Towards Circular Economy Through Industrial Symbiosis: A Case of Recycled Concrete Aggregates Using Agent-Based Simulation

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Abstract

Although Circular Economy (CE) provides promising solutions to deal with Construction and Demolition Waste (CDW), CE in the construction industry is still in its infancy. Towards the CE implementation, a key enabler from the recycling/reusing perspective is Industrial Symbiosis (IS). This study explores the IS collaboration of Recycled Concrete Aggregates (RCA) in the context of a concrete waste supply chain in the Twente region of the Netherlands. It tackles the CE transition challenge of lack of economic incentives in the construction industry by investigating the Industrial Symbiosis Network (ISN) emerged by replacing Primary Concrete Aggregates (PCA) with RCA. In particular, two simulation models are developed by integrating Enterprise Input-Output (EIO) models, Geographic Information System (GIS) and Agent-Based Simulation (ABS) modelling methods. This pair of models facilitate the CE policy-making by providing evidence of the dynamic evolution trend of the RCA supply chain under different policy scenarios. Based on the model simulation results and local knowledge obtained from interviews, the challenges of implementing IS in the construction industry are pointed out, and CE policy-making suggestions are provided.

Keywords: Agent-Based Simulation, Circular economy, Industrial symbiosis, Policy research, Supply chain management

1. Introduction

The construction industry has a high resource intensity. It consumes primary materials between 1.2 and 1.8 million tons (WEF 2015), which accounts for around 50% of the total material consumption in the Netherlands (The Ministry of Infrastructure & the Environment & the Ministry of Economic Affairs 2016). Meanwhile, Construction and Demolition Waste (CDW) generated through construction and demolition activities takes up 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 it makes up to 85% of the total waste generated on-site (Rimoldi 2010). The production of concrete brings a huge amount of CO_2 emissions and concrete waste is impossible to be decomposed naturally (De Brito and Saikia 2013). In the coming years, the amount of demolition concrete waste is expected to increase dramatically in Europe since the majority of concrete structures from the 1950s are coming to the end of their lives (Lotfi et al. 2015). As a result, it is almost impossible to avoid concrete waste in the future. Thus, innovative solutions are in great demand to recycle/reuse concrete waste, and further to reduce the dependency on primary resources and increase the efficiency of material consumption.

Confronting this challenge, Circular Economy (CE) provides 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 novel concept that focuses on maintaining the material value to the maximum extent by implementing the practices of reducing, reusing and recycling, and is believed to benefit the society both in the aspects of economy and environment without aggravating the burden of extracting the primary natural resources (Ghisellini et al. 2018; EMF 2015). Defined by the Ellen MacArthur Foundation (EMF 2015), 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. In this case, a practical application of CE is recycling concrete waste. Replacing Primary Concrete Aggregates (PCA) with Recycled Concrete Aggregates (RCA) is regarded as an effective solution to preserve natural resources and reduce the CO_2 emission (Betonakkoord 2018; Alnahhal et al. 2018).

The RCA implementation has its roots in Industrial Symbiosis (IS), which aims to extract and remain the value of by-products and waste. It is regarded as one of the most effective enablers for the transition towards a successful implementation of CE practices (Abreu and Ceglia 2018; Saavedra et al. 2018; Yazan and Fraccascia 2019). Originating from

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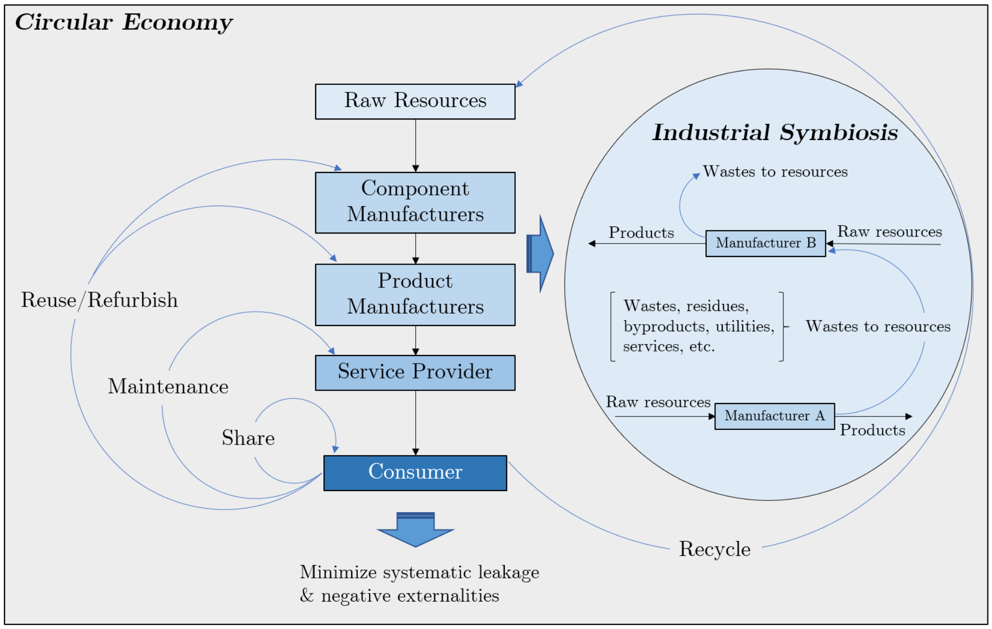

Figure 1: *Conceptual diagram of Industrial Symbiosis and Circular Economy, adapted from (EMF 2015; Abreu and Ceglia 2018)*

a prominent example of industrial facilities in Kalundborg, Denmark, IS refers to a synergic interaction between firms through which one's waste can be used as inputs for another including materials and energy (Jacobsen 2006; Lombardi et al. 2012).

It is pointed out that the expansion of IS relationships in the material supply chain would lead to the further implementation of CE practices, since the materials waste can be reused and recycled by others to maintain the utility value (Baldassarre et al. 2019). Also, IS provides opportunities to capture extra-economic profits by reducing material disposal and purchase costs. In summary, IS converts negative impacts resulted from the conventional linear model into the positive environmental and economic benefits by decreasing disposal pollution and reducing the demand of extracting raw material inputs (Chertow and Ehrenfeld 2012; Fraccascia and Yazan 2018).

Figure 1 schematizes the IS concept within a border range of the CE. On the basis of the *Circular Butterfly Diagram* proposed by EMF (2015), an extra circle of IS is added besides the recycling flow in the manufacturing stage. This circle entails the IS philosophy that manufacturer A cooperates with B by linking up resource and waste flows, using resources efficiently and ideally minimizing waste as well as natural resource exploitation (Abreu and Ceglia 2018; Ghisellini et al. 2018; Mendoza et al. 2017).

Among various factors that may affect the initiation of IS, such as technical, political, economic and financial, informational and organizational factors, *economic benefits* is regarded as a main driver for companies to get involved in a potential IS cooperation (Mirata 2004; Yazdanpanah and Yazan 2017). The establishment of such cooperation could be vulnerable and dynamic, since there is no standard recipe for a successful IS cooperation and the cooperation is highly related to mutual economic and environmental benefits (Mirata 2004; Chopra and Khanna 2017). In particular, the costs and profits should fulfil the desired expectation of any single participant and a fair benefit-sharing mechanism of economic benefit is essential to motivate them (Mirata 2004).

1.1. The Role of Policy Intervention

Although the implementation of RCA eases the negative impact of the Linear Economy model of take-make-dispose, its state is still far from the CE. In fact, a large amount of concrete wastes is down-cycled as road foundation materials while only little (3%) is recycled/reused in new projects. The cause could be that up-recycling processes require extra investments and the qualities of recycled aggregates may vary depending on the waste source (De Brito and Saikia 2013; The Ministry of Infrastructure & the Environment & the Ministry of Economic Affairs 2016). But the need for filling the foundation with RCA is expected to decrease due to a reduction in the net growth of road infrastructures (Lotfi et al. 2015). Meanwhile, the goal of a higher circular level will be reached by replacing PCA with RCA in the construction project (The Ministry of Infrastructure & the Environment & the Ministry of Economic Affairs 2016). Thus, there is a huge demand for up-cycling RCA. However, the construction CE implementation is still in its infancy, and there is limited understanding of the economic motivations for construction supply chain actors to cooperate and to collectively reach this goal (Adams et al. 2017; Ghisellini et al. 2018; Lieder and Rashid 2016).

To tackle the CE challenge of insufficient economic motivations, more than actors themselves, the government should get involved and take action (Abreu and Ceglia 2018; Schraven et al. 2019). Because the government body is one of the most important IS facilitators who consciously formulate strategies and implement policies by using incentives or enforcement (Boons et al. 2017), they can support and coordinate the CE transition by providing external forces. Countries with massive industrial demands, like Germany and China, regard CE as a prominent part of the national policy agenda since decades ago (McDowall et al. 2017). Explicitly, Zeng et al. (2017) pointed out that institutional pressures, such as normative policies, have a significant positive impact on sustainable supply chain designs. This implies the regulation of forbidding waste discharge or the subsidy intervention for circular cooperation (Yazan and Fraccascia 2019).

To coordinate the circular development of RCA supply chain, CE policies should be made carefully. The policy-making indirectly implies prediction, or at least some knowledge about the future, because actual real-world tests would be risky and costly (Ahrweiler 2017). One step before the consideration of a possible future, the current situation of the RCA supply chain should be well-understood. Particularly, the dynamic supply-demand of RCA should be mastered since it is the key to the establishment of IS. This is no doubt challenging in the construction industry.

1.2. Construction Supply Chain Management

One of most promising future scenarios of the construction industry is a highly industrialized built-environment where standardization and cleaner production are realized (McKinsey Global Institute 2011). But the study of IS collaboration is rare in the construction industry. Although it is proved that the development of IS contributes to the CE transition to a great extent (Abreu and Ceglia 2018; Saavedra et al. 2018; Fraccascia and Yazan 2018), the complex essence of the construction supply chain poses significant challenges to the CE implementation as well as IS collaborations.

Particularly, a set of complicated recycling processes are required to deal with CDW among various actors. The recycling supply chain is complex in the senses of spatial locations, temporal requirements, and fragmented information communication (Nam and Tatum 1988; Adriaanse 2014). Pointed out by Vrijhoef and Koskela (2000), the construction supply chain management has been scattered and partial, which threats the wastes minimization, cost-benefit optimization and labour reduction. Therefore, decision-supporting managerial tools are in great demand to efficiently coordinate the construction supply chain and facilitate the policy-making.

To coordinate the construction material supply chain, Geographic Information Systems (GIS) is widely applied. The importance of GIS is well-known in terms of logistic optimization, environmental impact evaluation and cost-benefit analysis (Delivand et al. 2015; Kleemann et al. 2017). Specifically, the spatial information can be incorporated with actors to visualize the distribution of resources. It also helps to manage the dynamics of a construction supply chain by combining accurate spatial information with on-site material information from Building Information Modelling (BIM) technologies (Deng et al. 2019; Xu et al. 2019). This integrated technology provides a strategic overview of the supply chain, and effectively reduces logistics costs, idle time and inventory (Deng et al. 2019; Thöni and Tjoa 2017). Furthermore, it enables transparent information communication and develops coordination mechanisms for the multi-stakeholder engagement.

