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RESEARCH ARTICLE

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# Circular (de)construction matchmaking

## A matter of space and time

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**Abstract**

Industrial symbiosis (IS) facilitates the transition toward a circular built environment. Following IS principles, multiple buildings can be symbiotically linked via closed-loop material flows beyond the boundaries of individual projects. However, there are few IS matchmaking methods that support the identification of IS opportunities among multiple deconstruction and construction projects. This research develops an agent-based model to fill this gap. The agent architecture is designed based on the concept of shearing layers. Circularity hubs are proposed to support IS matchmaking by allowing larger transportation ranges and keeping IS requests active for longer periods. The model's applicability is demonstrated through an industrial–urban symbiosis case in Enschede, the Netherlands. The model simulates the spatial–temporal dynamics of IS matchmaking as an emergent phenomenon under future scenarios. The results show operational evidence of IS matchmaking via the strategic implementation of circularity hubs. Overall, this research provides a new methodological perspective to explore the circularity in the built environment at scale.

**KEYWORDS**

agent-based modeling, circular economy, circularity hubs, dynamic matchmaking, industrial ecology; industrial–urban symbiosis

## 1 | INTRODUCTION

Circular economy (CE) implementation is crucial to build a sustainable future in the construction industry (Schroeder et al., 2019). CE represents a programmatic shift from downstream waste treatments to fundamental changes in upstream processes of production and consumption by engaging actors through the entire value chain (Bocken et al., 2017). This is a systemic circularity achieved across organisational boundaries, fostering circular material flows in a broader ecosystem (Holmes et al., 2021). However, a longstanding challenge lies in the need to manage the circular construction beyond the spatial and temporal boundary of a singular building (Chan et al., 2023). New methods are in demand to manage the spatial–temporal complexities of symbiotic material/waste streams among multiple building life cycles at different scales. This research aims to capture, understand, and predict such complexities of large-scale CE implementation in the built environment.

Following CE principles, deconstruction (i.e., selective dismantlement) is prioritized over demolition to preserve valuable building components (Thomsen et al., 2011). Deconstruction involves cautious planning and careful dismantling, which helps to turn "waste" to "resources" for various functional purposes. Such a *waste-to-resource* interaction between aged and new structures is a meaningful solution to accelerate CE in the built environment (Yu et al., 2021). It can be capsuled within *urban mining*, a CE practice that improves resource efficiency, treats anthropogenic stocks as "mine", and retains material value through reusing and recycling (Brunner, 2011). Urban mining is closely bonded with the theme of circular construction and it introduces a wider urban landscape to multi-project management (Koutamanis et al., 2018; Verhagen et al., 2021). Furthermore, these concepts are theoretically aligned with *industrial symbiosis* (IS), inter-organizational collaborations based on symbiotic exchanges of by-products, energy, water, and/or facilities, leading to a sustainable and circular transition across industry sectors (Chertow, 2000). This research considers urban mining as a particular branch of industrial–urban symbiosis connecting circular material streams between deconstruction and construction projects at an urban level (A.SPIRE, 2021).

The practice of identifying IS opportunities among heterogeneous actors is known as *IS matchmaking* (Yazan & Fraccascia, 2020). It aims to match suitable IS partners based on their supply–demand requests to achieve mutual benefits on economic, environmental, and social aspects (van Capelleveen et al., 2021). Prior studies proved IS matchmaking as a promising approach to IS opportunity exploration, facilitating IS network development, and leading to large-scale CE implementation in industrial zones (Fraccascia et al., 2020). However, there is a lack of evidence on efficient IS matchmaking in the built environment. A critical barrier is known as construction spatial–temporal dynamics, resulting in the lack of visibility of the supply–demand of the secondary construction materials (Heeren & Hellweg, 2019; Holmes et al., 2021). It is challenging to coordinate multiple material flows in a circular manner across vast space and time differences. Besides, fragmented construction supply chains involve diverse stakeholders who do not often share a common "language," leading to inefficient communications (Vrijhoef, 2011). Further, constructions are complex products where various materials interact in complex spatial–temporal dimensions based on unique physical characteristics and life cycles (Brand, 1994; Pomponi & Moncaster, 2017). Therefore, IS matchmaking in the built environment is highly uncertain and information intensive, which makes its operational feasibility can hardly be foreseen (Yu et al., 2023).

Three categories of prior studies established a preliminary knowledge basis for this niche. First, the decision-support systems developed for sustainable supply chain management (e.g., Lieder et al., 2017; Raimbault et al., 2020; Roci et al., 2022), which facilitate closed-loop supply chain integration. Second, the digital decision-support tools aiming to accelerate the CE transition in the built environment (summarized by Yu et al., 2022). They provided a basis to analyze CE-oriented information flows at a project level. Third, the studies investigating the strategic and operational development of IS (e.g., Batten, 2009; Ghali et al., 2017; Yazan & Fraccascia, 2020; Fraccascia et al., 2020). They developed IS perspectives and methods to tackle CE challenges. However, there is a lack of multi-disciplinary knowledge integration among the existing literature. IS studies generally did not consider the spatio–temporal complexity of building projects. Construction literature to date mainly focused on technical aspects of circularity confined within the boundary of individual projects (Chan et al., 2023). Scant efforts have been devoted to creating knowledge synergies and developing an IS-oriented method to manage circular material flows across heterogeneous projects at scale.

We argue that agent-based modeling (ABM) can be a valuable method to fill this gap, capturing the complex, nonlinear, and multifaceted nature of CE transition (MacAl & North, 2010). ABM has been widely applied to address CE-related issues that other modeling approaches from traditional analytical tools may find challenging (Walzberg et al., 2023). It provides a unique perspective to explore complex systems and test potential measurements by representing individual behaviors and interactions in a virtual environment (Shekhar & Xiong, 2008; Salgado & Gilbert, 2013). It simulates complex interaction contexts and articulates the emergent mechanisms among individual elements and aggregate systemic phenomenons in the IS research field (Axtell et al., 2001; Batten, 2009). This study views main contractors of deconstruction and construction projects as autonomous agents who actively make decisions to (1) manage internal project workflows, and (2) seek external IS collaborations. Through an ABM lens, we provide a methodological perspective to capture and explain the complex dynamics of IS matchmaking in the construction industry over space and time.

To accelerate large-scale CE implementation, *circularity hubs* are recently promoted as a potential solution (Tsui et al., 2023). They are physical warehouses where waste is collected, processed, stored, and redistributed among actors, fostering IS at various scales (A.SPIRE, 2021). Circularity hubs could play an orchestrator role in harmonizing two types of supply chains of demolition and construction projects from an information process perspective (van den Berg et al., 2020a; EC, 2022). Particularly, they could help to mitigate supply–demand uncertainties associated with (1) different supply–demand timing, (2) infeasible transportation ranges, and (3) unequal supply–demand quantity (EC, 2020). However, there is a lack of successful evidence of its effects on IS matchmaking. The feasibility and applicability of circularity hubs remain unexplored in the built environment. This creates a demand for an experimental ground that can help to test the potential effects of circular hubs on spatial–temporal dynamics of IS matchmaking in the built environment.

Therefore, this research develops an agent-based model that simulates the spatial–temporal dynamics of IS matchmaking and its potential responses to circularity hubs in the built environment. Further research objectives are threefold: (1) conceptualize an ABM framework for IS matchmaking in the built environment, (2) instantiate a case-specific model to simulate IS matchmaking dynamics over space and time, and (3) evaluate the effects of circular hubs on IS matchmaking performance. The developed model shows a new way of understanding the spatial–temporal dynamics of circular material interactions among multiple building projects.

This article is structured as follows: Section 2 presents the research method. Section 3 explains model development backgrounds and demonstrates a case-specific model. Simulation results of IS matchmaking and scenario effects of circularity hubs are shown in Section 5. Discussion and conclusions are provided in Sections 6 and 7, respectively.

