results, all quantity-related results of GIS model were up-scaled by 1000 times in Fig. 8.

As can be seen in Table 5 and Fig. 8, the results of the GIS supply chain model and EIO model shared a preferable consistency. Particularly, the GIS model carried out a larger quantity of concrete products (448,400 ton) and required more aggregates (354,000 ton) than the EIO model. However, the total supply amount of RCA of the GIS model was less (54,000 ton), which also led to a decrease in saved CO_2 emission (769,500 kg). Generally, the EIO model delivered a higher value of RCA usage proportion (0.18) than that of the GIS model (0.15).

Besides, the process data retrieved from the GIS model were plotted in Fig. 8 (a), which illustrated the tendency of how quantities of different materials increased over time. Specifically, several considerable leaps of PCA were witnessed throughout the entire simulation while RCA increased steadily with only minor fluctuations. This reflects the fact that PCA inputs were made by cargo ships whose capacities are ten times larger than normal trucks. Hence, the record of total output shares the same developing pattern with the total PCA input. In other words, the consistent supply of PCA was the focal force to sustain the concrete production. On the other hand, the quantity of RCA supply was much smaller and less predictable because the source of RCA was scattered in various sites. The non-linear slope indicates the RCA supplies were not directly proportional to time and the lags resulted from spatial and temporal differences compromised the supply consistency.

The GIS model is an ideal model that was developed in an open and transparent virtual environment where actors take their responsibilities and share information of both waste and products for mutual benefits. The ecosystem developed in the model echoes the philosophy raised by Deng et al. (2019) that one vital driver for an efficient construction supply chain management is the transparency of information exchanging. A well-developed communication system enables the waste quantity monitoring and forecasting and further provides more opportunities for IS collaborations.

4.1.1. Quantity-scenario sensitivity analysis

To investigate the effects of demolition waste amount and recycling efficiencies on the RCA usage, four quantity-related scenarios for sensitivity analysis are presented as follows:

- (SI) Waste supplies of demolition sites are doubled from 25 to 50 tons;
- (SII) Up-cycling efficiency is doubled from 0.4 to 0.8;

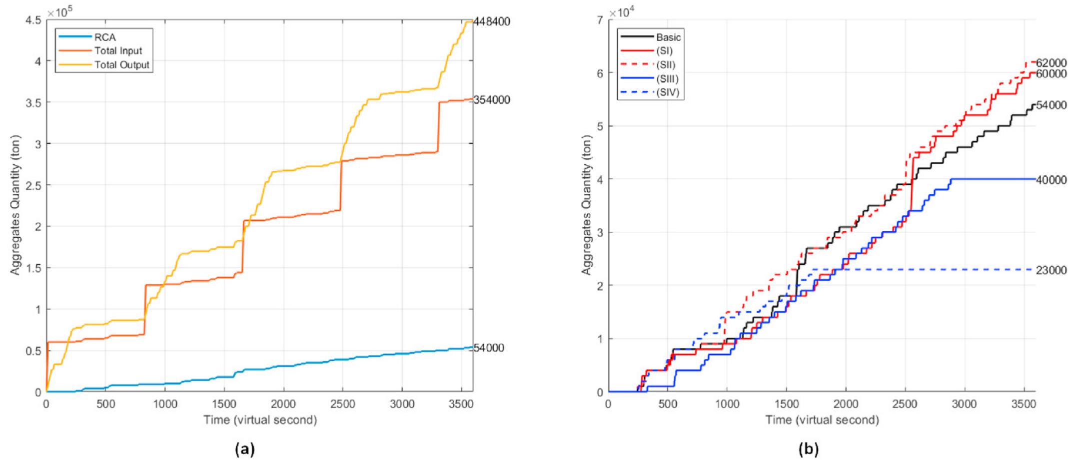

Fig. 8. GIS supply chain model result.

Table 5
Result comparison of EIO and GIS Model.