However, previous studies mainly focused on the real-time monitoring of on-site construction activities and logistics optimization. Scant attention has been devoted to the management of recycling material supply chains based on the concept of IS. Also, the collaborative interactions were missing. The projects were mainly analyzed individually and there is little systematic understanding of dynamic material interactions across projects. Furthermore, little implication of future development trend was provided. Under such a circumstance, the economic and environmental benefits of potential IS collaborations can hardly be quantified in detail. This hinders the policy-making process and policymakers struggle to tailor the strategies of CE policy interventions.

Therefore, the objective of this study is two-fold: 1) to investigate the IS cooperation dynamics among the actors of the RCA supply chain, and understand the challenges of implementing IS in the construction industry, 2) to develop a managerial tool to facilitate the CE policy-making by capturing the dynamic demand-supply of RCA and quantifying the economic and environmental benefits of IS collaborations in different future scenarios. The paper is structured as follows: first, the methodological background of developing the tool is provided in section two. Then, the tool is developed based on the literature and interviews with local actors in section three. Results are carried out in section four together with the scenario analysis. Afterwards, findings are discussed to provide CE policy-making suggestions in section five. Finally, conclusions are drawn in section six.

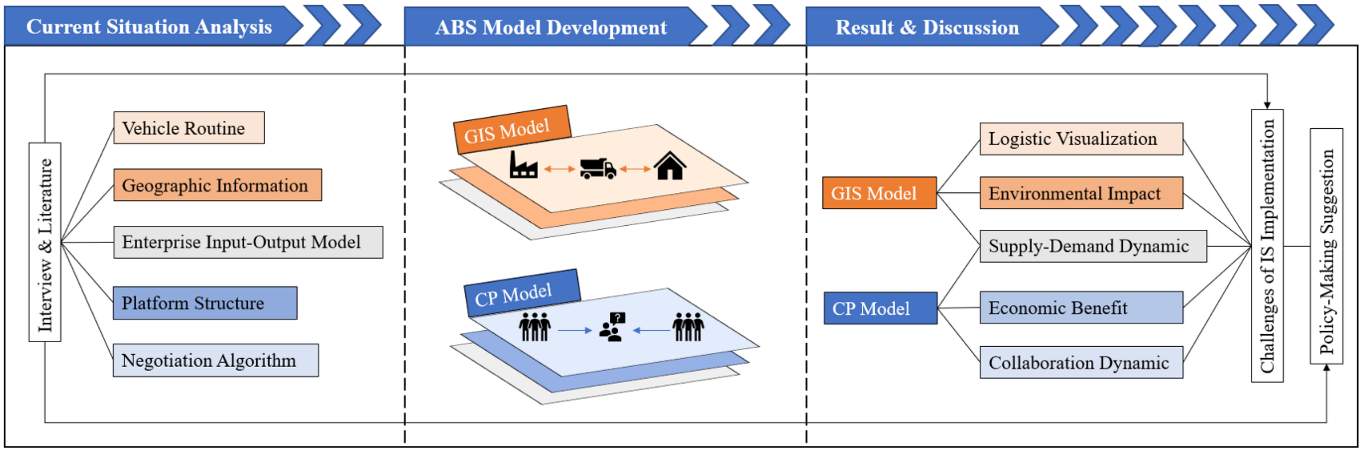

Figure 2: *Research framework*

2. Methodological Background

This research takes the RCA supply chain in the Twente region of the Netherlands as a case to study. Figure 2 shows a schematic overview of the research framework. The current situation of RCA supply chain in this region is investigated by interviews. Based on the practical information and a conceptual EIO Model, two ABS models are developed as managerial tools to simulate the decentralized material flows and multi-agent collaborations, respectively. Furthermore, the scenario analysis is conducted to reveal the challenge of IS implementation and provide CE policy-making suggestions.

2.1. Enterprise Input-Out Model

Many scholars provide various measurements to coordinate the IS collaboration while Enterprise Input-Output (EIO) models are applied widely. The EIO model is defined as a mathematical description of production processes, which include the input-output structure of a company that records material flow and financial transactions among various units (Lin and Polenske 1998; Grubbstrom and Tang 2000). The physical material and monetary flows can be expressed explicitly by applying EIO models within a company and between different companies and the overall market (Lin and Polenske 1998). With the research development, EIO models are proved to be suitable and valuable to analyse the IS cooperation in terms of economic profits as well as environmental impacts, since the costs generated from primary production inputs, by-products and waste outputs during the entire process are all taken into account in the model (Yazan et al. 2017; Fraccascia and Yazan 2018). For instance, scholars developed models of supply chains to compute product outputs, materials and waste flows and provided insights about resources consumption and environmental impacts accordingly (Albino et al. 2002; Zhang et al. 2018).

2.2. Agent-Based Simulation Model

The expansion of IS in a larger context with multiple actors is called Industrial Symbiosis Network (ISN) (Chertow and Ehrenfeld 2012). It is essentially a complex adaptive system 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 Complex Adaptive System (CAS) is applied extensively to tackle the challenges in dynamic supply chains (Holland 2006). It emphasizes a bottom-up approach that analyzes the system from the basic individual level. In this theory, it is believed that 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 Simulation (ABS) is proved to be one of the most suitable instruments to investigate dynamic interactions within such a system (Wilensky and Rand 2015; Paulin et al. 2018; Yazan and Fraccascia 2019). The basic individuals are programmed as agents that aim to execute their behaviours compassed by particular routines and value propositions (Heckbert et al. 2010). By using ABS, the individual behaviours are related to the collective behaviour of the system. Compared to traditional simulation approaches, ABS can enrich our understanding of the entire system with basic interaction principles from the bottom level (Ahrweiler 2017). It matches the theory of CAS and is used to provide visionary insight of the system's future development. Therefore, it is also regarded as a preferred approach to facilitate the policy-making (Zhang and Lin 2016; Luo et al. 2019).

In this study, two types of ABS models are developed based on the EIO analysis to investigate IS and serve as tools to manage the RCA supply chain. These models are built by the simulation 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 logistic monitoring (Ivanov 2017).

1. GIS Supply Chain Model: The GIS model developed in this research aims to simulate the recycling material flow emerged in the ISN of concrete waste. By using ABS, the RCA supply chain is studied by decentralizing the overall material flow into basic vehicle routines. These routines are executed by vehicles moving on the digital geographic system. In this way, the IS network is visualized directly from a realistic angle. Furthermore, the investigation is conducted from a bottom-up perspective without compromising ISN's characteristic of a Complex Adaptive System. Overall, this model aims to: 1) visualize the RCA supply chain network, 2) show how the overall material flow would evolve in the dynamic supply-demand environment as a result of actor's behaviour changes, and 3) provide logistic data to compute the effect of environmental impacts.

2. IS Collaboration Platform Model: To further analysis the IS cooperation dynamics, the Collaboration Platform Model is developed. This is a multi-agent model that simulates two types of companies attempt to make an IS deal via a collaboration platform. The negotiation algorithm and the platform structure are applied to vividly demonstrate the interactions among agents. In this model, the dynamic behaviours and interactions of heterogeneous agents (companies) are presented by rule-based and analytical functions. Depending on the cost-benefit outcomes of EIO models, a negotiation factor λ is introduced to indicate how the economic benefit should be shared among actors (Yazan and Fraccascia 2019). Based on shared benefits, companies are simulated as autonomous entities that can decide to initiate or interrupt the cooperation. Focusing on IS cooperation behaviours, the model simulates: 1) how the economic benefit would be shared between actors, 2) how likely a successful IS deal would emerge under different policies scenarios, and 3) how individual behaviour changes may influence the IS development.

3. Research Methods

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 supply chain actors to investigate the current situation of the concrete waste supply chain in the Twente region. Every interview lasts one hour and aims to find out: 1) actor's functions and responsibilities in the supply chain; 2) partners in his/her collaboration network; 3) specifications of concrete wastes management in terms of qualities, quantities and costs; 4) his/her expectations of strategic interventions from the government. The results of the first three topics are referred to as practical model inputs. The last one provides substantial local knowledge for the discussion.

3.1.1. *Material & Monetary Flows*

The main actors in this supply chain are concrete production factory, construction contractor, demolition company, and concrete waste recycling factory. This categorization matches the finding of Schraven et al. (2019). To better understand the material and monetary flows among these actors, the material supply chains are schematized in Figure 3.

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 products 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 concrete waste are generated from the sites and transported to the recycling factory;
- Both construction and demolition concrete waste are separated from other waste 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) waste are delivered to the road construction as foundation fillers.

Besides the material flow itemized above, the monetary flow follows the basic rules of:

- The concrete production factory purchases PCA from the conventional supplier; RCA and RCA* from the recycling factory;
- The construction contractor and the demolition company pay the recycling factory for collecting and recycling waste;

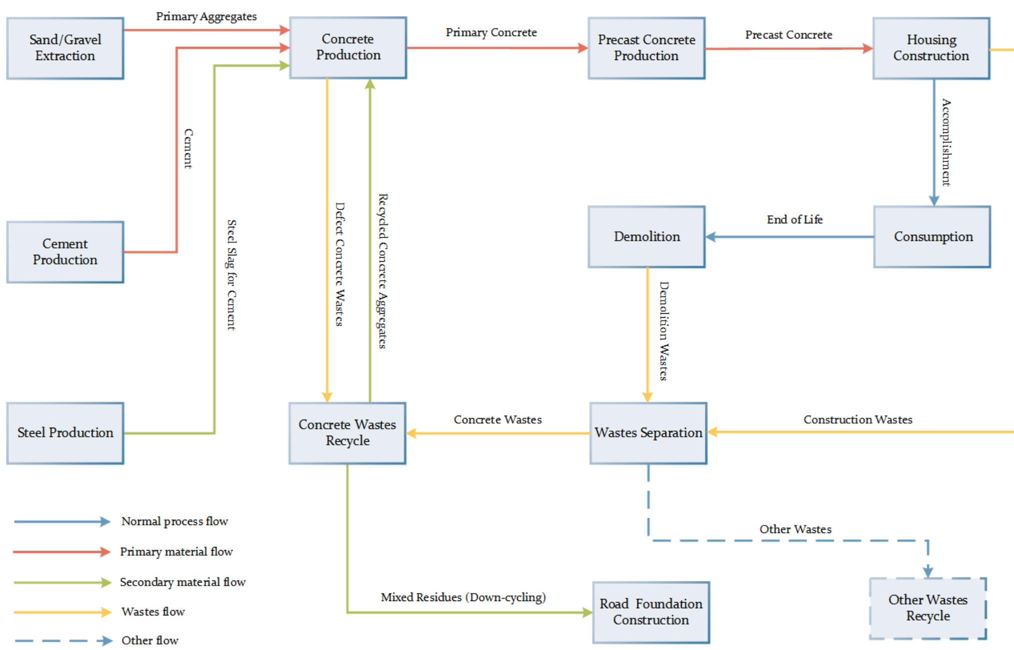

Figure 3: *Concrete supply chain material flow*

- The road construction contractor purchases DCC waste from the recycling company;
- The recycling company invests on the recycling equipment and labours.