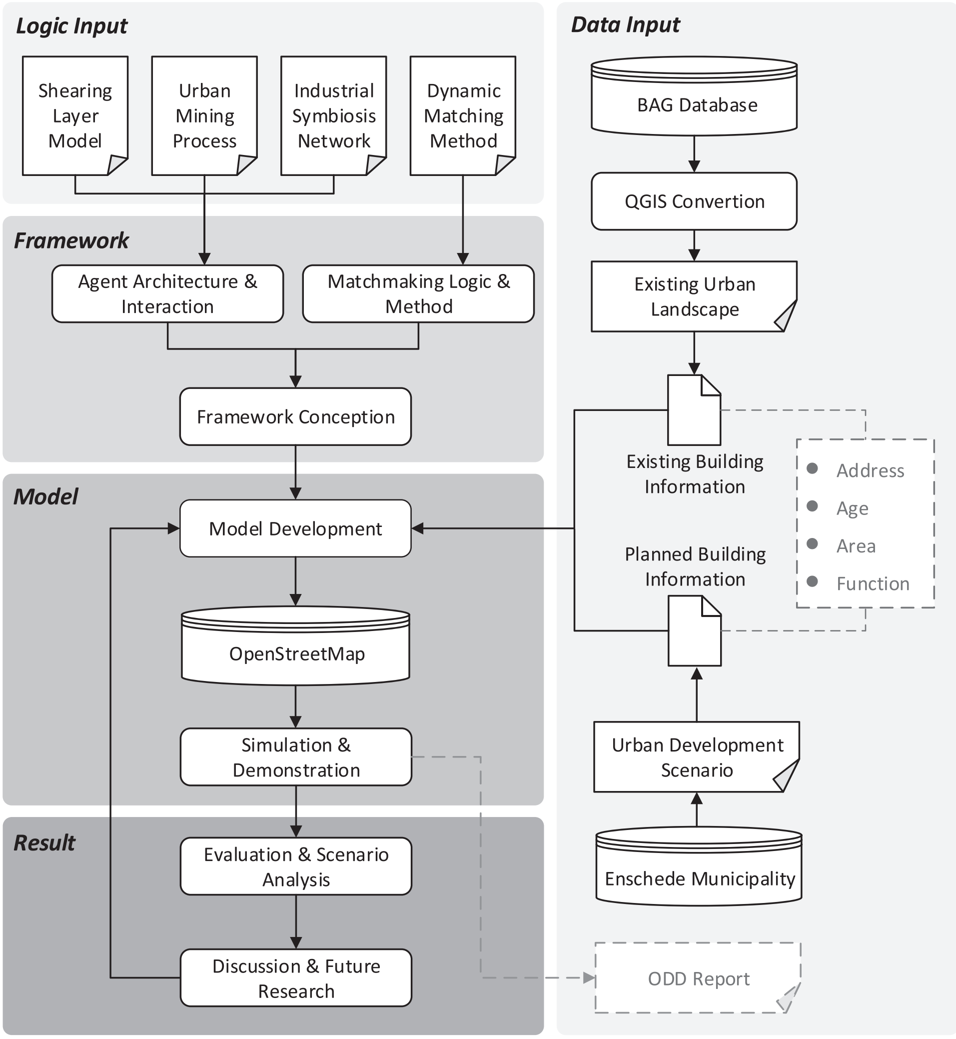


**FIGURE 1** Methodological research processes with main steps of: (1) taking relevant literature as logical inputs for framework conception, (2) developing and demonstrating the model based on case-specific data inputs, and (3) observing and evaluating target outcomes for future model development and evolvement (adapted from Salgado & Gilbert, 2013). BAG, Basisregistratie Adressen en Gebouwen; ODD, overview, design concepts, details. OpenStreetMap (2022) is used to position projects in the urban context and provide transportation distances among projects via AnyLogic.

## 2 | METHODS

We apply an adaptation of the ABM development methodology proposed by Salgado and Gilbert (2013) to this study because it (1) provides basic explanations of ABM, (2) identifies fundamental elements of ABM, and (3) offers an inclusive and coherent basis for different simulation contexts (Figure 1).

First, the relevant literature is taken as logical inputs for the model framework development including the model of shearing layers (Brand, 1994), urban mining processes (Rose & Stegemann, 2019; Tennakoon et al., 2022; Condotta & Zatta, 2021), industrial symbiosis networks (Yeo et al., 2019; Yazan & Fraccascia, 2020; Erol et al., 2023), and the dynamic matching methods based on stochastic arrivals under limited sojourn time (Anderson et al., 2017; Akbarpour et al., 2019; Aouad & Saritaç, 2022). Second, the framework is used as a design blueprint to develop a simulation model based on an urban IS case in Enschede City, the Netherlands. The model is developed and deployed by AnyLogic, a Java-based simulation development platform (Borshchev et al., 2002). Finally, simulation outcomes are evaluated, analyzed, and discussed.

Concrete is selected as a matchmaking material in the model because it is the most dominant construction material in the world (Gagg, 2014). The production of cement, which reacts with water to form a binder for the aggregates in concrete, and the process of heating limestone consume significant amounts of energy and lead to extensive carbon dioxide emissions (Pacheco-Torgal et al., 2013). Besides, up to 85% of the construction and demolition waste is concrete and the associated environmental impact of such an inert material is mostly derived from its logistics and land occupation (Gálvez-Martos et al., 2018). In this regard, recent studies provided empirical evidence on concrete reusing and recycling potentials (e.g., Yu et al., 2021). The reasons above make concrete a suitable material to study in the circular matchmaking context.

The temporal aspects of IS matchmaking are configured by estimating project life spans based on relevant databases. The spatial aspects are captured based on geographical information system (GIS) locations. GIS is often used in ABM because it provides a geospatial environment where agents can make spatial-relevant decisions (MacAl & North, 2010). The configuration data of existing buildings are retrieved from Basisregistratie Adressen en Gebouwen (BAG) database (Kadaster, 2022). It is a Kadaster database that stores Dutch building information regarding (1) addresses, (2) ages (construction years), (4) purposes, and (4) surface areas. The data retrieved from the BAG database are filtered and structured by QGIS, an application that supports viewing, editing, and analysis of geospatial data (QGIS, 2023). Further, the data of planned buildings are collected from prospective urban development plans published by the municipality of Enschede.

Next to this article, an overview, design concepts, details (ODD) report and simulation data sources are attached as Supporting Information. An ODD report provides a formal and comprehensive description of the model enhancing the model's transparency and replicability (Grimm et al., 2020).

## 3 | MODEL FRAMEWORK CONCEPTUALIZATION

The model framework conceptualization consists of: (1) an urban IS context in the built environment, (2) agent architecture and interactions, and (3) dynamic matchmaking logic.

### 3.1 | Industrial–urban symbiosis

We conceptualize the modeling context through a lens of industrial–urban symbiosis, a system approach to identify business opportunities and leverage underutilized resources (A.SPIRE, 2021). It involves cross-sectoral organizations that engage in mutually beneficial transactions to reuse waste and by-products, fostering innovative and symbiotic material flows within an urban area (Erol et al., 2023). In the built environment, it aligns with urban mining and can further be interpreted as a collaborative approach to multi-project symbiotic exchanges based on circular material flows beyond the boundary of individual projects (Yu et al., 2021). The main actors and their possible interactions are depicted in Figure 2 based on relevant prior work (i.e., EC, 2018; Zhang et al., 2020; Yu et al., 2021; Tennakoon et al., 2022).

Through deconstruction, qualified resources salvaged on-site could be directly reused in new construction (Condotta & Zatta, 2021). Regarding indirect reusing, circularity hubs could offer temporary storage, repair, quality control, and sorting services until suitable partners are found or sufficient quantity is reached for economical deals (EC, 2022; Tsui et al., 2023). However, due to the restrictions on construction waste quality and availability, recycling is applied more often in practice (Tennakoon et al., 2022). Recycled waste is used to substitute primary materials extracted from the earth (i.e., the material inlet) and to produce new products (De Brito & Saikia, 2013). Any residual waste after exhaustion of all recovery options is disposed back to the earth (i.e., the waste outlet).

We narrow down the simulation scope and focus on two types of interactions: (1) direct reuse among construction and deconstruction projects, and (2) indirect reuse via circularity hubs. This boundary setup helps to analyze building projects as autonomous entities fitting the concepts of IS providers and receivers.