Item	Description	EIO	GIS	Unite	Source
w_α	Total output of concrete products	400,000	448,400	ton	Table (1)
X_α	Total demand of concrete aggregates	315,789	354,000	ton	Eq (6)
X_β	Total supply of RCA	57,895	54,000	ton	Eq (7)
ΔE	Total save amount of CO_2 emission	825,000	769,500	kg	Eq (13)
X_β/X_α	RCA proportion	0.18	0.15	–	–

- (SIII) Waste supplies of demolition sites are halved from 25 to 12.5 tons;
- (SIV) Up-cycling efficiency is halved from 0.4 to 0.2.

Quantity-scenario simulations were carried out and the results of delivered RCA and reduced CO_2 are shown in Fig. 8 (b) and Table 6. This analysis shows that the up-cycling efficiency had a larger influence on the RCA production than the individual waste supply amount, and a lower efficiency could lead to a significant RCA shortage. Within the same period, the performances of the four scenarios varied. Specifically, (SII) achieved the highest amount of RCA, 62,000 ton, which was 15% more than the basic scenario. It is expected that RCA had the potential to further increase if longer simulation time were allowed. By contrast, (SIV) delivered the lowest amount of RCA of only 23,000 tons, which was 57% lower than the basic scenario. Since recycling trucks cannot be fully loaded efficiently when up-cycling efficiency was too low, the RCA supply was interrupted half-way through the simulation. Lastly, the reduction of CO_2 emission ranged from 327,750 to 883,500 kg among all scenarios.

4.2. IS Collaboration Platform model result

According to the knowledge obtained from the local actors, the up-cycling supply chain was established to a limited extent. The focus of the CP model is to investigate how IS can be improved under different cost-scenarios. Firstly, the EIO computation was applied to carry out the economic results under different cost-scenarios. Taking these results as inputs, the CP model was implemented to analyse the space of IS cooperation.

Table 6
Scenario analysis of GIS model.

Scenario	RCA (ton)	CO_2 (kg)	Deviation (–)
Basic	54,000	769,500	0
(SI)	60,000	855,000	11%
(SII)	62,000	883,500	15%
(SIII)	40,000	570,000	−26%
(SIV)	23,000	327,750	−57%

4.2.1. Cost-scenario sensitivity analysis

Addition to the basic scenario, four individual cost-scenarios and two combined cost-scenarios were composed. Each scenario contained the changes of doubling and halving different costs. They are listed as follows:

- (S1) Purchasing costs of PCA (C_α^1) are doubled/halved;
- (S2) Down-cycling costs of DCC (C_β^2) are doubled/halved;
- (S3) Purchasing costs of RCA (C_α^2) are doubled/halved;
- (S4) Up-cycling costs of RCA (C_β^1) are doubled/halved;
- (S5) Combined costs of traditional business model (S1+S2) are doubled/halved;
- (S6) Combined costs of circular business model (S3+S4) are doubled/halved.

Apart from the inputs of quantities, technical coefficients and costs, the transportation distances of PCA and RCA were acquired from the GIS model. However, the down-scaling of quantities in the GIS model compromised the accuracy of transportation distance because vehicles accomplished annual input-output amounts within limited simulation time (3600 virtual seconds) by virtual speeds. Therefore, instead of referring to exact distance results, a simulation result of the distance ratio of 5 between the transportation distances of PCA and RCA was applied to the EIO model. This is the reason why the sum of dynamic transportation distances of RCA was determined as 40 km in Table 1. The cost-scenario EIO analysis results are presented in Appendix B.

4.2.2. Cooperation space analysis

In Fig. 9, cost-scenarios were analysed in pairs because the costs of conventional materials, namely, PCA and DCC, were changed in (S1) and (S2), the RCA-related costs were modified in (S3) and (S4), and the combined costs were analysed in (S5) and (S6). For each scenario, only the halved-costs case (potential subsidy intervention) was simulated by the CP model because the collaboration would not be initiated if there is no cost reduction. The left column displays the relationship between the RCA supply-demand ratio and IS collaboration probability while the right column demonstrates their relationships together with the total cost reduction in 3D-spaces. The IS probability represents the space of cooperation between firms under different scenarios and it had great diversity. In the first pair of (S1) and (S2), a relatively high IS probability (around 80%) was spotted when the ratio was lower than 0.2 in (S1) but it descended dramatically to nearly 0% afterwards. On the contrary, the IS probability of (S2) remained low and only raised to 5% at the end.