3.1.2. *Recycling Specifications*

The recycling company plays a significant role in the supply chain, since it provides the key technology of separating and recycling concrete waste. The whole recycling procedure starts with specifying the concrete waste sources. The concrete waste is recognized mainly in two categories: 1) mixed concrete waste, namely, the concrete waste mixed with other CDW, such as woods, plastics and steels; 2) clean concrete waste, namely, the pure concrete waste without any other CDW. Besides, the defect concrete waste is regarded as clean waste.

Generally, the clean concrete waste is more valuable than the mixed ones, since they can be up-cycled into RCA and the material value remains. Instead of being used as concrete production inputs, mixed concrete waste are roughly processed to be road foundation fillers, also known as DCC, with less recycling costs. Furthermore, it is also possible to up-cycle the mixed waste into RCA. This is extra-processed RCA (RCA*) and often requires higher recycling costs.

Besides the basic costs of equipment, recycling costs mainly result from switching the machine setups for different incoming waste. Thus, recycling costs are able to be reduced if more clean waste is received. Furthermore, the quality of RCA and RCA* are mainly assessed by considering grading size, particle roughness and general cleanness (De Brito and Saikia 2013).

3.2. *EIO Model Development*

To quantify the material flow and further investigate the IS collaboration, an EIO model is developed. In this research, the IS occurs when concrete waste is recycled to RCA for replacing PCA. Therefore, the EIO model 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 of concrete products and defect concrete waste, as well as two inputs of PCA and RCA. The total demand for concrete aggregates X_α is:

$$X_\alpha = \gamma w_\alpha / W_\alpha \tag{1}$$

where W_α is the production efficiency of concrete production and w_α is the annual amount of concrete product output. γ is the component proportion of aggregates used in concrete 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* (X_β) is:

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

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 waste and demolition waste are regarded as one waste source, and all RCA and RCA* recycled by β are purchased by α.

The quantity related values, such as w_α and w_β, are influenced by the construction market. So they are inherently uncertain. They tend to increase when there is an active construction modification with large concrete demand and waste supply, such as an urban planning project. It can hardly be predicted since construction and demolition projects are spatially and temporally dynamic (Nam and Tatum 1988). Meanwhile, the technical coefficients, γ and δ, may change because of technological innovation. For instance, Lotfi et al. (2015) contributed to the novel concrete recycling technology, which may result in a higher level of δ. To summaries, the computational material flows are schematized in Figure 4:

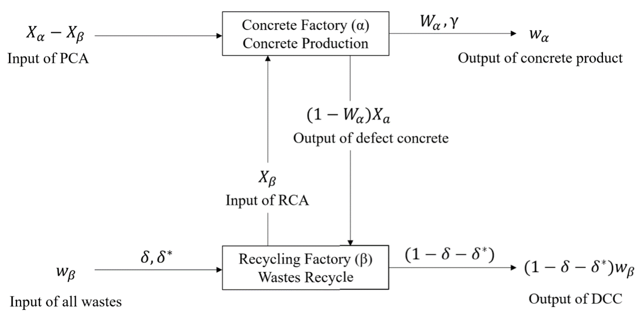

Figure 4: *Schematic material flow of EIO model*

3.2.1. Costs Computation

The focal driver of an IS collaboration is the economic benefit (Yazan and Fraccascia 2019). In this section, the IS cost of each actor is computed based on the unit price of different processes. This local information is obtained from interviews. 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_α^1) and RCA (C_α^2) are:

$$C_\alpha^1 = (C_{w_\alpha}^P + C_\alpha^T D_\alpha)(X_\alpha - X_\beta) \tag{3}$$

$$C_\alpha^2 = (C_{w_\beta}^R + C_\beta^T D_\beta)X_\beta \tag{4}$$

where $C_{w_\alpha}^P$ and $C_{w_\beta}^R$ are unit prices (euro/ton) of PCA and RCA, respectively. $X_\alpha - X_\beta$ represents the PCA amount. C_α^T and C_β^T are unit transportation costs (euro/km/ton) for PCA and RCA. D_α is the transportation distance between the mining site in Limburg, the Netherlands and α, while D_β is the distance between α and β. Instead of measuring the distance between α and β, the simulation distance ratio was applied. The value of D_β is further explained in the result chapter of scenario analysis of the CP model.

In terms of β, the recycling specifications were explained above. The cost of recycling CDW into RCA (C_β^1) and DCC (C_β^2) are:

$$C_\beta^1 = (C_{w_\beta}\delta + C_{w_\beta}^*\delta^*)[w_\beta + (1 - W_\alpha)X_\alpha] \tag{5}$$

$$C_\beta^2 = C_{w_\beta}^D(1 - \delta - \delta^*)[w_\beta + (1 - W_\alpha)X_\alpha] \tag{6}$$

where C_{w_β} and $C_{w_\beta}^*$ denote unit costs of recycling clean and mixed concrete waste into RCA. $C_{w_\beta}^D$ is the down-cycled unit cost of DCC. Finally, the transaction costs are necessary to be included to coordinate the collaboration (Esty and Porter 1998). They exist in the form of searching costs, negotiation costs and contract enforcement costs (Chertow and Ehrenfeld 2012). To simplify the computation, the transaction cost of each company is regarded as a percentage P of PCA purchase costs for α (C_α^3) and DCC recycling costs for β (C_β^3):

$$C_\alpha^3 = PC_\alpha^1 \tag{7}$$

$$C_\beta^3 = PC_\beta^2 \tag{8}$$

The total cost (C_0) of the basic scenario of the IS cooperation between α and β is the sum of the costs paid by α and the costs paid by β, and see Table 1 for the summary of all notations:

$$C_0 = \sum_{n=1}^{3} C_\alpha^n + \sum_{n=1}^{3} C_\beta^n \tag{9}$$

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 the PCA with RCA is quantified as the reduction of CO_2 emissions. Combined with the EIO model, computations of CO_2 emissions are carried out to estimate how much environmental benefits an IS cooperation would bring by replacing PCA with RCA. The key of CO_2 emission estimation lies in an appropriate emission factor (Alnahhal et al. 2018; Quattrone et al. 2014).

There are multiple measures to analyze the CO_2 emission of concrete since concrete contains different components. But for the sake of simplification, the computation elaborated here only takes into account the effects of different coarse

Table 1: *EIO model parameters*

Symbol	Description	Value	Unit
Technical coefficients & Quantities			
w_a	Total output of concrete products	400,000	ton
γ	Component proportion of aggregates	0.75	-
W_a	Production efficiency of concrete	0.95	-
δ	Recycling Proportion of RCA	0.4	-
δ*	Recycling Proportion of RCA*	0.1	-
w_β	Concrete waste received	100,000	ton
Unitary costs for the current situation			
$C^P_{w_\alpha}$	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	Distance between the mining site and α	200	km
D_β	Distance between α and β	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
P	percentage of transaction costs	0.1	-

aggregates. The specifications of CO_2 emissions of recycling concrete aggregates are listed in Table 2.

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**

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 this table, the total reduction of CO_2 emission (ΔE) due to the RCA can be computed by:

$$\Delta E = (e_P - e_R)(X_\beta W_\alpha/\gamma) * 1000/\rho \tag{10}$$

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, component proportion and production efficiency. The concrete density (ρ) used in this research is 2,400 kg/m^3, despite the fact that it actually varies between the concrete of different strengths.

3.3. GIS Supply Chain Model

This model aims to present a dynamic overview of how PCA/RCA are delivered throughout the whole supply chain in a virtual environment with realistic geographic information. It is developed from the agent definition. Two types of agents are defined: destinations and vehicles (Figure 5). Destinations are static agents that symbolize supply chain players by loading global coordinates on a GIS map. They store resources at specific locations. Vehicles, by contrast, are mobile agents that link destinations by loading, transporting and dumping PCA/RCA.

As shown on the right side of Figure 5, a number of vehicles and destinations are defined based on the case analysis. They are heterogeneous agents with similar components but different routines and parameters. Destinations are linked by arrows of different colours. These arrows represent different vehicle routines. The specific routines of each individual vehicle agents partially comply with the material flows presented in Figure 3, and are summarized as follows:

- Defect Truck: transfers defect concrete from the producer to the recycler, and return RCA from the recycler to the producer;
- Producer Truck: transfer concrete products from the producer to construction sites;
- Demolition Truck: transfer demolition waste from the demolition sites to the recycler;
- Recycler Truck: transfer construction waste from the construction sites to the recycler, and feed the producer

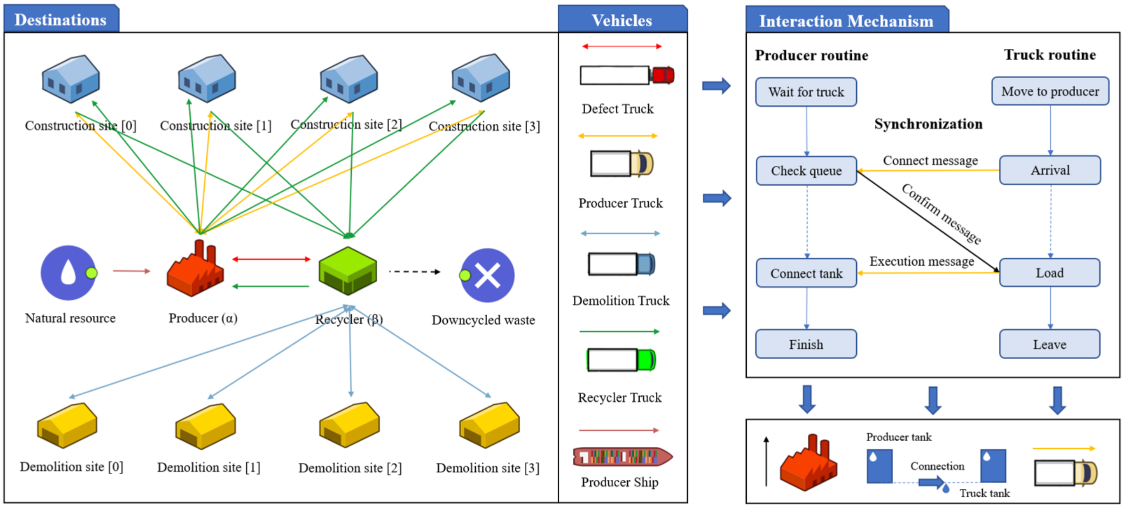

Figure 5: *Agent definition of GIS model*

with RCA;

- Producer Ship: transfers primary aggregates from the nature mining site to the producer.