### 3.2 | Agent architecture

To capture the workflow complexity of building projects, we draw on the seminal work of Brand (1994) that considers buildings as a collection of shearing layers with their own life cycles. Adapted from its original setup, we propose three overarching layers to design the agent architecture as follows (the upper diagram in Figure 3):

- Internal layer (I): Stuff (e.g., furniture);
- Middle layer (II): Services and space plan (e.g., floors and doors);
- External layer (III): Site, structure, and skin (e.g., external walls and load-bearing elements).

This is a simplified version of shearing layers that captures the workflow complexity of a building project. The key reason for designing building layers in such a way is that the main contractors of deconstruction and construction projects shall plan their workflows in an opposite order (i.e., deconstruction: I, II, and III; and construction: III, II, and I). Accordingly, what is available first from a deconstruction site could be the last item that is required by another construction firm. For example, deconstruction contractors first remove furniture from old buildings while construction

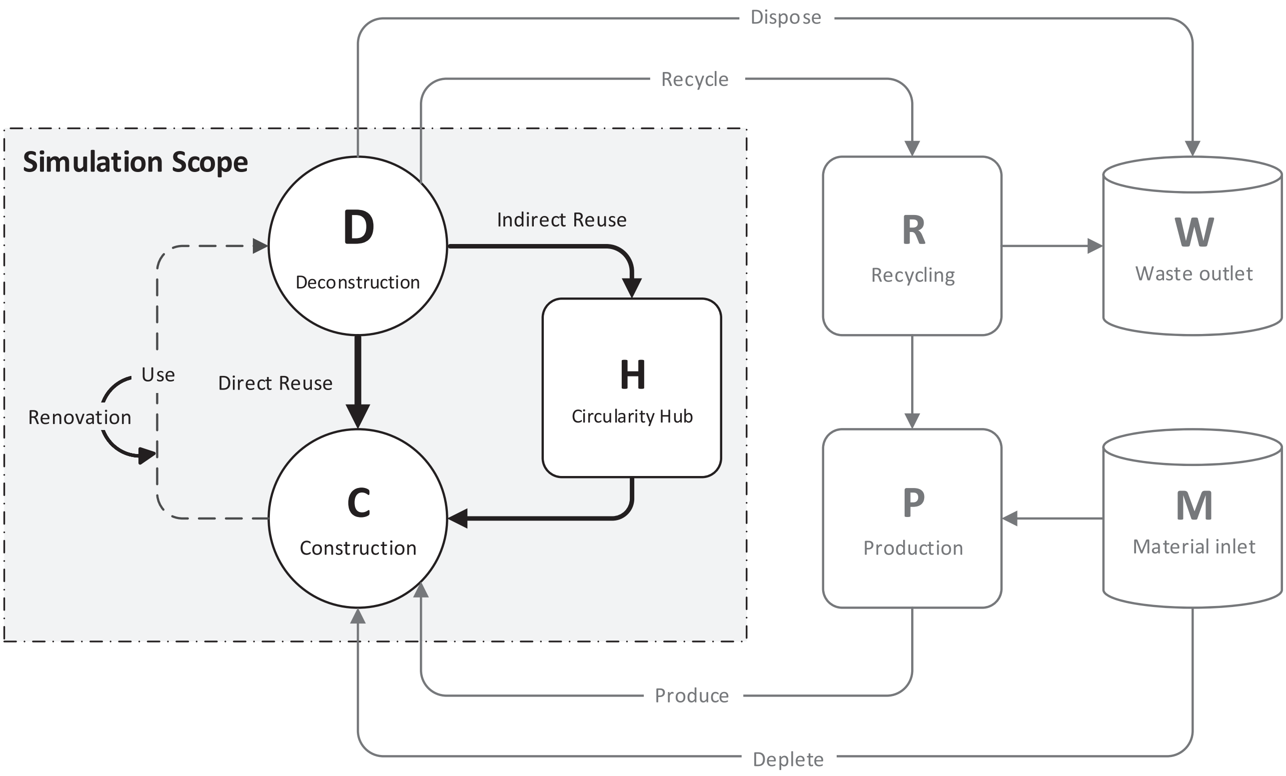


**FIGURE 2** Industrial–urban symbiosis: A case in the construction industry with key actors and their interactions.

contractors need to first build foundations for new buildings (see van den Berg et al., 2020b). This setup makes temporal supply–demand mismatch among heterogeneous projects explicit in the model.

This model regards deconstruction and construction project contractors as supply and demand agents, respectively. Consider $n$ supply agents and $m$ demand agents joining and departing a matchmaking program randomly. The *randomness* indicates that project agents initiate IS supplies or demands stochastically without predefined spatial–temporal orders. Let $S$ be the entire set of supply agents and $D$ be the entire set of demand agents, then the total supply–demand space can be expressed as: $S = \{S_1, S_2, \dots, S_n\}$ and $D = \{D_1, D_2, \dots, D_m\}$.

Joining the matchmaking program is only the first step toward a successful IS match. Then, project agents are matched based on $k$ types of criteria (e.g., quantity, quality, cost, and transportation distance). The entire criteria space $R$ can be expressed by: $R = \{R_1, R_2, \dots, R_k\}$. Further, we use $i$ and $j$ to index the demand agent and the supply agent who are currently under matchmaking, respectively. We denote all the possible matchmaking pairs by $A = \{(i, j) | 1 \leq i \leq m, 1 \leq j \leq n\}$. Thus, the entire supply–demand space with all project agents based on all potential criteria can be expressed by the matrix in the lower part of Figure 3.

## 3.3 | Matchmaking logic

This research introduces a stylized model of dynamic IS matchmaking in the built environment (Figure 4). The matchmaking logic is adapted from the prior work of dynamic matching with stochastic arrivals and departs under limited sojourn time (Anderson et al., 2017; Akbarpour et al., 2019; Aouad & Saritaç, 2022). This is a three-layer matchmaking program occurring in continuous space and time. At the timepoint $t$, agents $i$ and $j$ who already joined the matchmaking program are matched over a criterion $k$ based on the policy below:

$$|R_{i,k} - R_{j,k}| \leq \Delta R_k \quad (1)$$

where $\Delta R_k$ denotes a predefined benchmark measuring the quantitative difference between the demand ($R_{i,k}$) and the supply ($R_{j,k}$) regarding a specific criterion $R_k$. This means that agents are matched because their supply and demand are quantitatively similar within a predefined threshold (see e.g., Yazan & Fraccascia, 2020). Equation (1) must hold true for all criteria $R = \{R_1, R_2, \dots, R_k\}$. Otherwise, the matchmaking fails.

