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Evaluate design principles for flexible use of railway station areas: Through research-by-design and agent-based simulation

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ABSTRACT

Design principles are widely used in the design field, yet some remain visionary rather than grounded in real-world applications. Assessing their effectiveness is therefore essential before implementation. This study focuses on a set of visionary design principles intended to promote the flexible use of railway station areas: (1) Ensuring event visibility by aligning paths and spaces; (2) Incorporating reconfigurable elements and reconfiguration-supportive layouts; (3) Establishing high-quality connections at different scales; (4) Adopting scattered layouts for high capacity or vibrancy; (5) Prioritizing core spaces for humans instead of vehicles. This study **aims** to address the gap in validating these design principles. Recognizing the potential of jointly employing research-by-design and agent-based simulation, this study presents a major research **question**: *How effective are these design principles, as demonstrated through research-by-design (RbD) and agent-based simulation (ABS)?* **Methodologically**, it first applies the design principles to Station Xtreme and generates multiple design proposals, then simulates the generated proposals, followed by assessments and reflections. The **results** suggest that the principles are generally effective, though limitations emerged: for example, quality connections may demand greater investment and space, while scattered layouts can increase wayfinding difficulty and operational complexity. This study **contributes** to the growing body of design knowledge by validating these flexible-use principles. It also introduces a transferable conceptual framework that integrates RbD and ABS, offering a novel methodological approach for testing other visionary design principles.

1. Introduction

Design principles are widely used in the design field. Design, with its pioneering nature to invent better solutions for a better future, is often about creating new solutions that do not exist in the real world yet [1,2]. Design principles, correspondingly, are often developed as instructions toward the visionary better futures. Thus, these kinds of ‘design principles’ are actually ‘hypotheses.’

Regarding the design practice of stations, a few manuals of design principles have been developed. For example, the company Network Rail in the UK has developed design guidance for stations [3] and station areas [4]. The company Spoorbeeld (the Dutch word for ‘Railway Image’) in the Netherlands has developed design guidance for different aspects of stations, including architectural and urban design of station areas [5]. One thing often missing in the current design principles is validation. Ideally, whether design principles are effective should be observed before and after the construction of the projects that use the principles. However, this is

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Table 1
Design principles for flexible use of station areas with supporting heuristics.

Design principles	Heuristic basis
1. *Ensuring event visibility by aligning paths and spaces.*	Events on the plaza of the current Rotterdam Central Railway Station (RS) easily attract pedestrian attention, enlivening the environment, while any events in Beijing West RS's sunken south plaza remain unseen from ground level.
2. *Incorporating reconfigurable elements and reconfiguration-supportive layouts.*	In Fig. 1, Layout B (inspired by pedestrian controls in airports and stations) supports efficient non-peak time transfers and safe long-distance peak-time transfers, while Layout A (referencing Allianz Arena, where the metro station is far away from the arena) does not.
3. *Establishing high-quality connections at different scales.*	In Utrecht Central RS and Rotterdam Central RS, there are high-quality city axes and pedestrian passages, enabling easy pedestrian movement to enliven the environment. In contrast, Beijing West RS has inconvenient footbridges and tunnels, and pedestrians only use them out of necessity.
4. *Adopting scattered layouts for high capacity or vibrancy.*	Shanghai RS has eight bus stations scattered around it, while Beijing West RS has two major bus stations concentrated.
5. *Prioritizing core spaces for humans instead of vehicles.*	The current Rotterdam Central RS has a human-oriented plaza supportive of leisure events, while the former plaza was dominated by vehicles, trams, and a metro station, leaving no space for such events.

practically challenging because large infrastructure projects like railway stations often take years or even decades to be built, and this time range usually falls out of typical research projects' time frames. The following Section 1.1 introduces a set of visionary design principles – design principles of flexible use of stations, which address a specific design issue – overcrowding and underutilization in stations.