Based on these routines, vehicle agents move and interact with destination agents to realize the processes of loading and dumping materials. A sample of the interaction mechanism is illustrated on the left side of Figure 6. In this sample of interaction mechanism, the producer and the truck are both autonomous agents that execute a set of routines by changing their states. And states are changed when certain conditions are fulfilled. For instance, trucks shall not leave the destination unless they are fully loaded. The network is built when agents are all able to accomplish their own tasks.

The major task of agents is to realize material transferring. They have to work collaboratively to establish connections between their tanks (virtual resource containers) by exchanging messages. These messages show their current states and requests for others. For example, the material will only be transferred when the destination targets a certain vehicle that is ready to be loaded. This process of recognizing each other and confirming that both are in ready-states of transferring materials is regarded as *synchronization* (Figure 6). It ensures the connections are correct and ordered among heterogeneous agents in a complex system.

3.3.1. *GIS Model Parameters*

The interaction mechanism between all agents share the same idea with the one explained above. When interactions occur simultaneously and repeatedly, the network starts to operate as a whole and the material flow emerges. The overall flow can not be manipulated directly since it is a phenomenon without any central control. But it can be affected by individual parameter changes. These parameters are mainly quantity-related:

- Destination agents: storage capacity (ton), material flow rate (ton/s) and flow efficiency (-);
- Vehicle agents: agent number (-), vehicle capacity (ton), flow rate (ton/s), and the priority of choosing a site (-).

These parameters have different values under different supply-demand situations. By changing them at the basic agent level, different systematic phenomenons are observed as a consequence. Although their changes are not fully applied in this research, it is valuable to equip the model with these basic parameters for realistic operations.

3.3.2. *GIS Model Stochasticity*

The waste supply is inherently stochastic and dynamic due to the fact that the waste is not produced upon demand (Yazan and Fraccascia 2019). It means that the waste quantity match between supply and demand is difficult to achieve, when the waste emerges as incidental material flows. There are a number of factors that may influence the waste delivery, such as construction phases, site locations, weather and traffic conditions. To better represent the real-world situation and capture both spatial and temporal characteristic of waste supplies, the model is designed to be stochastic (Wilensky and Rand 2015).

The stochasticity of this model lies on the decision-process of how a truck determines which construction or demolition site to go. During this process, each site is encoded as a unique digit, and each truck randomly chooses a digit(site) to deliver materials. The digit is randomly renewed for each new round of truck's routine. Although the model's stochasticity is limited, it makes one step further towards a better representative of the realistic situation than traditional deterministic models.

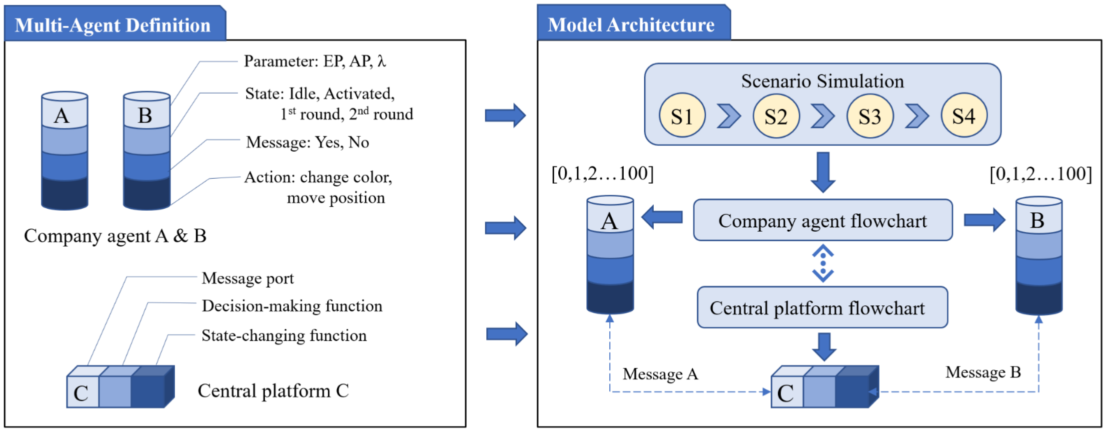

Figure 6: *Agent definition & Model architecture*

3.4. *Collaboration Platform Model*

To further investigate the IS cooperation between α and β from the economic perspective, an ABS 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 and one platform agent. Figure 6 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 can make decisions and take actions in favour of their own interests. The agent architecture consists of parameter, state, message and action. In terms of different economic benefits, they would make decisions on whether to participate in the collaboration by comparing actually received benefits and their own benefit expectations. Based on this comparison, it makes corresponding actions, such as sending messages to C to indicate their decisions. The platform agent C serves as a mediator that establishes the connection between A and B. Its major function is to moderate the cooperation by detecting and reacting to the responses from company agents.

3.4.1. *CP Model Parameters & Stochasticity*

Parameter stands for numerical factors, such as Expected Profits (EP), and Actual Profits (AP) received by each agent. Based on the computation of the EIO model, the overall economic benefit (ΔC_i) is calculated as the cost variations of different scenarios, where *i* refers to the code of scenarios:

$$\Delta C_i = C_0 - C_i \tag{11}$$

A profit-sharing factor λ is suggested to moderate the cooperation by determining the percentage of ΔC_i received by each company. Specifically, the AP gained by α (Δ_α) and β (Δ_α) can be computed as follows:

$$\Delta_\alpha = \lambda \Delta C_i \tag{12}$$

$$\Delta_\beta = (1 - \lambda)\Delta C_i \tag{13}$$

In this study, λ is generated by C as a stochastic value that follows the normal distribution of (0.5, 0.2) (Yazan and Fraccascia 2019). Meanwhile, the Expected Profit Δ^*_α and Δ^*_β are adaptive values that fluctuate according to a threshold factor η. The factor η is a random value that ranges from 0.05 to 0.5 (Albino et al. 2016). The EPs of each company are computed by:

$$\Delta^*_\alpha = \eta_\alpha C_\alpha \tag{14}$$

$$\Delta^*_\beta = \eta_\beta C_\beta \tag{15}$$

where η_α and η_β are threshold factors of α and β, respectively. Besides, *State* indicates the extent to which the agent reaches in the whole cooperation process. And the information is conveyed among agents by sending *Message*. Stimulated by the signal/message from another, agents may take different *actions*, such as changing colours and moving positions. These actions are captured and recorded by the central platform C.

3.4.2. *CP Model Interaction Mechanism*

The mechanism of the ABS model is an interactive negotiation process realized by message communication among agent A, B and C. First, company agents A and B initialize the cooperation by determining whether the cooperation is profitable. When there is a positive economic benefit that can be shared between A and B, the EP of each company is computed accordingly. Previous studies pointed out that the challenge of the further CE implementation is lacking of economic benefits (Adams et al. 2017; Schraven et al. 2019) and the IS cooperation is more likely to be successful once each company receives a benefit that is no less than its expectation (Yazan and Fraccascia 2019). Thus, the main IS assessment process is comparing the AP computed from the EIO model with the EP that is set by the company.

During the assessment, a two-round negotiation is performed. 1) In the first round, the cooperation is successful if both companies receive sufficient profits, while it is failed if neither of them is satisfied. 2) Adapted from the model of Yazan and Fraccascia (2019), the negotiation is recognized as "NotYet" and continues to the second round if there is only one company which is willing to make the deal. In the second round, the profit is re-shared in favour of the unwilling side. To be exact, the factor λ is altered and a profit proportion ranges from 0.05 to 0.1 is redistributed to the unwilling side.

Furthermore, new APs are regarded as $\Delta_{\alpha}^{'}$ and $\Delta_{\beta}^{'}$, separately. The 2^{nd} round cooperation turns from the state of "NotYet" to "Successful" once companies are both satisfied with the new sharing proportion. Otherwise, the cooperation is marked as "Failed". To ensure a significant simulation result, 100 company agents of each kind are designed in the model. Check Appendix A for the decision-making flowcharts of agents.

4. Results

This section presents the results of the case study. First, model interfaces are explained. Second, the GIS model is applied to the basic scenario to compare the results. Then, the CP model investigates the impact of supply-demand quantities and costs on the IS.

4.1. Model Interface

The interfaces of the two models are captured in Appendix B and C. In the GIS supply chain model, the white truck hoppers are filled with colours if they are loaded. Red means PCA, green means RCA and yellow is concrete waste. The resource data of each destination is tracked in-time, which includes 1) individual quantities of construction and demolition sites, 2) major input-output quantities of α and β, and 3) saved amount of CO_2 emission.

In the CP model, the agent of company A is simplified as a *circle* while the *square* represents company agent B. 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 successful in the 2^{nd} round) and move to the zone of *Successful Zone*. And the zone of *Failed Zone* gathers the agents with colour red (dark red means the case is 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 statistic monitoring window.

Models were uploaded and stored on AnyLogic Cloud, please click links to operate them: GIS Supply Chain Model and IS Collaboration Platform Model.

4.2. Basic Scenario of EIO & GIS model

As the GIS model simulated the effects of supply-demand variations on the process of ISN development, its results should comply with the computation of EIO models. Thus, according to the information provided in Table 1, GIS simulation settings are listed in Table 3. Meanwhile, the technical coefficients were identical with those in Table 1.

Table 3: *GIS model basic scenario settings*

Capacity Type	Agent No.	Value/agent	Unit
Construction site	4	100	ton
Demolition site	4	25	ton
Construction truck	4	5	ton
Demolition truck	4	5	ton
Recycler truck	4	5	ton
PCA ship	2	50	ton

The total capacity of construction sites and demolition sites were exactly 1000 times smaller than those of the realistic situation presented in Table 1. This required less computing power of the program and effectively delivered smooth simulation visualization with a concise geographic layout. Otherwise, a large number of destination sites were needed to represent the huge annual input-output amount. And the transportation network could be overwhelmingly intense. To restore the data and make them comparable to the EIO model's results, all quantity-related results of GIS model were up-scaled by 1000 times in the final figure plot 7.

As can be seen in Table 4 and Figure 7, the results of 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).