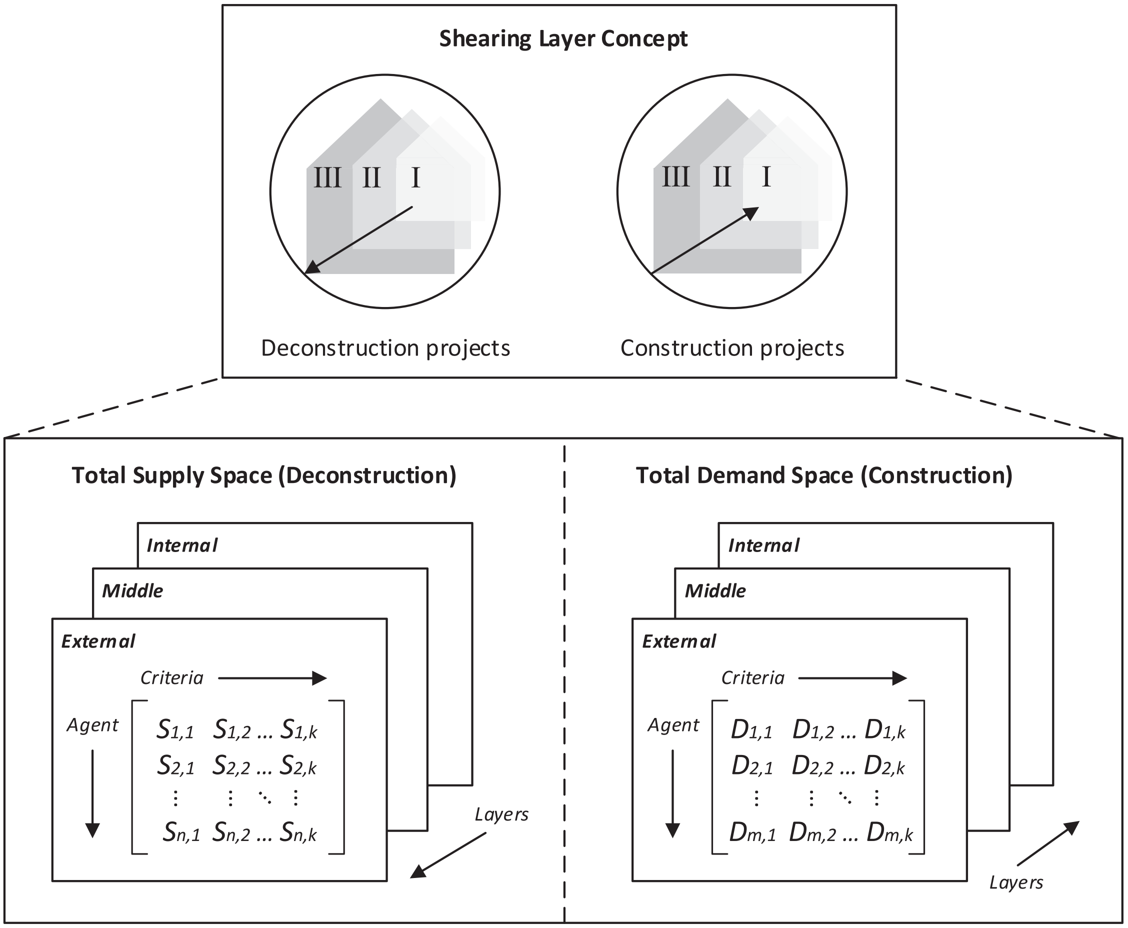


**FIGURE 3** Agent architecture based on shearing layers.

### 3.3.1 | Temporal and spatial setup

The matchmaking program consists of three major steps, namely, (1) receive supply–demand project agents, (2) match agents based on customized criteria, and (3) share matchmaking results with specific agents. Joining the program means that supply or demand requests from project agents are activated but not yet matched. Every newly arrived agent will be matched over all the existing agents waiting in the matching pool based on first-in–first-out principle within limited sojourn time (Figure 4a). Sojourn/waiting time stands for the time that an agent invests in waiting for a possible match. It also indicates how long a project agent keeps its supply–demand request activated. Once an agent waits in the program longer than the predefined limitation without finding any suitable partners, it will be forced to the next layer. After all three layers are exhausted, project agents can decide whether to rejoin the program or not. The maximum rejoin frequency can be customized by model users.

This temporal setup reflects the fact that: (1) IS supply–demand requests emerge stochastically based on different project life spans and locations, and (2) IS opportunities are only valid for a limited duration considering the practical pressures of extra storage and quality decay. This logic is applied to each shearing layer of a project agent. Both successful and failed results will lead agents to the next layer. Note that the matchmaking order is opposite between deconstruction and construction agents based on their agent architecture (Figure 4b). Furthermore, project agents are located at unique GIS points and the model measures agent distances based on urban transportation routes (Figure 4c).

### 3.3.2 | Circularity hub setup

This model considers circularity hubs as transition points allowing larger transportation ranges and longer sojourn times. For the sake of simplicity, we did not consider practical parameters that are important for hub development, for instance, economic investment and technological feasibility (Tsui et al., 2023). Specifically, if an agent decides to match via a hub, this agent will be provided with more sojourn time in the model. Besides, the transportation range will be increased since the distance threshold is applied between the agent and the hub instead of between two agents directly (Figure 4a). When multiple hubs exist, a pair of agents must recognize the same hub as the closest hub to them to achieve successful matchmaking.

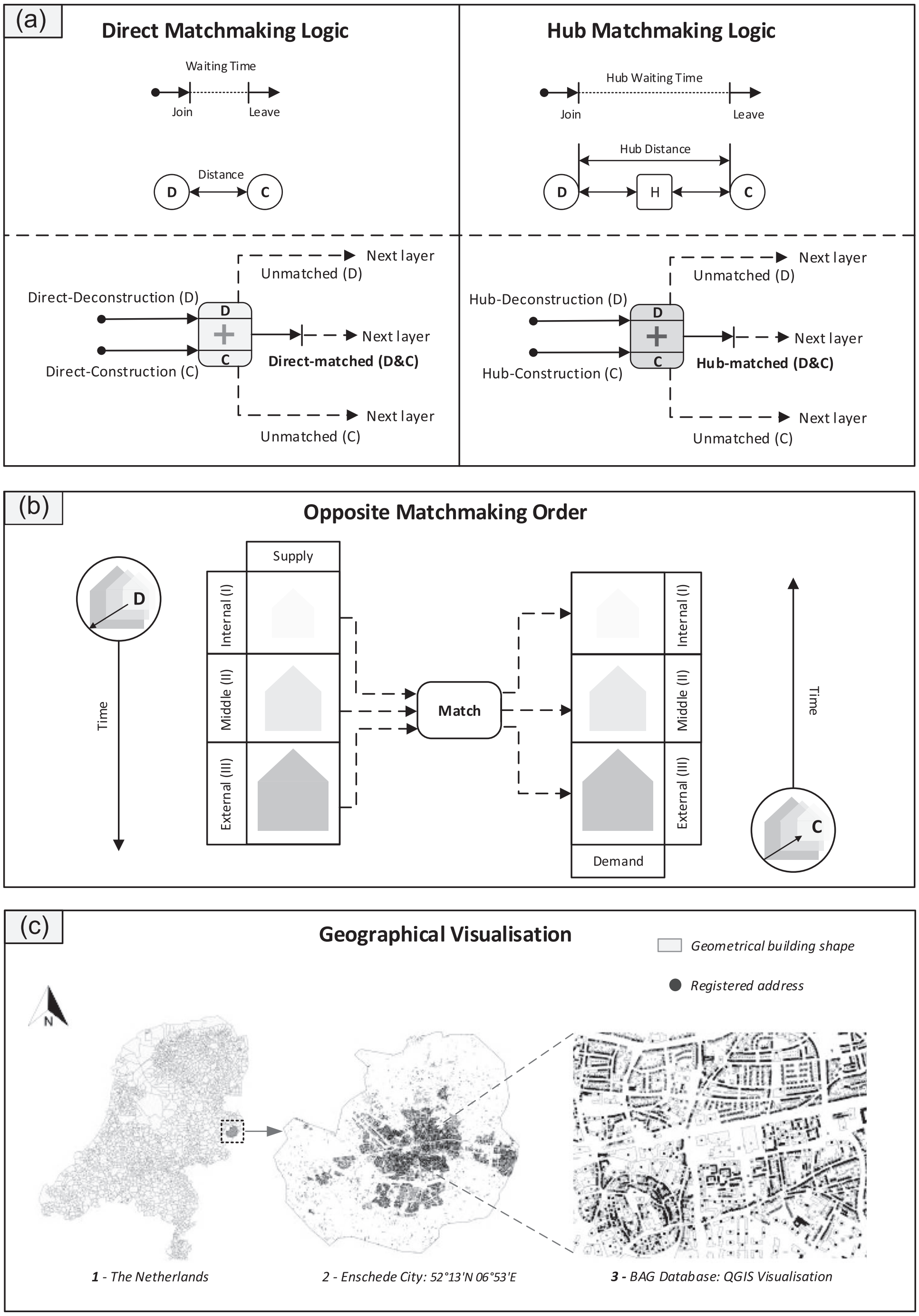


**FIGURE 4** Matchmaking logic: (a) Matchmaking logic comparison where hubs provide extra waiting time and allow larger transportation distances; (b) Opposite matchmaking order at three shearing layers; (c) Visualization of project agents at geographical information system points in the modeling context.