1.1. Research background: Promote flexible use to address overcrowding and underutilization

Overcrowding and underutilization (O&U) happen in certain railway stations. Beijing West Railway Station is a clear example illustrating the phenomenon of O&U. The station is occasionally criticized as overcrowded during peak times [6] and underused during off-peak periods [7]. Beyond Beijing West Railway Station, many other stations periodically experience overcrowding and underutilization [8–11]. For instance, in China and South Korea, major stations in megacities face overcrowding during the Spring Festival due to mass migrations [8,9]. Similarly, in Europe, all stations in Amsterdam are challenged by overcrowding during King's Day; stations like Amsterdam Bijlmer Arena and Manchester Victoria are challenged during sports games and concerts [10,11]. Conversely, these stations usually remain underutilized during off-peak periods. Overcrowding is a safety concern [12–16]; underutilization is a waste of space resources. It is crucial to prevent overcrowding and reduce underutilization. The phenomenon of O&U happening on the same stations reflects fluctuation in station use across different times, highlighting the temporal dynamics that challenge a consistent and positive *user experience* and an efficient and safe station management.

In a research project that this study is part of, the research hypothesizes *flexible use* as one strategy to ease overcrowding and underutilization, which can be combined with the strategy of *station-city integration*. Assume a station supports flexible uses, and is well integrated with the city, it provides the following possibilities: During peak or disruption times, the station shares neighboring city spaces to reduce overcrowding or accommodate stranded passengers; During normal times, the station shares its own spaces with the city, letting city users have leisure activities/events to reduce underutilization.

The hypothesis of flexible use is based on two heuristics. First, the word 'flexible' linguistically means 'able to change or be changed easily according to the situation,' enabling it as a solution to change across different times for addressing overcrowding and underutilization. Second, flexible use has been seen in station cases like Rotterdam Central Station and Shanghai Railway Station. In the Rotterdam Central Station case, during the Rotterdam Summer Carnival time (non-peak time of transport), the station front plaza is used for event-goers dancing; During the station's opening ceremony, the nearby neighborhoods' spaces were occupied by the station to accommodate participants. If transport disruptions happen, the same neighborhoods' spaces can be used by the station to accommodate detained passengers. In the Shanghai Railway Station case, the station's large South and North plazas are designed to accommodate transportation needs during holiday peak travel periods. During non-peak days, older adults gather and dance on this plaza in the evenings, effectively utilizing the space.

To support the spatial design for the flexible use of railway station areas, in another work package within the same research project, five major spatial design principles were developed based on corresponding heuristics, as listed in Table 1 (See also the detailed principles on the projectwebsite). In developing these principles, positive and negative cases are selected, the features of their spatial configurations are examined, and sometimes comparisons between cases are made. The positive cases include: Shanghai Railway Station (RS), the current Rotterdam Central RS, and the current Utrecht Central RS. The negative cases include: Beijing West RS, the former Rotterdam Central RS, and the former Utrecht RS. These positive cases have flexible use happening in their station areas, and have relatively less overcrowding or underutilization phenomena. In contrast, the negative successful cases lack such flexible use and experience more frequent overcrowding or underutilization. When relevant, the authors also draw on personal experience and observations from non-station cases, such as stadiums and airports. Based on these cases, the design principles are derived through iterative observations, analytical drawings, and inference. Despite these design principles being developed, their effectiveness is hypothetical, as not all of them are implemented in the real world; therefore, more validation is helpful to test their effectiveness (see Fig. 1).