In addition, the process data retrieved from the GIS model were plotted in Figure 7, which illustrated the tendency of how quantities increased over time. For instance, several considerable leaps of PCA were witnessed throughout the whole simulation while RCA increased steadily with only

Table 4: *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 (1)
X_β	Total supply of RCA	57,895	54,000	ton	Eq (2)
ΔE	Total save amount of CO_2 emission	825,000	769,500	kg	Eq (10)
X_β/X_α	RCA proportion	0.18	0.15	-	-

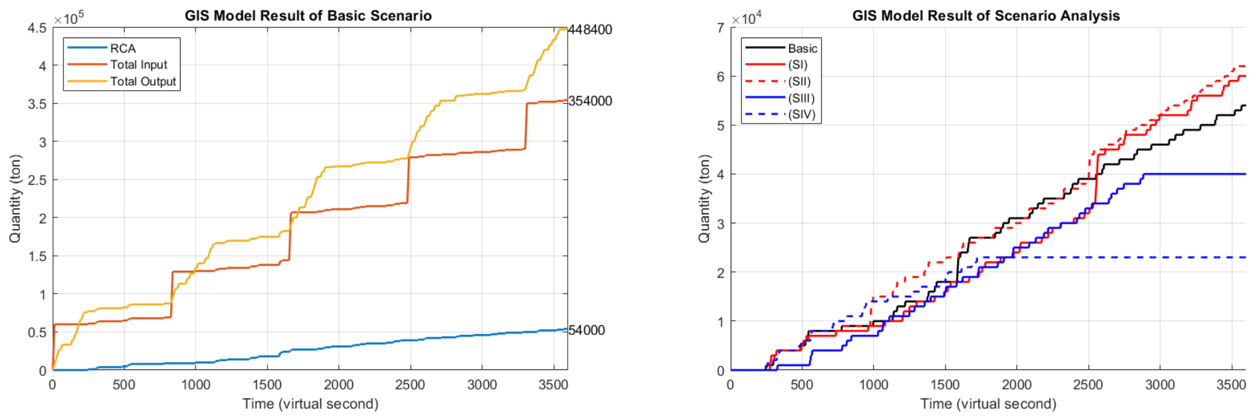

Figure 7: *GIS supply chain model result*

minor fluctuations. This reflected the fact that PCA inputs were made by cargo ships whose capacities are ten times larger than RCA trucks. Moreover, by operating the model, the material shortage and logistic intensity were able to be observed in great detail.

4.3. Scenario Analysis

4.3.1. Quantity-scenario analysis of GIS model

To investigate the effects of demolition waste amount and recycling efficiencies on the RCA usage, four quantity-related scenarios were 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;
- (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.

Scenario simulations were carried out while the quantity results of RCA and reduced CO_2 are shown in Figure 7 and Table 5. Within the same period of time, the performances of four scenarios varied. Specifically, (SII) achieved the highest amount of RCA, 62,000 ton, which is 15% more than the basic scenario. It is expected that RCA has great potential to further increase if only a longer simulation time were allowed. By contrast, (SIV) delivered the lowest amount of RCA of only 23,000 tons, which is 57% lower than the basic scenario. Because recycler trucks cannot be fully loaded when up-cycling efficiency was too low, the RCA supply was interrupted half-way through the simulation. Last, the reduction of CO_2 emission ranged from 327,750 to 883,500 kg among all scenarios.

This analysis shows that the recycling efficiency has a larger influence on the RCA production than the waste amount. And the lower efficiency could lead to a significant RCA shortage.

Table 5: *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%

4.3.2. Cost-scenario analysis of EIO model

Based on the quantity computation of EIO model, the CP model simulation of cost-sharing negotiation between companies was performed. Addition to the basic scenario, another four cost-related scenarios and two combined scenarios were composed to perform the scenario analysis. 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 (S1+S2) are doubled/halved;
- (S6) Combined costs of circular business (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. In fact, the down-scaling of quantities in the GIS model compromised the accuracy of transportation distance since 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 ratio of 5 between the transportation distances of PCA and RCA was applied to the EIO model. This is the reason why RCA distance was regarded as 40 km in Table 1.

The cost-related scenario results of the EIO model are illustrated in Figure 8. Each subplot shows the total costs of different scenarios as a function of the RCA supply-demand ratio (X_α/X_β). The ratio represented the market dynamic and increased when the total demand of aggregates remained as 400,000 tons while the supply of RCA surged with an interval of 50,000 tons. Green curves represent the costs reduction while the red ones indicate extra costs. Plots all followed a similar curving pattern that a significant inflection occurred when the ratio (X_α/X_β) = 1.0. At this critical point, the supply amount of RCA matched the demand of all aggregates and the contribution that C_α^1 made to the total costs no longer existed. Therefore, the linear pattern of purchasing costs of PCA (C_α^1) was interrupted and the slope was changed.

Taking a closer look at Figure 8, the total costs of different scenarios deviated from the basic scenarios to various extents. When the ratio = 1.0, (S0) had the lowest total cost of around 15.6 million euro. Please note that the first two sub-plots had a scale of the y-axis that was two times smaller than the remaining four. (S1) had a same lowest value at this point and followed the same path with the basic scenario since purchasing costs of PCA were modified but they did not add up to the total costs when the ratio exceeded 1.0. Meanwhile, (S2), (S3) and (S4) shared the same curve pattern, and (S3) showed the widest deviation among them with a lower value of 10.7 million euro to an upper value of 25.5 million euro, approximately. In terms of combined scenarios, (S5) had a larger deviation before the critical point, and achieved a lower cost of 14.2 million euro and a higher cost of 18.5 million euro. By contrast, the deviation range of (S6) kept to extend from the beginning and presented a cost range between 9.2 to 28.4 million euro at the critical point.

The GIS model was developed in an open and transparent environment where actors take his/her own responsibilities and share information of both waste and products with each other for the common benefit. The ISN 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 provides more opportunities for IS collaborations.

4.3.3. *Cost-scenario analysis of CP model*

After the computation of costs, the simulation of benefit-sharing on collaboration platform was performed. The simulation settings of the CP model are listed in Table 6.

Table 6: *CP model simulation settings*

Symbol	Description	Value
ΔC_i	Overall economic benefit	Eq(11)
λ	Cost-sharing factor of α	Normal(0.5,0.2)
Δ_α	Actual profit of α	Eq(12)
Δ_β	Actual profit of β	Eq(13)
η_α	Threshold factor of α	Random(0.05,0.5)
η_β	Threshold factor of β	Random(0.05,0.5)
Δ_α^*	Expected profit of α	Eq(14)
Δ_β^*	Expected profit of β	Eq(15)

A sample simulation result of (S6) at the point of (X_β/X_α) is presented in Figure 9. For each simulation, the changes of the following parameters were monitored in four subplots. In the first one, the probability of successful IS cooperation was recorded, which was measured as a ratio of the number of green agents and the total amount of processed agents. And the red lines were the values of λ of all 100 cases. The second and third plots present the records of the EP and the AP of two firms, respectively. The fourth one shows threshold values of each firm in each case.

It can be observed in Figure 9 that the IS probability was high since the AP was always higher than the EP of both two firms. Therefore, the green line in the first plot stayed close to the maximum boundary and the IS value at the 900 virtual seconds (95%) was regarded as the overall IS probability of this demand-supply ratio. By filling in the costs result of the EIO model of each (X_β/X_α) ratio, the CP model followed the same procedure to carry out the result of IS probability. For each scenario, only the halved-costs case was simulated, because the negotiation would not be initiated if there is no cost reduction.