## 4 | MODEL DEVELOPMENT AND DEMONSTRATION

A case-specific model is instantiated based on the proposed modeling framework. First, an urban context of Enschede City is introduced. Second, key parameters, matchmaking criteria, and variables of the model are presented with assumptions. Third, a simulation overview is demonstrated. The developed model can be accessed in AnyLogic Cloud via the link.[1]

[1] Model link: https://cloud.anylogic.com/model/e05c5efb-2e79-4852-be6b-860dc96e0253

## 4.1 | Case in Enschede City

Being a major city in the eastern part of the Netherlands, Enschede has urban development plans with intensive construction activities in the coming decades (CBS, 2022). Particularly, construction projects in the model are based on five actual urban development projects in Enschede as follows (Enschede Municipality, 2022):

- **De Kop**: Mix business–residential area, 600 units, 80–150 $m^2$ per unit, 2023–2032 year;
- **Janninkkwartier**: Residential area, 150 units, 110–200 $m^2$ per unit, 2022–2025 year;
- **Cromhoff**: Mix historical–residential area, 500 units, 100–200 $m^2$ per unit, 2023–2033 year;
- **Eschmarkerveld**: Residential area, 600 units, 100–200 $m^2$ per unit, 2025–2030 year;
- **Het Leuriks**: Luxury residential area, 64 units, 520–800 $m^2$ per unit, 2022–2028 year.

The construction demand baseline consists of five major real-estate projects above adding up to 1914 residential units. Meanwhile, the deconstruction supply baseline contains 2000 existing residential buildings with various ages in Enschede randomly selected from the BAG database. Unlike deconstruction projects scattered in the city, construction projects are planned within specific areas. This spatial setup creates special supply–demand dynamics because deconstruction project agents tend to spread materials in a divergent manner while construction project agents would collect materials in a convergent manner (see e.g., Vrijhoef, 2011).

## 4.2 | Environment and timeline

The simulation environment consists of geographical locations of buildings and urban transportation networks in Enschede. Whenever a matchmaking event occurs, the potential transportation distance between two agents is computed and used as one of the matching criteria. The registered building addresses in Enschede are retrieved from the BAG database and filtered by QGIS (Figure 4c).

The simulation starts from the year 2023 and runs 15 years into the future since most construction projects are planned within this time frame. The model runs in continuous time with one simulation time unit equaling one month in reality. The ages of existing buildings are constantly updated by the model as the simulation runs. We apply a default life span of 75 years to existing buildings as an age threshold according to the Dutch Environmental Database (2020). Existing building agents that reach this age threshold would trigger decision-making processes and decide whether to join the matchmaking or not. Planned building agents join the matchmaking program based on the actual urban planning introduced above.

## 4.3 | Parameter, variable, and assumption

A matchmaking event is configured based on: (1) agent numbers, (2) temporal and spatial factors, and (3) matchmaking criteria (Table 1). First, project agents are defined based on the aforementioned case to populate the model. Second, temporal and spatial factors are configured for each agent based on relevant databases. Third, the model includes three quantitative criteria of quantity, cost, and distance that are important for IS matchmaking (Yazan & Fraccascia, 2020). A pair of agents are matched if their supply–demand differences are within the predefined thresholds of three criteria. The accuracy and strictness of matchmaking can be modified by changing these thresholds:

- Quantity threshold: The predefined quantity differences between supply and demand;
- Cost threshold: The predefined unit cost differences between supply and demand;
- Distance threshold: The predefined transportation distance between supply and demand projects.

Concrete is selected as a matchmaking material in the simulation because of its massive consumption, significant environmental impact, and reusing and recycling potentials. Besides, concrete is a bulk material whose quantities can be estimated based on gross floor areas. Referring to the average height of residential buildings in the Netherlands and the floor areas retrieved from the BAG database, we take cubic concrete as a computational basis to estimate the concrete quantity at each layer.

We assume that deconstruction contractors conduct on-site quality inspections to ensure concrete quality. However, the quality of demolition and construction waste is a complex factor in reality, which often requires destructive or non-destructive testing and certification (EC, 2018). For the sake of simplicity, we define the quality of tradeable materials as an arbitrary proportion (up to 20%) of the total material quantity per agent per layer ($\alpha$). It acts as a selective mechanism that helps to (1) qualify a limited amount of materials and (2) capture the randomness of quality variations in reality. The adjustment of this proportion can be considered as a flexible representation of the quality factor. Specifically, the qualified material

**TABLE 1** Key parameters, criteria, and variables ([] is a continuous value range including lower and upper boundaries; uniform[] is a function that generates a random value uniformly distributed on the specified interval).

| Parameter | Explanation | Value | Source |
|---|---|---|---|
| $m$ | Deconstruction project population (agent) | 2000 | BAG (2022) |
| $n$ | Construction project population (agent) | 1914 | Enschede (2022) |
| $T_{LifeSpan}$ | Default life span (year) | 75 | NMD (2020) |
| $T_{Decon}$ | Construction years of existing buildings (year) | [1820, 2023] | BAG (2022) |
| $T_{Con}$ | Construction years of new buildings (year) | [2024, 2030] | Enschede (2022) |
| $A_{Decon}$ | Addresses of existing buildings (-) | Database | BAG (2022) |
| $A_{Con}$ | Addresses of new buildings (-) | Database | Enschede (2022) |
| $S_{Decon}$ | Surface area of existing buildings ($m^2$) | [13, 258] | BAG (2022) |
| $S_{Con}$ | Surface area of new buildings ($m^2$) | [80, 800] | Enschede (2022) |
| $H_{Average}$ | Average height of a building unit per address (m) | uniform[5, 13] | Building Decree (2012) |
| $C_{Average}$ | Average unit cost of concrete (euro/t) | uniform[320, 350] | GlobalProductPrices (2023) |
| $\rho_{Average}$ | Average concrete density (t/$m^3$) | uniform[2.3, 2.4] | Building Decree (2012) |
| $\alpha_{I, II, III}$ | Quantity coefficient for three layers (-) | uniform[0, 0.2] | Concrete Handbook (2013) |
| $\beta_{I, II, III}$ | Cost coefficient for three layers (-) | uniform[0.5, 1.0] | Assumption |
| $P_{Hub}$ | Probability to choose hub match (-) | uniform[0, 0.2] | Assumption |
| $P_{Circular}$ | Probability to choose a circular model (-) | uniform[0, 0.9] | Assumption |
| $P_{Linear}$ | Probability to choose a linear model (-) | uniform[0, 0.1] | Assumption |
| $T_{Sojourn}$ | Sojourn time (month) | uniform[1, 12] | Assumption |
| **Criteria** | **Explanation** | **Value** | **Source** |
| $\Delta R_{Quantity}$ | Quantity threshold (t) | [0, 10] | Customizable |
| $\Delta R_{Cost}$ | Cost threshold (euro/t) | [0, 10] | Customizable |
| $\Delta R_{Distance}$ | Distance threshold (m) | [0, 2000] | Customizable |
| $\Delta_{Rounds}$ | Maximum matchmaking rounds (-) | 4 | Customizable |
| **Variable** | **Explanation** | **Value** | **Source** |
| $Age$ | Building's age (year) | [0, 200] | Auto-update |
| $X_{Distance}$ | Transportation distance between agents (km) | OpenStreetMap | Auto-update |
| $Rounds$ | The frequency of joining the matchmaking (-) | [0, 1, 2, 3] | Auto-update |
| $Q_{Decon, I, II, III}$ | Deconstruction supply quantity (t/layer) | Equation 2 | Auto-update |
| $C_{Decon, I, II, III}$ | Deconstruction supply cost (euro/t/layer) | Equation 3 | Auto-update |
| $Q_{Con, I, II, III}$ | Construction demand quantity (t/ layer) | Equation 2 | Auto-update |
| $C_{Con, I, II, III}$ | Construction demand cost (euro/t/layer) | Equation 3 | Auto-update |

quantity of each layer $Q_{I, II, III}$ is estimated as follows:

$$Q_{I, II, III} = S * H_{Average} * \rho_{Average} * \alpha_{I,II,III} \quad (2)$$

where $S$ stands for the surface area of project agents, $H_{Average}$ is the average height of a residential unit ranging from 3 to 15 m (Dutch Building Decree, 2012), $\rho_{Average}$ is the average density of concrete material varying from 2.3 to 2.4 t/$m^3$, and $\alpha_{I, II, III}$ is an arbitrary conversion factor that differs in each layer per agent. $\alpha$ determines the qualified concrete quantity per layer with an assumed limitation up to 20% (Pacheco-Torgal et al., 2013). Similarly, the unit cost of qualified concrete of each layer $C_{I, II, III}$ is calculated based on:

$$C_{I, II, III} = C_{Average} * \beta_{I, II, III} \quad (3)$$

where $C_{Average}$ is an average unit cost of secondary concrete material ranging from 320 to 350 euro/t (GlobalProductPrices, 2023), and $\beta_{I, II, III}$ is a coefficient that varies in each layer per agent. $\beta$ stochastically determines the final unit cost with a range between 50% and 100% of the average cost. It introduces cost uncertainties into the model, which represents market dynamics in reality. Finally, a series of additional assumptions are proposed to simplify matching conditions as follows:

- One unit of secondary concrete can replace one unit of primary concrete;
- Once a matchmaking result is determined, both parties are willing to accept the result;
- Transaction costs generated by searching and waiting for partners are excluded;
- New buildings planned in one urban development project will be built in multiple phases;
- Project agents choosing to adopt a circular model is assumed as a stochastic decision based on a random distribution ($P_{Circular}$)
- Project agents choosing to match via transfer hubs is assumed as a stochastic decision based on a random distribution ($P_{Hub}$);
- The investment costs, location feasibility, and waste treatment details about circularity hubs are excluded.

### 4.4 | Simulation overview

The simulation starts with initial configurations. Users can configure the simulation environment by determining project agents' locations, surface areas, construction years, population sizes, and matchmaking criteria thresholds. Once the simulation runs, project agents continuously update their ages. When the age exceeds the predefined age threshold, project agents make stochastic decisions and participate in the matchmaking program. The matchmaking program matches a pair of agents whose supply–demand requirements are within the predefined thresholds. Project agents receive matchmaking results and update their visual characteristics (i.e., color and transparency) accordingly. The final ending colors are green and grey indicating successful and failed matchmaking, respectively. Project agents continue to match at the next layer until (1) all shearing layers are successfully matched or (2) a maximum rejoining frequency is reached. The variables of project agents, matchmaking status plots, and the model interface are updated simultaneously (Figure 5).

## 5 | RESULTS

The ABM simulations show how IS (mis)matches between the supply and demand evolve over space and time. First, spatial and temporal mismatches are observed and explained. Second, circularity hubs are simulated as a potential solution to mitigate these mismatches. This section can be regarded as a preliminary evaluation that ensures the model's rationality under different scenarios.

### 5.1 | Emergent phenomenon: Spatial–temporal dynamics of IS matchmaking

Figure 6a–d shows time-based tracking records of project agents in the matchmaking program via direct or hub matchmaking. Construction and deconstruction agents demonstrate different temporal patterns. In this case, construction agents need to accomplish their projects within the next 5 years approximately. There is a great construction demand in a relatively short time. However, the supply provided by deconstruction agents emerges stochastically at a slower pace. The first demand peak appears in the 25th month while a significant supply peak is only observed in the 100th month. Since the supply is not temporally dependent on the demand, the supply from existing buildings can hardly meet the demand of construction projects based on the current scenario setup. Therefore, most project agents remain unmatched or matched incompletely at the end of the simulation.

Besides, Figure 6 e1–e4 presents time-based snapshots of matchmaking status. The dynamics of IS matchmaking can be observed by comparing the changes of agent's color in different snapshots. Existing buildings are scattered around the city while new buildings await to be built at limited target sites. This shows an operational conflict of IS matchmaking that deconstruction supply could originate from all over the place but construction demand usually occurs within a narrow spatial range. Moreover, the quantity mismatch complicates this situation. The supply from an individual building can hardly be comparable, in the sense of quantity, with the demand of an integrated project including clusters of buildings. In this case, the buildings in Het Leuriks project were designed with larger surface areas with higher quantity demands, which could be the reason for their lower matchmaking performance.

Project agents interact via matchmaking stochastically based on their schedules and locations at the bottom level. Such multi-agent interactions lead to a greater IS supply–demand phenomenon at the systemic top level. A potential emergent pattern of IS matchmaking can be inferred based on (1) the frequency and amplitude of wave-shaped curves of agent numbers presented in Figure 6a–d, and (2) the spatial distribution of agents with different colors in Figure 6 e1–e4. Specifically, the frequency shows the temporal supply–demand pace and the amplitude represents the supply–demand intensity. Combining statistical graphs with status snapshots, the model (1) answers the questions of when and where are buildings ready for IS, and (2) describes the progress of how industrial–urban symbiosis evolves over space and time.

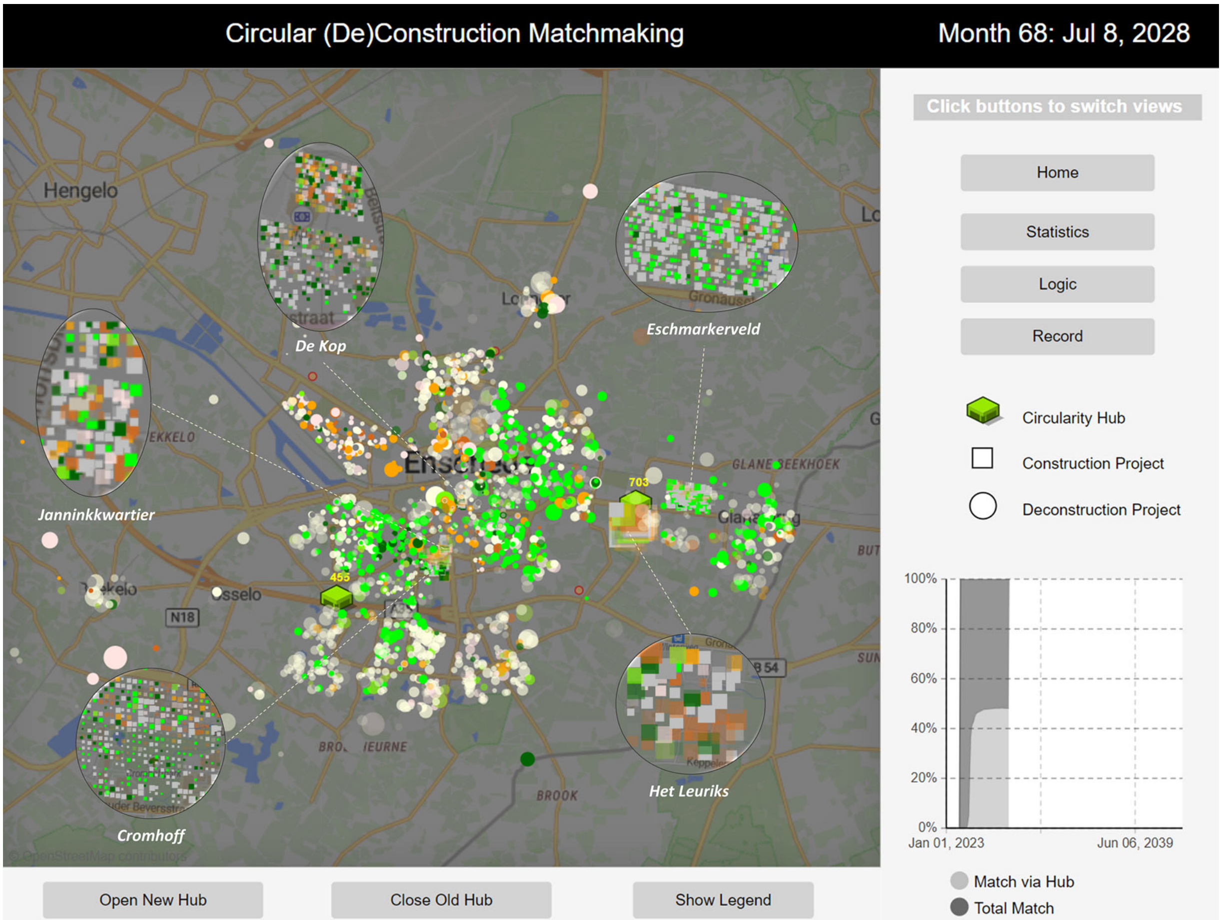


**FIGURE 5** Simulation overview: Existing buildings (circles) and planned buildings (squares) are visualized on a map of Enschede. The more the tradeable materials, the larger the agent shape; agent's color becomes darker and more solid as time passes by. The legend of agent colors can be inspected by clicking the button of legend. A circularity hub can be opened or closed by clicking action buttons; User views can be switched by clicking view-point buttons. Underlying geographical information systems and Basisregistratie Adressen en Gebouwen data for agent setups are available in sheet 1 of Supporting Information S2.