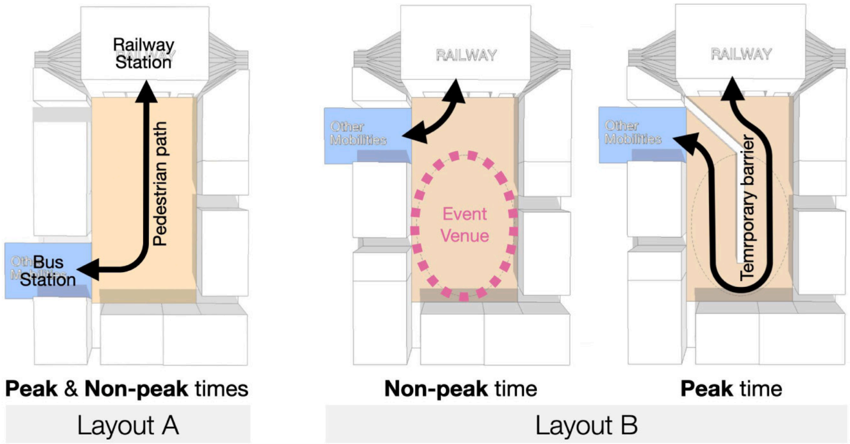

Fig. 1. Layouts that are unsupportive vs. supportive of reconfigurations during different times.

1.2. Research-by-design and agent-based simulation for design assessment

This study sees two methods – research-by-design and agent-based simulation – as potentially helpful for validating visionary design principles. **Research-by-design**, also called 'research through design' or 'study by design,' is a methodological approach where design practice becomes the primary mode of inquiry to generate new knowledge. Unlike traditional research that analyzes designs only *after* they are completed, research-by-design integrates research into the design process itself—exploring questions and generating knowledge *before* designs are built. By using prototyping, making, and iteration as research tools, research-by-design actively investigates how different design solutions and their contexts influence one another [17, p.21]. In this way, design solutions are intrinsically assessed.

Simulation is a fast-developing technology [18] used for various domains including spatial design [19]. Simulation models are typically built based on existing evidence and are applicable to new scenarios before physical implementation. This is especially useful for large, complex projects like railway stations, which are expensive to build. One powerful approach in simulation is **agent-based simulation**, which models a system by simulating interactions between individual agents and their environments.

Agent-based simulation has been commonly used in crowd movement simulation, where agents mimic real-world pedestrians, having abilities to sense the environment and make route choices and movement decisions [20–23]. In design research, studies have developed the vision ability of agents to experience spatial environments [24,25] or to mimic human–environment interactions [26, 27]. Agent-based simulation is a relatively valuable approach for spatial design assessment. This is because, in the spatial spaces practice, the spaces being designed are mostly for humans to use; Agent-based simulation, using agents mimicking humans, actually takes the end-users into core consideration in design.

1.3. Research objectives and conceptual framework

Building on the research background and technical potentials outlined above, this study sets two objectives: *(1) to address the gap in validating design principles for flexible use (which address overcrowding and underutilization in stations)*, and *(2) to explore the potential of combining research-by-design with agent-based simulation in the assessment of design principles*. To achieve these objectives, an initial challenge arises: design principles cannot be modeled through agent-based simulation, as design principles are not systems themselves. To address this, the study designed an indirect approach—applying the design principles to a design project to transform them into design proposals, then simulating the design proposals, and finally, by observing the performance of the design proposals, it is feasible to see the effectiveness of the corresponding design principles. With this methodological adaptation, this study proposes a conceptual framework illustrated in Fig. 2.

In this conceptual framework, multiple components work together to integrate and enhance one another. In the process of generating design proposals through research-by-design and the follow-up assessment through agent-based simulation, new understandings emerge, allowing critical reflections on the design principles' effectiveness. By introducing computational quantification, agent-based simulation complements traditional spatial design assessment methods like research-by-design, which rely heavily on expert judgment. In the practice of research-by-design, where design principles' effects are examined, this study also provides an opportunity to reflect on the limitations of agent-based simulation (Fig. 2). Within the framework, this study addresses a major question and a minor question:

> ***How effective are the design principles for flexible use of stations, as demonstrated through research-by-design and agent-based simulation?*** *What are the limitations of agent-based simulation in assessing complex projects like railway stations?*