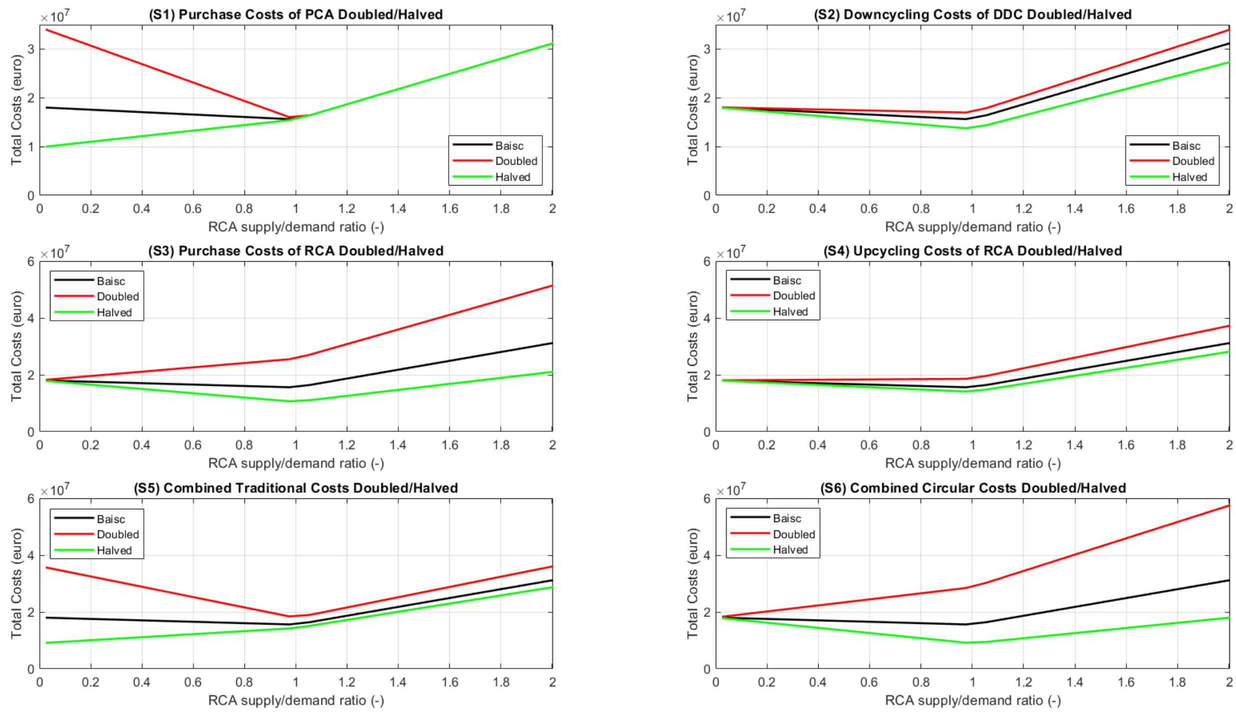

Figure 8: *Scenario analysis of EIO model result*

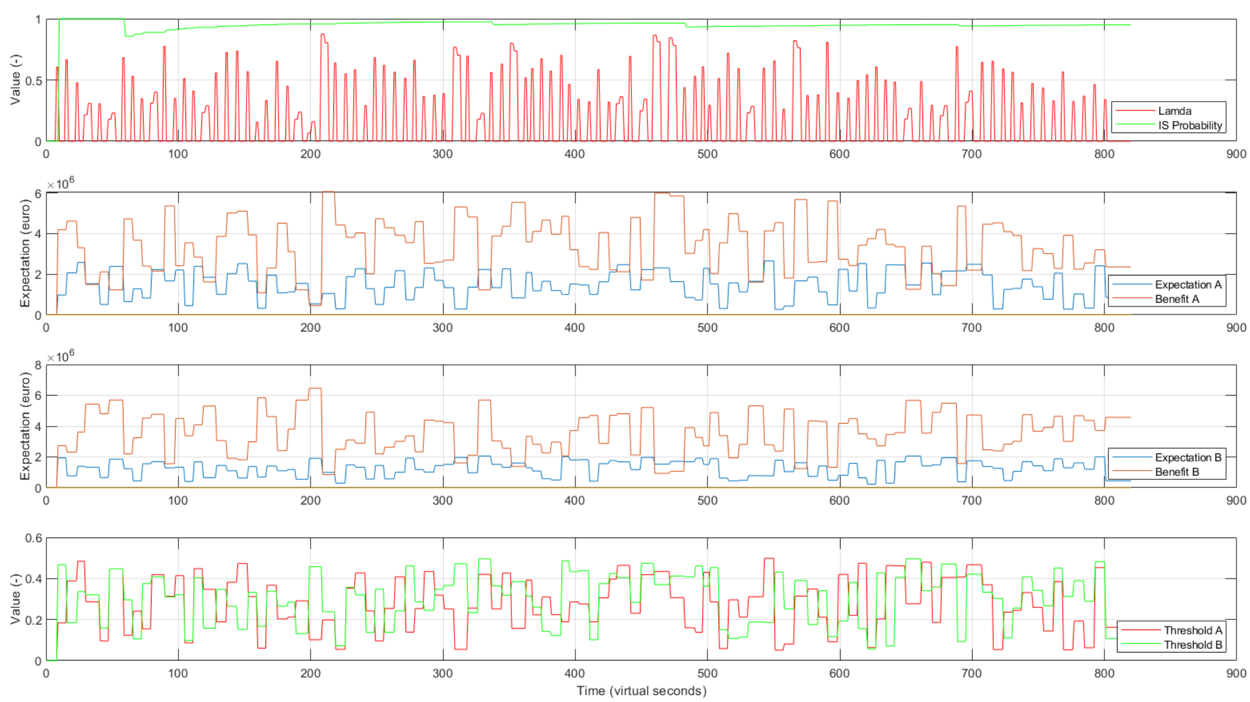

Figure 9: *S6 simulation record when* $(X_\beta/X_\alpha) = 1.05$

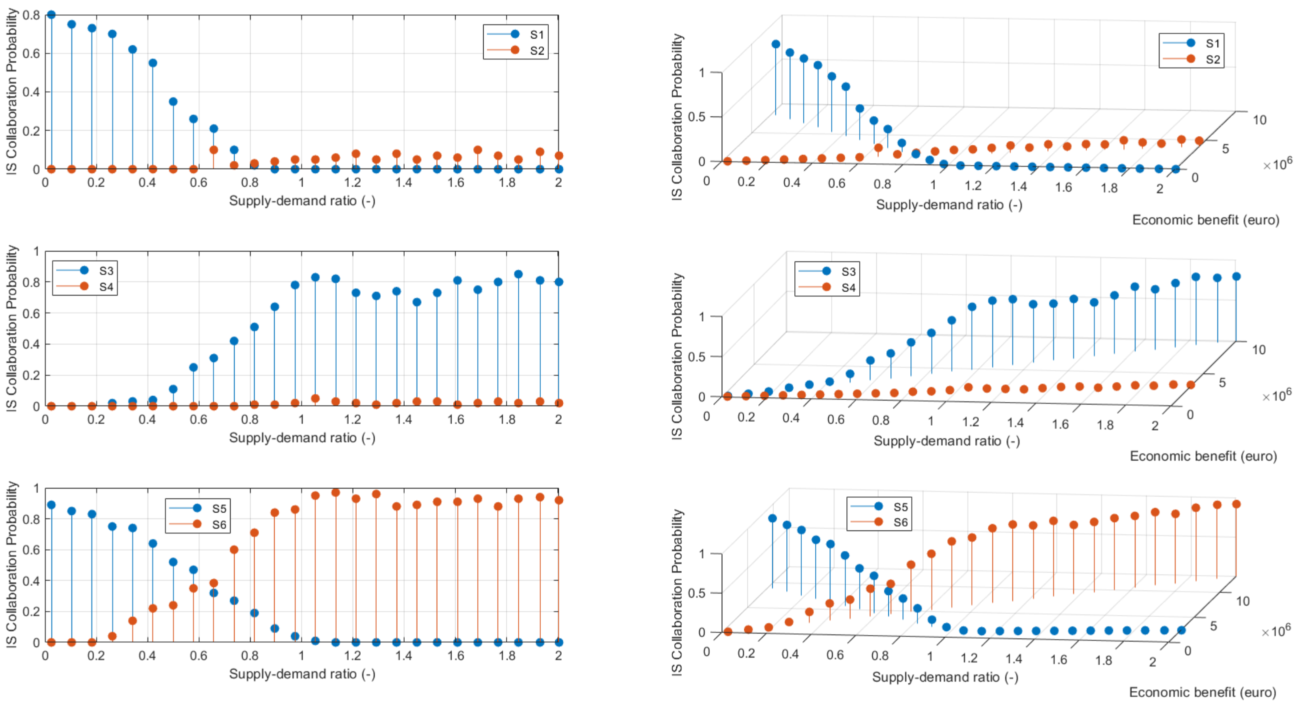

Figure 10: *IS probabilities of scenarios*

In Figure 10, scenarios were analysed in pairs. The left column displayed the relationship between the RCA supply-demand ratio and IS collaboration probability, while the right column demonstrated their relationships together with the total economic benefit in a 3D-environment. The IS probability represented the space of cooperation between firms under certain circumstances, and it had a great diversity among all scenarios. 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% when it passed the critical point. However, the probability of (S2) remained low and only raised up to 10% throughout the whole ratio range.

In the second pair, the cooperation space of (S4) was merely available though the total economic benefit showed an increasing trend. On the contrary, that 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 combination pair presented an intersected situation. The IS probability of (S5) started with a value of 89% and continuously declined to 0% as soon as it passed the critical point. Meanwhile, (S6) had a reversed tendency and came across (S5) when the ratio was around 0.5. After the critical point, it performed the highest probability level of around 90% among all scenarios.

In summary, a higher economic benefit is more likely to open the window of IS cooperation. By reducing the costs of different items, different IS probabilities were observed. For example, the reduction of PCA purchasing costs was more effective when the $X_\alpha / X_\beta < 1.0$, while the costs of recycling RCA should rather be reduced after the critical point. In this way, the CP model reveals that economic coordination strategies are not static but should be constantly updated to keep pace with the dynamic RCA demand-supply situation.

4.3.4. *Threshold-scenario analysis of CP model*

Thresholds (η) that were used to determine the EP of each firm could also influence the IS probability, because it is a special factor that relates to the desired return on the IS collaboration (Albino et al. 2016). To analyze its impact on the IS probability, a higher and a lower value of η were implemented in scenarios (S1) and (S3). Based on the original threshold boundary (0.05, 0.5), two additional scenarios are:

- (Threshold + 0.2): The upper boundary of the threshold is increased from 0.5 to 0.7, which means a firm is more greedy for the IS benefit;
- (Threshold - 0.2): The upper boundary of the threshold is decreased from 0.5 to 0.3, which represents a company emphasizes less on its own benefit;

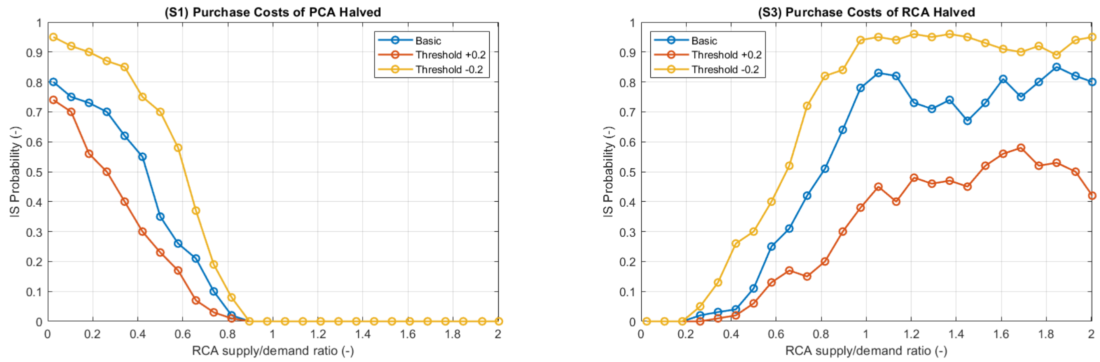

Figure 11: *Threshold effect on IS probability*

The simulations of (S1) and (S3) were re-performed with different threshold values, and the results were plotted in Figure 11. This analysis showed how the collaborating behaviour of an individual company would influence the IS collaboration. Confronting the same economic benefit, the lower-threshold scenario had a better IS performance.

The lower threshold value led to a higher IS probability because participants are willing to make the deal with an expectation of a lower benefit return. On the other hand, the higher threshold value resulted in less space of cooperation, since firms would not agree with each other unless a higher benefit return is promised. This underlines that if a company tries to occupy the benefit created by IS without considering other's needs, then the collaboration has a high chance to fail. Furthermore, the change of threshold was insignificant once the IS probability dropped to zero. It indicates that the changing of collaborating behaviours is only effective when there is a niche of cooperation space.

5. Discussion

5.1. IS Challenges in Construction Industry

Based on the local knowledge from supply chain actors, the IS collaborations of RCA exist but are still underdeveloped. Interpreted from the results, four challenges of implementing IS in the construction industry are pointed out.

- Scattered locations of demolition/construction sites and inconsistent waste qualities;
- Insufficient data collection of on-site waste and fragmented information exchange among various actors;
- IS collaboration strategies require high transaction costs to update and maintain;
- Economic benefits dominate the IS collaboration while environmental benefits are overlooked.

In the EIO computation, the dynamic input-output of concrete aggregates waste was represented by a quantity ratio of X_α/X_β. When it is smaller than 1.0, α receives both PCA and RCA to produce concrete products. In this stage, the more RCA are supplied, the more overall costs are saved and the more CO_2 emissions are reduced. The optimal situation is reached when the ratio equals one, which means all aggregates required by α are supplied by β without any traditional PCA purchase. Therefore, the perfect quantity match between RCA demand and supply is regarded as the favourable nourishment for IS collaborations. This finding is consistent with the results of previous studies (Yazan and Fraccascia 2019; Fraccascia and Yazan 2018).

However, the perfect condition of the waste quantity match is challenging to reach in the construction industry. First, the locations of demolition/construction sites are highly scattered. The material treatment process can hardly be completed without switching to various locations. The spatial differences of actors pose significant challenges to quantity management. Moreover, the quality of concrete waste is influenced by various factors and can hardly be consistent (De Brito and Saikia 2013; Lotfi et al. 2015). For instance, the long life-span of constructions indicates that most material information is untraceable. To deal with demolition concrete waste of different qualities, a higher processing investment is required.

Second, the information system of waste demand-supply is underdeveloped. The waste information is insufficient because contractors pay more attention to construction materials than waste. Moreover, the construction industry has a massive multi-actor supply network of huge spatial and temporal differences. A lot of IS opportunities are missed due to the insufficient data storage and fragmented information exchange among various actors (Yazan and Fraccascia 2019). In this case, people simply do not know there is such an opportunity.

Third, IS collaboration strategies need to be updated according to the real-time market situation, which poses higher transaction costs that hinders the development of IS. Without a well-developed information system, actors have to invest higher transaction costs to initiate and maintain the collaboration (Esty and Porter 1998). In particular, the long-term trust and collaboration are hard to cultivate in the construction industry, because this industry is known as a project-based industry where one-off coalitions are constantly formed by various independent participants (Vrijhoef and Koskela 2000).