In the second pair, the cooperation space of (S4) was merely available though the total cost reduction showed an increasing trend. On the other hand, the cooperation space of (S3) experienced a significant development when the ratio was between 0.4 and 1.0 and remained at a level of 80% afterwards. Finally, the combined scenarios presented a contradictory situation. The IS probability of (S5) started with a value of 89% and continuously declined to 0% as soon as it passed the ratio of 0.8. Meanwhile, (S6) had a reversed tendency and came across (S5) when the ratio was around 0.5. After the point of 0.8, it performed the highest probability level of around 90% among all scenarios.

One of the collaboration rules applied in this model is that one's expectation is set according to the initial cost, and a higher initial cost indicates a lower chance of reaching an IS agreement. In these proposed scenarios, the supply-demand ratio increased, which means more RCA were supplied by β. Although the overall costs declined, the amount of RCA increased and β invested more to treat RCA. Compared to recycling investment of β, the shared benefit could be too insignificant to motivate β to show collaboration behaviours. Therefore, the IS collaboration between the waste recycler and secondary material receiver is different from the traditional IS collaboration where the recycling treatment process was excluded (Yazan and Fraccascia 2019).

Furthermore, the recycling factory in the study has already reached a higher level of waste treatment where the down-cycled concrete is supplied to fill the road foundation instead of irresponsible disposal. Thus, the waste that is down-cycled in this case does not necessarily bring any economic loss to any participant. This explains why β was unable to save cost when the up-cycling rate increased and less waste was down-cycled. At last, the results indicate that the economic coordination strategies for the IS collaboration are not static but should be constantly updated to keep pace with the market dynamics. More details of the intermediate results of the CP model simulation can be found in Appendix C.

5. Discussion

Responding to the call of CE by 2050 in the Netherlands, construction actors actively participate into the Concrete Agreement and take the up-cycling of concrete waste as a crucial practice to enable circular material flows and to further realize a resource-efficient built environment. In the case study, the nascent symbiotic network emerged amongst the recycling factory, the concrete production factory and multiple construction/demolition sites, equips with the characteristics of an ISN.

From the perspectives of reusing and recycling, IS has been considered as a vital mechanism to realize CE. Although recycling is viewed as a low-rank circular practice locating at the most outside range of the *Butterfly Diagram*, its environmental significance should not be underappreciated. The fact is that numerous existing constructions were not designed circularly while there is hardly any other option left to deal with CDW. Thus, the development of ISN based on the up-cycling of concrete waste can be regarded as a practical mechanism to manage the excess CDW in the coming decade and contributes to CE implementation for the construction industry. The remaining part of this section discusses 1) the existence of IS in the construction industry, 2) the relevance of ABM for the IS supply chain management, and further provides 3) the outlook of IS improvement.