## 5.2 | Scenario analysis of circularity hubs

Circularity hubs are proposed to mitigate IS mismatches by allowing longer waiting/sojourn time and larger transportation ranges. Five potential hubs are created in the model surrounding the city as a ring following the main ring road of Enschede. This setup helps to compare hub effects on urban zones in different directions. Specifically, five hubs are located in the directions as follows:

- Hub No. 1: South
- Hub No. 2: South-east
- Hub No. 3: South-west
- Hub No. 4: North-west
- Hub No. 5: North

### 5.2.1 | Temporal effect: Longer waiting time

The effects of maximum hub waiting time of 6, 8, 10, and 12 months on overall matchmaking status are plotted in Figure 7a. Construction agents are plotted in the upper part of the figure while deconstruction agents can be seen in the lower part. For the sake of explicit demonstration, we only plot the changes of agent status at the middle layer. Due to extra waiting time, agents are allowed to keep supply–demand requests active for a longer period. This makes more IS alternatives available in the matchmaking program, therefore, thickens the IS market (see Akbarpour et al., 2019 for thickness and information in dynamic matching markets).

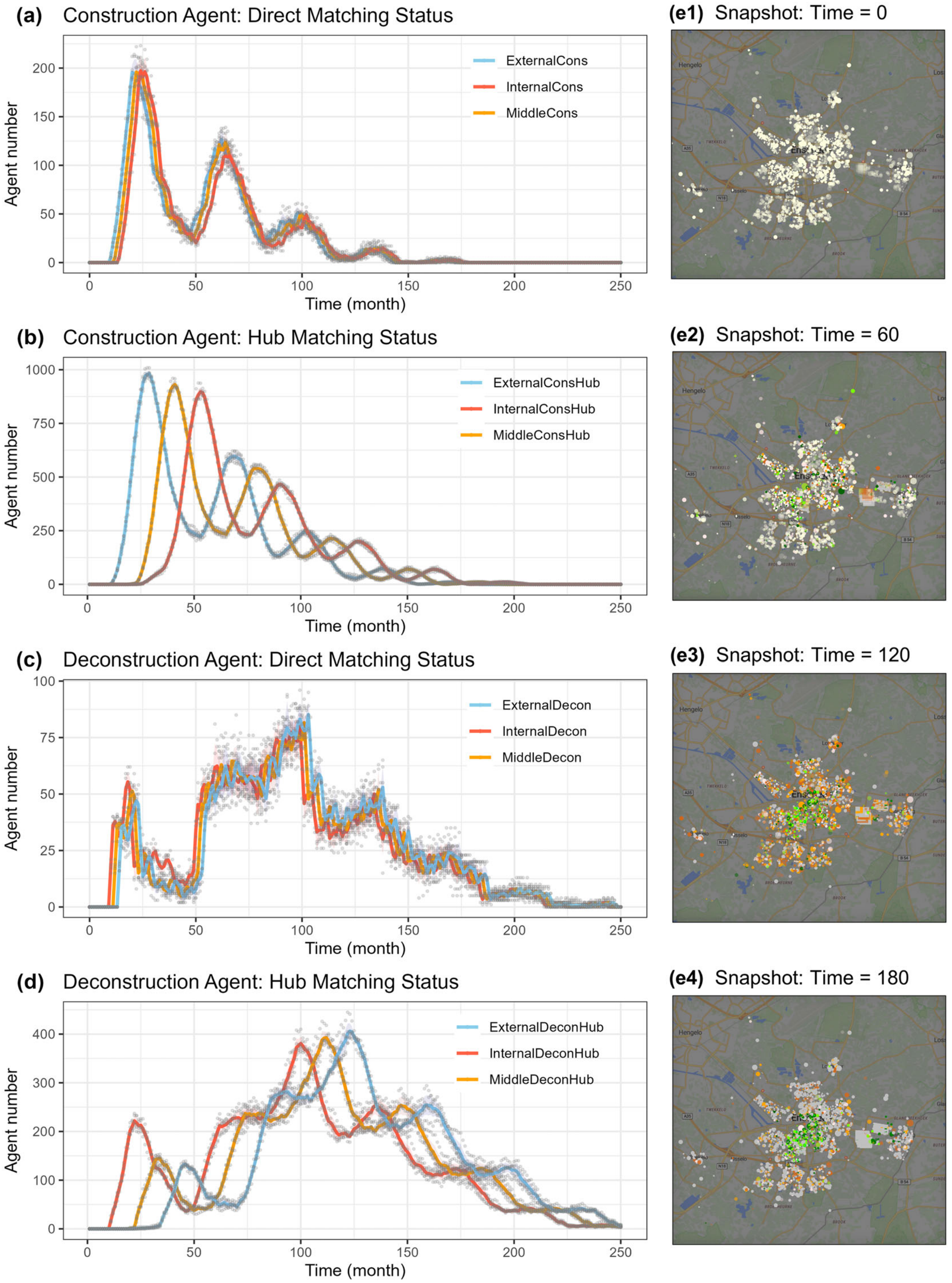


**FIGURE 6** Matchmaking status and stages. (a–d) Five simulation iterations: curves stand for average agent numbers in the matchmaking program, points are actual values of each iteration, and areas indicate 95% confidence intervals. (e1–e4) Time-based snapshots of matchmaking stages). Underlying data for industrial symbiosis matchmaking dynamics are available in sheet 2 of Supporting Information S2.

In Figure 7b, the waiting time of direct and hub matchmaking are adjusted simultaneously, which leads to different final results of successful matchmaking rates.[2] The maximum waiting time for direct matchmaking is assumed as 6 months while hub waiting time can be extended to 12 months. It can be observed in Figure 7b that the longer waiting time mostly contributes to successful matchmaking (i.e., up to 22% at the upper right corner). On the contrary, the IS opportunities can hardly be seized if the waiting time is too short (i.e., only 3% at the lower left corner). However,

[2] The number of agents who achieved successful matchmaking at all three layers divided by the total agent number.


**FIGURE 7** Scenario analysis. (a) Effects of maximum hub waiting time of 6, 8, 10, and 12 months on agent numbers in the matchmaking program. (b) Combinational time effects on successful rates. (c) Singular hub performance of IS connections. (d) Collective hub performance of IS connections and successful rates. (d1-d6) Spatial layout of successful matchmaking agents per hub combination. Underlying data for hubs analysis are available in sheet 3 of Supporting Information S2.

these are conceptual results. In practice, longer waiting time also indicates higher transaction investments, which would interrupt a matchmaking event. The practical hub operation and development remain as a future research topic.

To summarize, the model captures the temporal dynamics of IS matchmaking from two perspectives: (1) urban morphology (e.g., when a group of buildings reach the age threshold collectively) and (2) matchmaking marketplace (e.g., how long an offer stays active in the market). The findings indicate that longer waiting/sojourn time provided by circularity hubs could potentially be beneficial to IS matchmaking.

### 5.2.2 | Spatial effect: Larger transportation range

The spatial performance of a singular hub is evaluated by relocating hubs in different directions. Figure 7c shows successful IS connections[3] achieved by each hub during the simulation period, respectively. It can be seen that hubs at locations 1 and 3 attract more IS connections because they are surrounded by comparatively larger numbers of construction and deconstruction projects. Thus, hubs act as middle transaction points connecting more agents in a larger transportation range. Compared to non-hub scenarios, they improve geographical IS proximity and contribute to higher matchmaking performance.