Fourth, environmental benefits are often overlooked while stakeholders put most emphasizes economic benefits during the IS cooperation. The value definition is utterly quantified from the economic aspect. In this case, the IS cooperation of RCA is more likely to flourish when there is adequate cost reduction while the contribution of environmental advantage is insignificant. Thus, it is difficult to launch an environmentally promising but economically challenging IS collaboration.

5.2. CE Policy-Making Suggestions

Based on the discussion of IS challenges, and combined with the findings of interviews, four CE policy-making suggestions are provided:

1. Enhance the on-site monitoring and controlling of waste quality and quantity to improve the demand-supply match: The fact that CDW cannot be directly utilized by others results in a series of fragmented recycling processes with different actors. A better managerial overview of the supply chain can be obtained if the on-site monitoring of waste quality and quantity is enhanced (Lieder and Rashid 2016; Deng et al. 2019). This suggestion is interpreted from the scenario analysis results of the GIS model.

With sufficient on-site information about waste quality and quantity, IS cooperation has a better basis to be initiated. In terms of quality control, the first step is to strictly implement construction waste separation on-site to ensure the waste purity and adapting deconstruction techniques to reserve the value of demolition waste.

2. Establish an information-sharing platform to allow transparent communication between actors: All the data gathered from sites should be shared and analyzed collectively, such as the way how the GIS model processed data: every vehicle knows the information of every site. Once a central information platform is established, the waste inventory of each site can be organised effectively by knowing "who has how much what where and when" (Fraccascia and Yazan 2018). Then, IS partners can be efficiently matched and connected. In this way, an ISN or CDW ecosystem emerges immediately.

The CP model can be regarded as a conceptual illustration of how this platform would operate. However, the precondition of developing this information system is that stakeholders are actively involved in this platform and willing to do so. Although the effort from each individual should be appreciated, they should not be alone. The concrete agreement is a promising start of sustainable collaborations in the future (Betonakkoord 2018). However, the government should also step in to coordinate this network by taking the leading position and sharing the risk with firms (Abreu and Ceglia 2018; Schraven et al. 2019).

3. Adapt circular construction procurement regulations to increase the market demand of RCA: An assumption made in all models was: α would certainly receive RCA once they are available and supplied by β. But in reality, the residual value of concrete waste is not fully-recognized. On the one hand, strict quality controls of RCA should be carried out to ensure the quality of RCA. On the other hand, people should challenge the traditional mindset by asking "what is new or valuable?" and "does it have to be new if it is valuable?" The value definition should not remain as if second-hand items or shared facilities are less valuable (Andrews 2015).

Beyond the subjective mindset changing, the circular procurement regulations also help to increase the demand for RCA by regulating how much RCA should be implemented in a new project. By identifying the demand for circular designs, the waste can be reduced and purchasing plans of recycled materials have to be made when a project is initiated (Adams et al. 2017). Then, people are more motivated to apply RCA and it also gives demolition contractors an opportunity to perform careful deconstructing tasks to ensure the material purity.

4. Provide subsidies to up-cycling technology innovation and circular business models to enlarge the cooperation space: As shown in the scenario analysis, costs reduction of purchasing and recycling RCA effectively supported IS collaborations. However, the cost of both RCA and PCA varies depending on a number of factors. For instance, weather, material qualities and the location proximity. Under such an uncertain circumstance, the companies need incentives to maintain and increase the profitability of CE business (Adams et al. 2017; Lieder and Rashid 2016).

We suggest the government to take a leading role in sustainable cooperation and provide subsidies to up-cycling technology innovation and circular business models. This is the most straightforward measurement to develop IS in a short-term. The subsidy can effectively compensate the costs spent on various aspects of implementing RCA, and support environmentally promising but economically challenging cases. Besides, the CP model can be applied to facilitate the decision-making process of subsidy interventions.

6. Conclusions

This study explored the IS collaboration based on RCA in the context of a concrete waste supply chain in the Twente region of the Netherlands. It tackled the CE transition challenge of lack of economic incentives by investigating the ISN emerged by replacing PCA with RCA. In particular, two simulation models of this RCA supply chain were developed by integrating EIO, GIS and ABS modelling methods. This pair of models served as policy-making tools that provide evidence to forecast the dynamic evolution trend of the whole supply chain for different policy scenarios. Specifically, a scenario analysis was performed, which revealed the effects of subsidy interventions and company behaviour changes on the system in the form of CO_2 reduction and IS cooperation spaces.

It is found that the quantity match of RCA supply-demand plays a significant role in determining the IS economic benefit. This dynamic feature was well-visualized by the GIS model simulation. Accordingly, four challenges of implementing IS in the construction industry are summarized as 1) scattered locations of demolition/construction sites and inconsistent waste qualities, 2) insufficient data collection of waste on-site and fragmented communication among actors, 3) IS collaboration strategies require a high transaction cost to update and maintain, and 4) economic benefits dominate the IS collaboration while environmental benefits are overlooked.

Furthermore, the governmental subsidy provides nourishment to support environmentally promising but economically challenging cases. Particularly, the CP model was designed to facilitate this policy intervention adaptively according to different market situations. Four policy-making suggestions were provided: 1) enhance the on-site monitoring and controlling of waste quality and quantity to improve the demand-supply match, 2) establish an information-sharing platform to allow transparent communication between actors, 3) adapt circular construction procurement regulations to increase the market demand of RCA, and 4) provide subsidies to up-cycling innovation and circular business cases to enlarge the cooperation space.

The main contribution of this research is exploring IS dynamics in the AEC industry by applying innovative simulation measurements. It provides a practical managerial overview of the supply chain with firms to actively improve their business strategies, and a scientific ground with the governmental body to tailor policies towards the CE transition. The limitations of this study are 1) the quality variation of waste demand-supply is not included in the model, 2) the simulation duration is limited so that the long-term seasonality of waste demand-supply cannot be fully seized, and 3) the negotiation agents are not able to learn from the previous experience. Therefore, future studies could focus on 1) developing a multi-criteria negotiation process by involving the quality specifications and the environmental impact, and 2) developing intelligent agents with adaptive behaviours based on self-learning abilities.