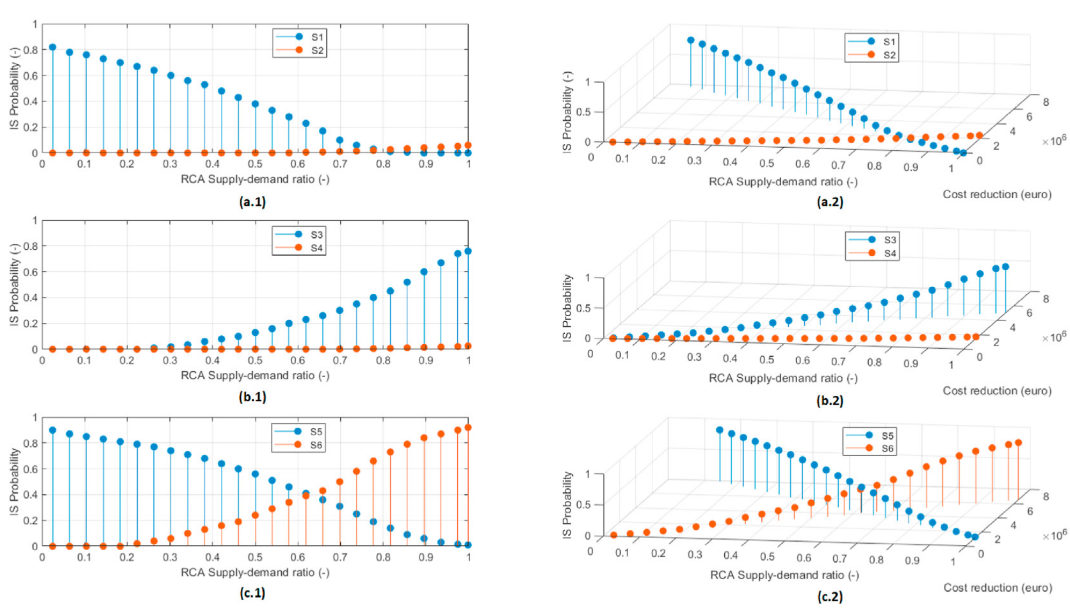

Fig. 9. CP model results of IS cooperation space.

5.1. Existence of IS in construction industry

Chertow and Ehrenfeld (2012) developed a three-stage model that covers 1) sprouting, 2) uncovering 3) embeddedness and institutionalization, to generalize the evolvement process of an ISN. This model falls under the theory of CAS and its characteristic of self-organizing distinguishes IS from other types of industrial clusters. By observing the simulation process and interpreting the simulation results, we conclude that the ISN based on construction/demolition concrete waste is still at its sprouting stage where a limited network of interlinked flows takes shape. It echoes the description raised by Chertow and Ehrenfeld (2012) as "such systems may lead to occasional cooperative exchanges, however, they do not provide sufficient information to ensure the development of a robust network." The equilibrium of circular material flows can be easily interrupted by the fragmented and inconsistent waste supply because the anchor waste provider is not a single entity but a cluster of homogeneous actors, namely, construction/demolition sites.

Since the delay penalty of a construction project delivery could be significantly high, actors prefer to choose the conventional manufacturing process to ensure the steady material supply. This is the focal reason why the production factory is reluctant to purchase RCA. Although RCA are of environmental importance and more economically attractive due to the location proximity, the current construction industry is yet prepared for its implementation on a large scale. The exchanges of RCA require not only the support of recycling technologies but also robust information management to enforce regulations and contracts outside of the conventional business regime (Chertow and Ehrenfeld 2012; Boons et al., 2017). The long-term operation, maintenance and expansion of such a network could be even more information-intensive considering the complex temporal and spatial differences embedded in construction/demolition projects.

Essentially, the concept of IS belongs to a branch of Industry Ecology and is widely applied in the industrial sector where the supply chain is highly integrated and structured (Boons et al., 2017). However, the IS practices in the construction industry are implicit, which leads to a new identification of IS taxonomy: *Implicit IS*. The project-based approach to construction projects and the fragmented supply chain structure in the construction sector can hardly provide any nourishment to implement IS directly but rather *hide IS behind the curtain*. The implicit IS, therefore, is identified as a particular type of IS that emerges in constructions where the equilibrium of symbiotic material flows can hardly be reached without the recycling factory acting as an intermediary, and tends to be interrupted by the spatially fragmented and temporally inconsistent supply of construction/demolition waste. This could be inevitable for large-scale construction projects with complex supply chains of numerous materials concerning quantities and categories.

5.2. Relevance of ABM for the IS supply chain management

Although actors reached a primary consensus to collaborate, the ISN based on concrete waste is still underdeveloped. In this case, the concrete waste supply is significantly small compared to the operational input-output capacity of the production factory. In fact, the consumption of RCA only takes up 10% of the total aggregates consumption. Moreover, the holistic overviews of the supply-demand dynamics and economic performance of the circular supply chain are missing. Therefore, the simulation approach is proposed to facilitate the development of such an ISN. The focus here is not to optimize the partners' combination regarding the supply-demand capacities or locations of actors. Rather, the motivation is to evaluate the IS collaboration as an emerged systematic performance given different operational and economic scenarios. This sheds the light on the development of a regional ISN in the context of the construction industry. However, the optimization of partner combination is valuable for future research when more actors participate in a broader scope. The optimization goal could be searching and matching satellite actors, namely, construction/demolition sites with the anchor actors, namely, the production factory and the recycling factory to minimize the supply-demand capacity mismatching.