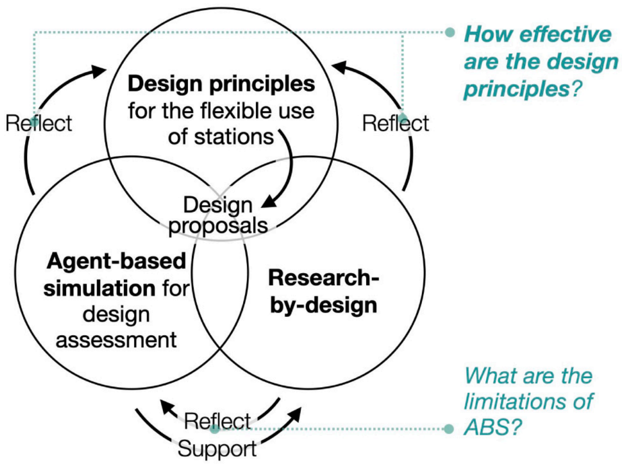

Fig. 2. The conceptual framework.

To answer these questions, this study employs the conceptual framework, develops design proposals for a railway station, assesses the proposals' performance, analyzes the corresponding design principles' effectiveness, and reflects on agent-based simulation. This study contributes to the accumulated design knowledge by providing detailed insights into the design principles. It also highlights the potential and limitations of agent-based simulation in design assessment. The remainder of this study is organized as follows: Section 2 describes the study design; Section 3 presents the assessment results; Section 4 discusses the relevant research implications, contributions, and limitations; and Section 5 concludes.

2. Study design

This section implements the conceptual framework (Fig. 2) with practical details. This study first employs the research-by-design approach, applying the design principles to Station Xtreme and generating multiple design proposals. Then, it simulates the generated proposals through agent-based simulation, followed by assessments and reflections. The following subsections explain the context of the station case (Section 2.1), the features of design proposals (Section 2.2), the settings of simulations (Section 2.3), and the logic of assessments (Section 2.4).

2.1. Context of the case

This study uses Station Xtreme – a virtual station instead of a real-world one – as the case for applying the design principles. The lack of strict real-world contextual constraints allows the case to incorporate multiple relevant features that a single real-world case might not have, and make the results more generalizable to different contexts.

This virtual case includes multiple features highly relevant to the study's research background—overcrowding and underutilization, flexible use, and station–city integration (Section 1.1). In the case's setting, a stadium is situated near the railway station, with fluctuating numbers of users transferring between the stadium and the station. The peak time number is set referencing Amsterdam Bijlmer Arena station's passenger number from its nearby stadium, Johan Cruijff ArenA [10]. This setting challenges the station design, requiring it to be supportive of flexible use to reduce overcrowding and underutilization. The station's spatial layout is set referencing the Amsterdam Sloterdijk Station area, where the station and the nearby city areas are significantly separated by traffic roads, viaducts, and open-air parking lots. This setting challenges the station design, requiring it to promote station-city integration. The origin–destination (OD) matrix of passengers, which highly relies on spatial layout, is set referencing Amsterdam Sloterdijk Station's (see Fig. 3).

2.2. Design proposals

Four district-level proposals (indexed as DX) with different features were made (Fig. 4 and Table 2). Proposals D1 and D2 have a more scattered layout with three station buildings. D1 has a landscape with many connections (i.e., pedestrian paths) and supports more reconfigurations of the connections (e.g., closing some connections during certain time periods). While Proposal D1 emphasizes the quantity of connections, D2 emphasizes the quality of connections. D1, D2, and D3 are human-centered, with pedestrian-friendly paths and human-scale buildings. In contrast, D4 is a vehicle-oriented proposal, with wide roads and a large vehicle parking area in front of the station's main entrance. The new buildings in D4 are also relatively large and tall, following a 'modernism' style. Regarding these features, this study rates the proposals with relative rankings of 'High' or 'Low', or categories of 'Yes' or 'No' (Table 2).