Next, collective performances of hub combinations are presented in Figure 7d. The bar chart shows the hub's connections in different combinations with a total successful rate at the end of each simulation. The final spatial layouts of six hub combinations are depicted in Figure 7 d1–d6. The fourth combination of hubs nos. 1 and 3 achieves the most IS connections and the highest successful rate of 17%. However, hubs nos. 4 and 5 fail to make any connections when all hubs exist, though they are capable of doing so individually. This is partly due to their disadvantageous locations far away from construction projects. Further, it indicates that a competitive hub market could emerge when multiple hubs exist and operate simultaneously. Hubs compete with each other and the most advantageous hub would dominate the market.

To better contextualize the results, we elaborate on the potential challenges of matchmaking the concrete material in practice. First, the transportation viability is closely related to the form and volume of concrete. More detailed logistic planning is required to ensure the final mile delivery. Second, operational details of concrete processing and treatment should be considered for hub development. For instance, extra waiting time could compromise the quality of concrete, especially, for those at the end-of-life phase. Therefore, careful quality examination and prediction based on material characteristics are required to ensure the successful development and management of circularity hubs.

Overall, under the scenarios where circularity hubs are characterized based on transportation ranges and matchmaking waiting/sojourn time, simulation results quantitatively suggest an interesting phenomenon. A larger number of hubs does not necessarily contribute to a higher successful matchmaking rate. Instead, the strategic hub implementation based on the spatial distribution of different projects is the key to effective IS matchmaking.

## 6 | DISCUSSION

In this section, the model's novelty is discussed first. Then, the practical indications of simulation outputs are discussed linking IS operational conflicts with circularity hubs. Finally, future research directions and limitations are pointed out.

### 6.1 | Dynamic IS matchmaking in the built environment

Adding to the prior ABM studies in the CE literature (Lieder et al., 2017; Raimbault et al., 2020; Yazan & Fraccascia, 2020; Roci et al., 2022), this model demonstrates the spatial–temporal dynamics of complex IS interactions in the built environment. The modeling structure captures the unique characteristics of building projects, where the internal workflows of each project agent are coherently linked with external material exchanges at an urban level. The proposed agent-based approach also echoes the prior work in the spatial–temporal analysis of construction material flows (i.e., Heeren & Hellweg, 2019; Lausselet et al., 2020; Verhagen et al., 2021), forecasting the evolvement trend of circular urban metabolism.

Although dynamic matchmaking is known as a classic problem in the field of operations research (Anderson et al., 2017; Akbarpour et al., 2019; Aouad & Saritaç, 2022), its CE-oriented application in the built environment is understudied. The proposed model simulates dynamic IS matchmaking with stochastic arrivals and departs under limited sojourn time based on an ABM structure. In this case, heterogeneous project agents join and leave the matchmaking program autonomously. A complex and dynamic phenomenon of IS matchmaking emerges from individual decision-making in a bottom-up manner. The proposed modeling structure and logic provide a novel lens to explore circular construction at scale.

### 6.2 | Operational conflict of circular construction at scale

The simulation results indicate an operational conflict of IS matchmaking in the built environment: organized project workflows encountering the stochastic emergence of secondary resources over vast spatial–temporal differences. The model illustrates IS mismatches between reverse and forward supply chains, which is theoretically echoed with divergent and convergent supply chain concepts proposed by Vrijhoef (2011). Deconstruction projects provide waste stochastically across a longer period of time, whereas most construction projects demand resources within a tight

[3] Connections entail matched IS per shearing layer and three connections at all layers make one successful match.

schedule. Further, secondary materials are scattered around the city, which is spatially inconvenient for a number of demands concentrated in limited construction sites.

We raise attention to investigate the input–output structures of resource consumption and waste generation among building projects through multiple shearing layers. Connecting these inputs and outputs symbiotically through multiple spatial–temporal levels is vital to fostering circular material loops in a broader scope. This is consistent with the recommendation of focusing on how systematic CE performance would respond to the supply–demand dynamics of material flows over different temporal and spatial scales in the literature (Holmes et al., 2021; Yazan & Fraccascia, 2020).

### 6.3 | Circularity hubs support IS matchmaking

Taking the construction industry as an anchor industry, circularity hubs are envisaged to coordinate circular material flows among diverse industries and foster a larger industrial ecosystem. This is aligned with a higher ambition of achieving hubs for circularity (H4C). Defined by A.SPIRE (2021), H4Cs are self-sustaining economic industrial ecosystems for full-scale industrial–urban symbiosis and circular economy, closing energy, resource and data loops, and bringing together all relevant stakeholders, technologies, infrastructures, tools, and instruments necessary for their incubation, implementation, evolution, and management. Future research is required to unlock the potential of circularity hubs beyond the construction industry and promote boundaryless CE in the direction of H4C.

The circularity hubs proposed by this research are practical enablers for H4C. They can help to form an integrated solution to (1) increase the visibility of IS opportunities, (2) allow flexible spatial and temporal scales of IS proximity, and (3) coordinate the supply–demand dynamics of secondary material markets (EC, 2020). Depending on the scales of industrial ecosystems, circularity hubs can facilitate the management and optimization of cross-sectoral resource flows based on different capacities. Adding to the prior work of Tsui et al. (2023), this research provides a spatial–temporal perspective to analyze the hub's effects. Specifically, sojourn time is introduced as a temporal factor capturing limited IS availabilities. The developed model offers an analytical basis to facilitate the temporal and spatial planning of circularity hubs.

### 6.4 | Future research directions and limitations

The model has the potential to unlock various future applications including (1) serving as a matchmaking engine in an online marketplace recommending IS opportunities (van Capelleveen et al., 2021), and (2) supporting strategical allocation of circularity hubs (A.SPIRE, 2021). Moreover, the model provides a modeling foundation to expand and build a large ABM framework involving more elements and agents. Following the future path of CE-oriented ABM proposed by Walzberg et al. (2023), this model could explore how the interplay of technologies, behaviors, business strategies, and policy could benefit CE transition. From an educational perspective, such an application can support the social learning of CE where diverse stakeholders experience the trade-offs of CE through gamification (Fraccascia et al., 2021; SRCLab, 2023).

The research limitations exist in three aspects. First, the model lacks a consistent data source for scenario development. The data used to create future construction projects are mainly based on envisioned plans of local authorities that are subject to changes. This could lead to deviations between the model's predictions and actual project timelines. Second, the motivations of agent decision-making are mainly probabilistic oriented. Although this setup helps to capture the real-world randomness, more empirical evidence needs to be collected to validate simulation results and enhance the decision-making framework. Third, the model focuses on concrete without specifying its material characteristics in detail. This is due to the fact that we aim to set up a general modeling structure and context for IS matchmaking in the built environment. Based on the methodological basis developed in this research, more relevant and detailed features could be incrementally added to the model later. For instance, more efforts can be devoted to (1) incorporating a complete version of shearing layers, and (2) including life spans and quality factors of different materials.

## 7 | CONCLUSIONS

We applied an agent-based perspective to explore IS matchmaking among deconstruction and construction projects over space and time. The simulation showcased the potential spatial–temporal dynamics of industrial–urban symbiosis based on concrete in the city of Enschede, the Netherlands. The concept of shearing layers was adapted to design agent architecture and capture the workflow complexity of building projects. A dynamic matchmaking program is proposed based on stochastic arrivals and departs under limited sojourn time. The results (1) demonstrated potential spatial and temporal mismatches of IS and (2) provided operational proof of developing circularity hubs as a future solution to mitigate these mismatches. The research revealed an IS phenomenon that can hardly be observed in reality over vast distances and time frames. Instead of directly carrying out a numerical result, the model "grows" the emergent IS phenomenon and provides a new perspective to explore the complexity of circular construction ecosystems. Overall, this research contributes to multi-scale CE implementation in the built environment.

## CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

## DATA AVAILABILITY STATEMENT

Data available on request from the authors.

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## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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