On the other hand, the GIS model demonstrates the dynamics of the RCA supply-demand naturally and realistically (Deng et al., 2019; Lemire et al., 2019). The dynamics are related to the information of how much and when the RCA are supplied. In the traditional static models, this dynamic character is compromised by manually setting a linear program (Hiete et al., 2011; Yazan et al., 2011). But in the proposed model, the time lags between supplies are fully illustrated and visualized with the realistic geographic layout. The ups and downs of RCA supplies come along with basic transportation routines. The circular supply chain is not designed but emerged as a collective performance (Batten 2009; Wilensky and Rand 2015; Paulin et al., 2018; Ahrweiler 2017). This provides a deeper understanding of supply-demand dynamics and how different interventions would impact the supply chain resource-efficiency at the bottom level of the system (Heckbert et al., 2010). Furthermore, the proposed models were designed to be future-proof. They were programmed in a modular manner that the modification of an individual part can be made without influencing the major model structure. Thus, the models can be updated and tailored for different cases efficiently.

In this study, simulation approaches were proposed to tackle with the coordinative challenges rooted in IS, which follows the research direction suggested by Dentchev et al. (2018). However, the basic understandings concerning the values, societal structures, cultures, underlying world-views and the paradigmatic potential of CE remain largely unexplored (Korhonen et al., 2018). For instance, collaboration capacities are multidimensional organizational construct in Cleaner Production regarding sustainable supply chain management (Van Hoof and Thiell 2014), and dynamic capabilities in the supply chain are critical for corporations to foster sustainable business transformation (Bocken and Geradts 2020). Industrial actors would also invest in these organizational aspects, together with the development of information technologies, to improve their competitiveness. Therefore, we recommend to take them into account by applying multi-disciplinary approaches to broaden the scope of future studies.

5.3. Outlook of IS improvement

1. Implement strict waste classifications on-site to ensure the waste purity: According to Fig. 1, the recycling process is of lower value than those closer to the centre of the system diagram because of the extra labour and energy consumption, material losses and equipment costs (EMF 2015). However, the ISN based on concrete waste inevitably entails recycling due to the natural characteristics of concrete. The quantity-scenario analysis indicates that up-cycling efficiency is the key to enhance the symbiotic flows because it affects the quantity of up-cycled RCA and the reduction of CO_2 emission significantly. The up-cycling efficiency not only highly depends on the innovation of recycling technologies but also strongly relates to the incoming waste quality (De Brito and Saikia 2013). Indeed, it is challenging to ensure the quality of waste provided by different sites with various production backgrounds. But implementing a clear and strict waste classification could be one of the most effective approaches to keep waste purity and reduce recycling costs.

2. Establish the information-sharing platform to improve the business communication: The information system of waste supply chain in the construction sector is underdeveloped. Firstly, the waste information is insufficient because contractors generally pay more attention to construction materials than waste. Secondly, the information exchange is fragmented and inefficient among actors. These hindered the innovative business collaboration and actors can hardly predict the potential economic convenience of sustainable collaborations (Lieder and Rashid 2016; Geissdoerfer et al., 2018; Liu et al., 2020). Thus, an information-sharing platform is recommended to facilitate the decision-making of circular business collaborations. In this study, the architecture of the CP model is platform-based, which contributes to the future research of information platform development. One potential direction of future research could be integrating the regulatory framework into the information platform. The real-time data of the local supply chain captured by the platform can feed the policy-making process intelligently, and enable a bi-directional policy-making mechanism that articulates the information flows considering circular supply chain management between public and private actors.

As shown in the case analysis, the CP model is an interactive system where decisions are made based on the individual agent's communication. This interaction mechanism represents the transparent and collaborative information-exchanging in the desired condition. However, the precondition of developing this information system is that stakeholders are actively involved and willing to share the information. Although the effort from each individual should be appreciated, they should not be alone. In the sense of creating collaborative momentum, the Dutch concrete agreement is a promising start (Betonakkoord 2018). Moreover, the literature and the interviewed actors agreed that the government should participate into this network by taking the leading role and sharing the potential business risks and opportunities with firms (Abreu and Ceglia 2018; Schraven et al., 2019; Korhonen et al., 2018).