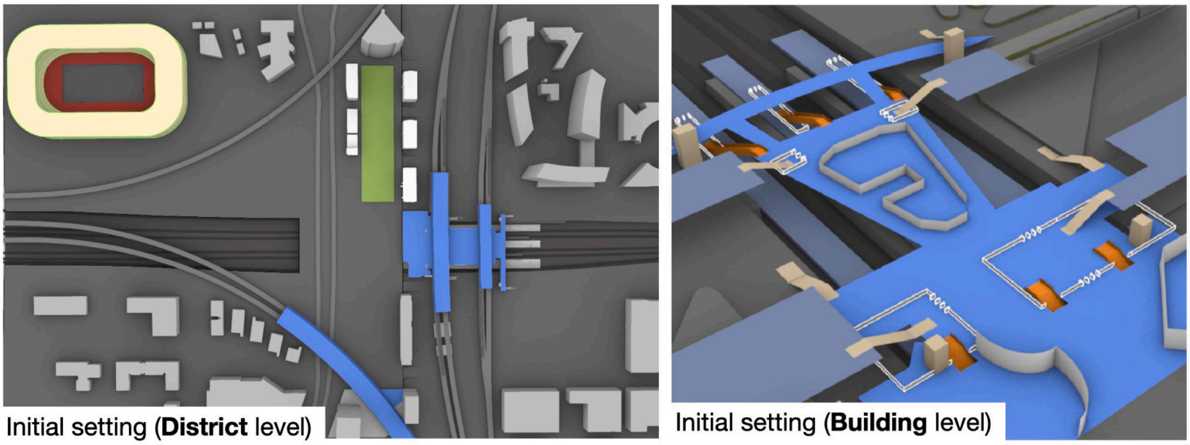

Fig. 3. The initial spatial settings of the case at the district and building levels.