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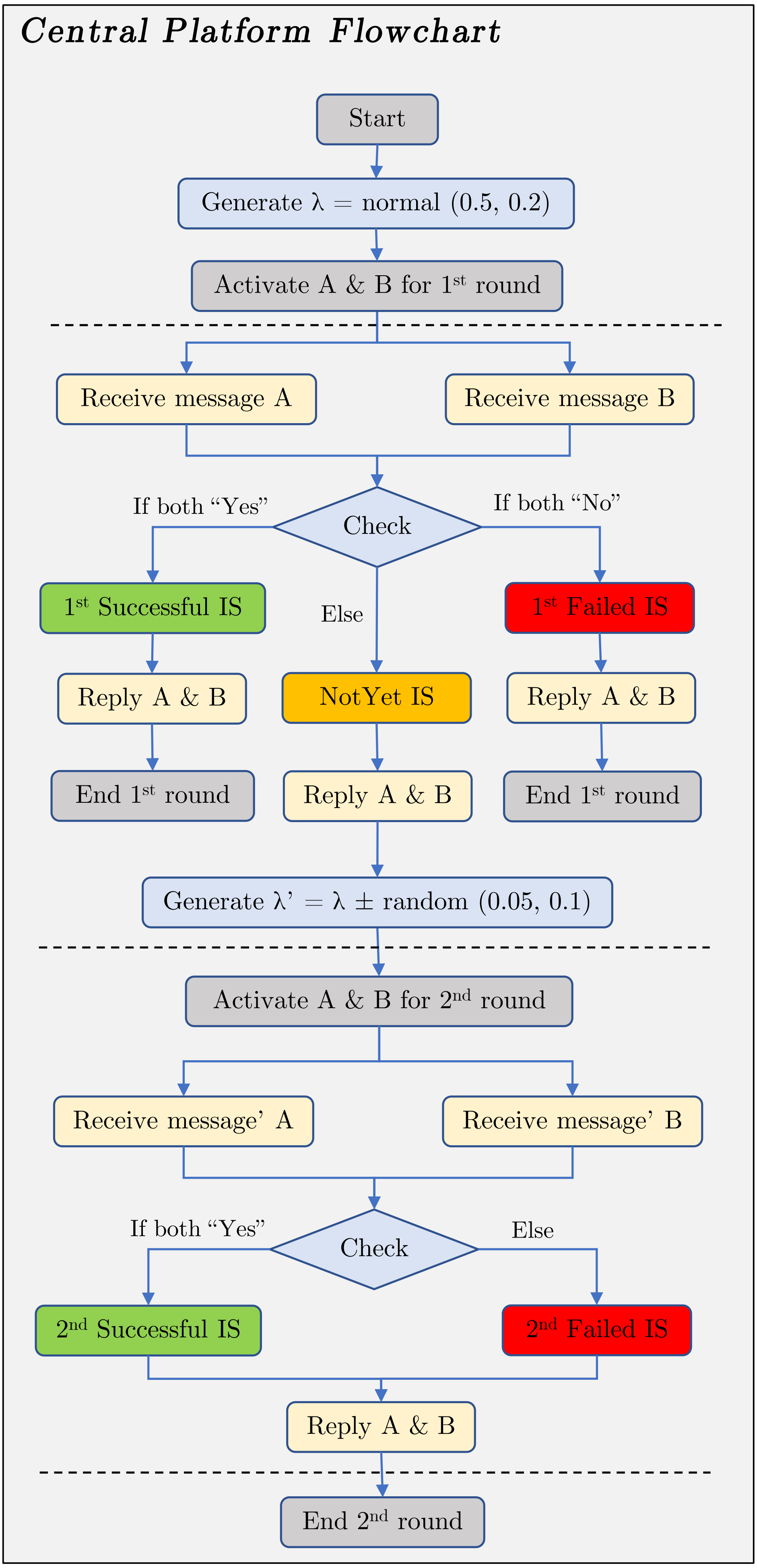
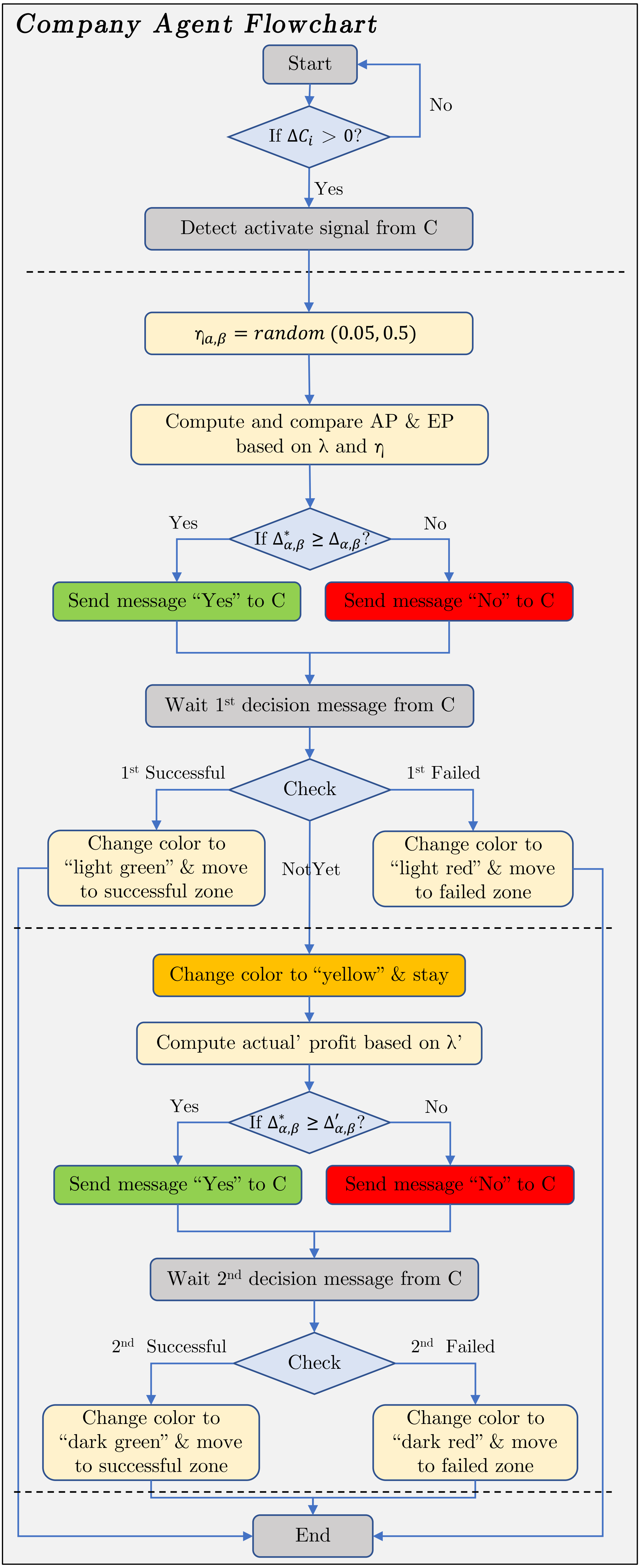
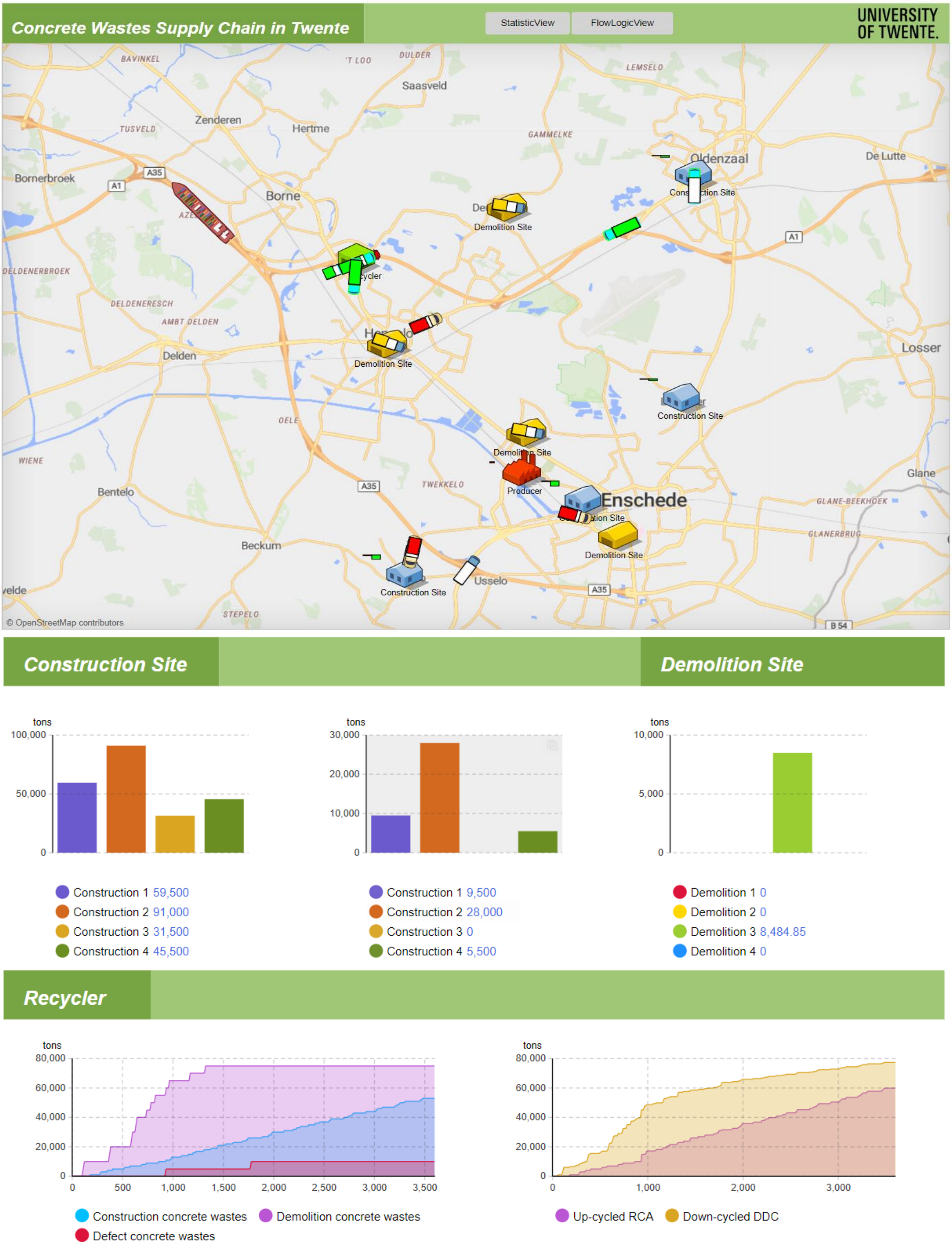
Appendix A: Agent Decision Flowchart of CP Model

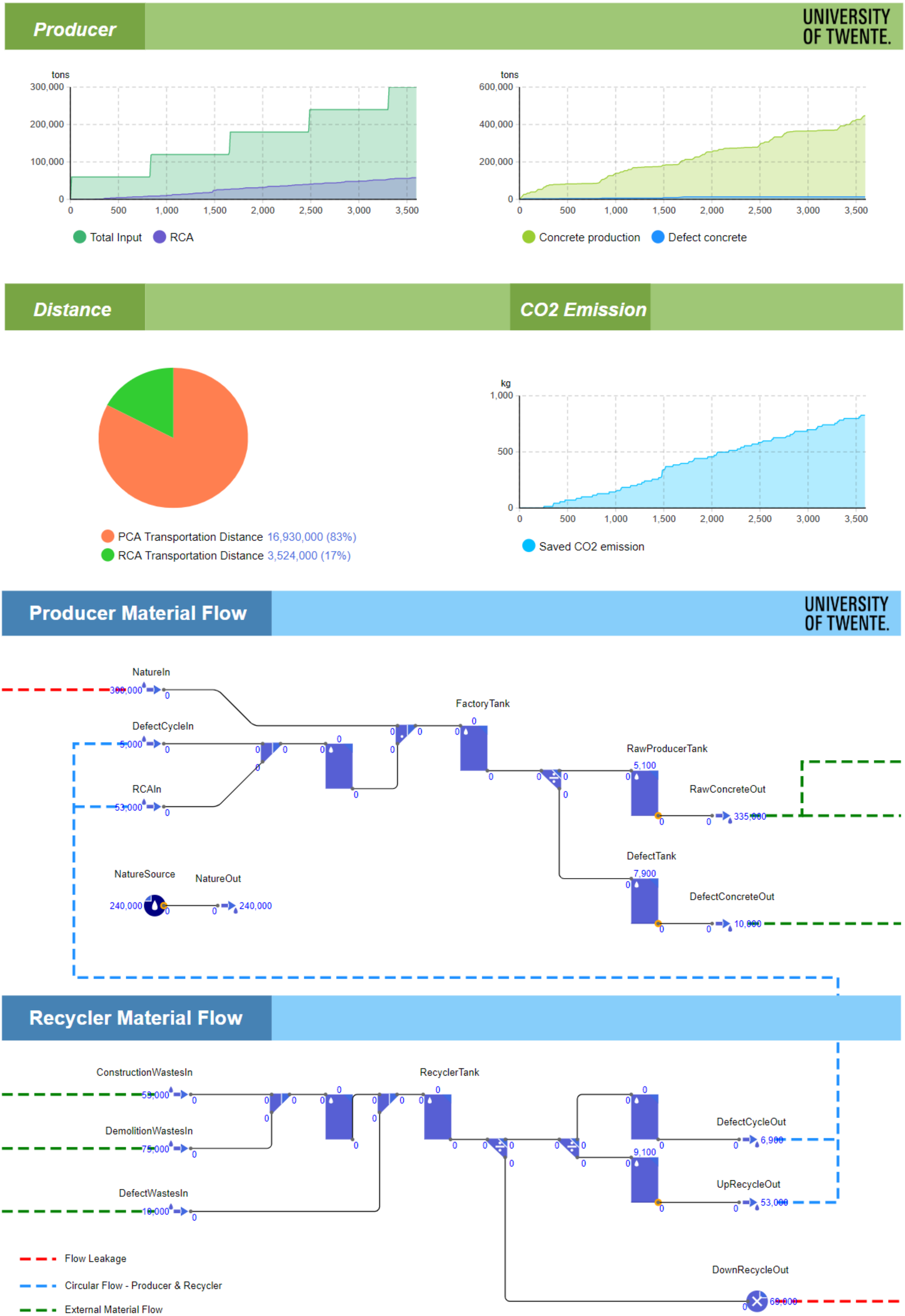



Company Agent Flowchart
Start
If $\Delta C_i > 0$?
No
Yes
Detect activate signal from C
$\eta_{\alpha,\beta} = random\ (0.05, 0.5)$
Compute and compare AP & EP based on λ and η
Yes
If $\Delta^*_{\alpha,\beta} \geq \Delta_{\alpha,\beta}$?
No
Send message "Yes" to C
Send message "No" to C
Wait 1st decision message from C
1st Successful
Check
1st Failed
Change color to "light green" & move to successful zone
Not Yet
Change color to "light red" & move to failed zone
Change color to "yellow" & stay
Compute actual' profit based on λ'
Yes
If $\Delta^*_{\alpha,\beta} \geq \Delta'_{\alpha,\beta}$?
No
Send message "Yes" to C
Send message "No" to C
Wait 2nd decision message from C
2nd Successful
Check
2nd Failed
Change color to "dark green" & move to successful zone
Change color to "dark red" & move to failed zone
End

Appendix B: Operation Interface of GIS Model (1)



Appendix B: Operation Interface of GIS Model (2)



Appendix C: Operation Interface of CP Model