3. Provide subsidies to up-cycling technology innovations and circular business models to enlarge cooperation space: The emergence of ISN is limited by only relying on internal resources provided by the collaborations amongst the industrial actors. The external forces, namely, the institutional power in the form of taxes or incentives are necessary for the improvement (Abreu and Ceglia 2018). The government and policy-makers have essential roles to play in transforming the linear industrial setting into a circular model (EMF 2015). Therefore, we suggest the government to take a leading role in the IS cooperation and provide subsidies to up-cycling technology innovation and circular business models. The subsidy can effectively compensate the costs spent on various aspects of implementing RCA and support environmentally promising but economically challenging cases (Liu et al., 2020; Lieder and Rashid 2016; Yazan and Fraccascia 2019). Particularly, the CP model can be applied to facilitate the decision-making process of subsidy interventions. By varying the costs of different subjects, different IS probabilities were observed. In this way, the CP model reveals the extent to which economic policy interventions would affect collaborations. Therefore, the industrial actors and the government can adjust their economic strategies proactively.

6. Conclusions

This study explored the IS based on RCA in the context of a concrete waste supply chain in the Twente region of the Netherlands. It tackled with CE transition challenges by investigating the potential IS emerged by replacing PCA with RCA. In particular, an ABM approach integrated with GIS was developed to provide industrial actors and government bodies with 1) a systematic overview of the RCA supply chain dynamics, and 2) predictive insights into the circular collaboration benefits and dynamics.

It is found that the IS exists in the construction industry with special characteristics, which entails: 1) the recycling factory acts as an anchor actor in between the waste providers and receivers because the concrete waste can hardly be used directly; 2) the material has to be transferred through multiple processes across large spatial and temporal differences, which leads to fragmented and inconsistent waste sources and secondary materials supply lags. Thus, the IS practices implemented in the construction industry is defined as Implicit IS.

Focusing on the implicit IS between the production factory (α) and the recycling factory (β), the economic competitiveness of RCA lies on the lower transportation costs thanks to the geographical proximity. However, the supply of RCA could be inconsistent and insufficient because of the temporal and spatial differences of construction/demolition projects. Therefore, the production factory was reluctant to receive RCA though the overall cost showed a decreasing tendency when more RCA were offered. The quantity-scenario analysis suggested the up-cycling efficiency is the key to the IS development. Meanwhile, the cost-scenario analysis revealed the effects of subsidy interventions on the IS cooperation space. The proposed approach is relevant and valuable for companies and government bodies to constantly adapt economic strategies to the dynamic market situation. Furthermore, three CE policy-making implications are provided: 1) implement strict waste classifications on-site to ensure waste purity, 2) establish the information-sharing platform to improve the business communication, and 3) provide subsidies to up-cycling technology innovation and circular business models to enlarge the cooperation space.

The main contribution of this research is exploring IS based on RCA dynamics in the Dutch construction industry systematically by applying innovative modelling approaches. Theoretically, it enriches the IS taxonomy by defining Implicit IS. Practically, it provides a managerial overview of the supply chain with firms to actively operate and improve their CE business strategies, and a scientific ground with the governmental bodies to tailor CE policies. We suggest future research focus on the extent to which the integration of regulatory frameworks and the information-sharing platform leads to the successful CE implementation with a larger group of actors. Also, the development of collaboration capacities and dynamic capabilities in the sustainable supply chain should be investigated by applying multi-disciplinary approaches to broaden the scope of future studies.

CRediT authorship contribution statement

Yifei Yu: Conceptualization, Methodology, Writing - original draft, Data collection, Formal analysis, Visualization. **Devrim Murat Yazan:** Conceptualization, Methodology, Writing - review & editing, Visualization. **Silu Bhochhibhoya:** Conceptualization, Methodology, Writing - review & editing. **Leentje Volker:** Conceptualization, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Supplementary data

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