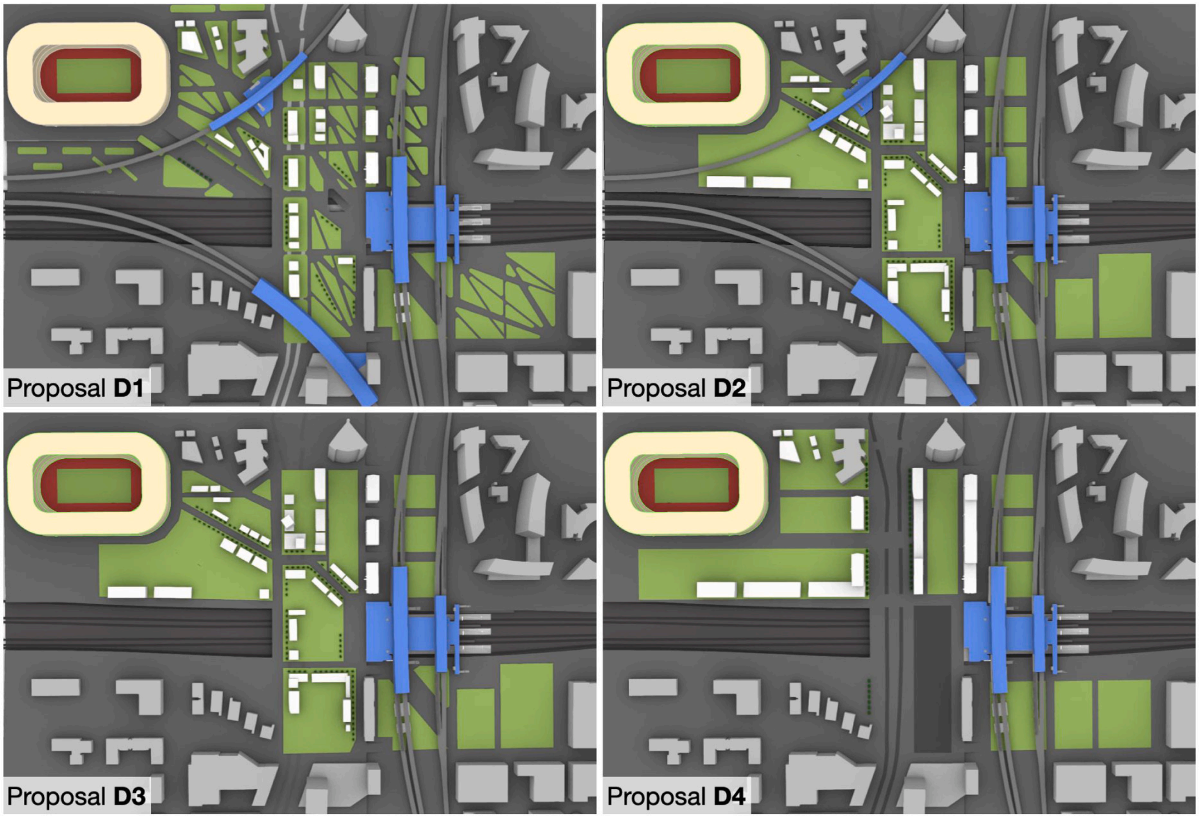

Fig. 4. District-level proposals.

Table 2
District-level design proposals.

Design proposals	D1	D2	D3	D4
Event visibility	–	–	–	–
Reconfigurability	High	Low	Low	Low
Connections	High	Low	Low	Low
Scatteredness	High	High	Low	Low
Human-centered spaces	–	–	Yes	No

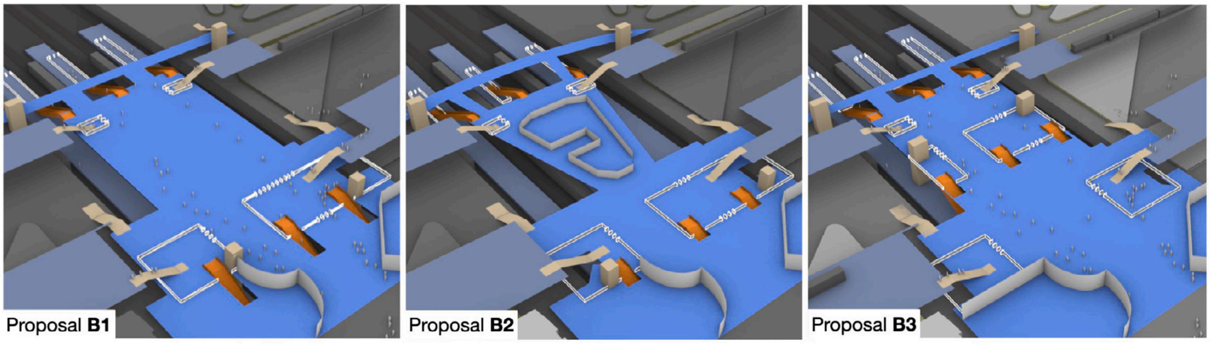

Fig. 5. Building-level proposals.

Table 3
Building-level design proposals.

Design proposals	B1	B2	B3
Event visibility	High	–	High
Reconfigurability	High	Low	–
Connections	High	Low	–
Scatteredness	High	High	Low
Human-centered spaces	–	–	–

Three building-level proposals (indexed as BX) with different features were made (Fig. 5 and Table 3). Proposal B1 and B3 support events to be held in the hall, while B2 has no large space for holding events. B1 has a wide station hall, supporting more routes (which essentially are ‘connections’ from origins to destinations) choices. B1 and B2 are more scattered regarding their layout of stairs (colored in orange in Fig. 5), while B3 is more concentrated. Regarding these features, this study rates the proposals with relative rankings of ‘High’ or ‘Low’ (Table 3).

2.3. Settings of agent-based simulation for the assessment

This study adopts the agent-based simulation framework from Enshan et al. [24]’s work. This framework provides systematic evaluation criteria for assessing stations’ performances (Section 2.3.1) and the digital tools for simulation (Section 2.3.2). This simulation framework requires agent origin–destination matrix data as a necessary setting (Section 2.3.4), provides optional settings including temporal scenarios associated with flexible uses (Section 2.3.3), and has initial settings of agent parameters (Section 2.3.4).

Of notice, in the simulations, the *inputs* are different design proposals (Section 2.2), and the *outputs* are design proposals’ performances, which are based on evaluation criteria (Section 2.3.1). Other things, including agent parameters, the OD matrix, and temporal scenarios (Section 2.3), are *settings*; Although the *inputs* and *outputs* are different from proposal to proposal, the *settings* are all the same in simulations.

Regarding the validation of the framework, according to Enshan et al. [24], this simulation framework’s overall usefulness is validated through a case study on the current and the former Rotterdam Central stations, where simulation results and real-world observations are compared; The framework’s different components have varying levels of validity—the movement simulation is more accurate while the visual simulation is less accurate.

2.3.1. The evaluation criteria for station performances

The evaluation criteria for station performance are adopted from Enshan et al. [24]’s assessment framework. Initially based on five types of user needs [28], these criteria are translated into measurable indicators:

- Safety [indicated by agents’ crowding density during *peak time*, the space capacity to accommodate stranded passengers during *disruption time*, and ’eye-on-the-street’ [29] during *normal time*]
- Transfer distance
- Ease of wayfinding [indicated by the agents’ degrees of direction change]
- Comfort of facilities [Not applicable in this study]
- Visual experience [calculated through a linear regression formula that incorporates multiple factors in agents’ views: the proportion of trees, sky, buildings, water, and the number of pedestrians]

Table 4
The OD matrix simulating the transfers between stations and other places.

Origins \ Destinations	Railway station(s)	Neighborhood [Walking]	Bike parking [Cycling]	Bus/tram stations [Bus/tram]	Car parking [Car]	Stadium
Railway station(s)	0.2[a]	0.50	0.11	0.35	0.05	[Normal time] 5 / [Peak time] 0
Neighborhood [Walking]	0.13	–	0	0	0	0
Bike parking [Cycling]	0.38	0	–	0	0	0
Bus/tram stations [Bus/tram]	0.40	0	0	–	0	0
Car parking [Car]	0.08	0	0	0	–	0
Stadium	[Normal time] 30[b] / [Peak time] 0	0	0	0	0	–

Note: [1] Each value represents a number of agents as a proportion of the total passenger count. The total passenger count is 711/h (access/egress separated) during the weekday non-rush hours.
[2] In the district-level design proposals, there are three possible stations, with 10, 2, and 1 rail tracks. The ratio of agent numbers for these stations is correspondingly set as 10 : 2 : 1.
[3] The ratio of agent numbers per hour during evening rush time : off-peak time is set as 4.75 : 1.
[a] Passengers who switch between platforms.
[b] It may seem strange here as the agent number for ‘normal time’ is higher than ‘peak time.’ This is because these scenarios are named from the perspective of the railway station instead of the stadium. Normal time is ‘normal’ for passengers in railway transport, whereas it is a kind of ‘peak’ time for people in the post-match dispersal from the stadium. The flow from the stadium is simulated for a short period of 5 min to mimic a post-match dispersal, referencing the data from Amsterdam Bijlmer Arena station [10]. Compared to the rushed egress from the stadium, ingress is typically smoother, as spectators arrive gradually over several hours before the match begins.

Table 5
Proposal comparisons.

Related design principles	Proposal comparisons	Performances to examine
(1) Make event visible	(B1 – B3)	[Normal time] visibility of events
(2) Reconfiguration-supportive layouts	(D1 – D2) (B1 – B2)	[Normal time] transfer distance; [Peak time] crowd density
(3) Quality connections	(D1 – D2) (B1 – B2)	[Normal time] visual experience, transfer distance, ease of wayfinding; [Peak time] crowd density
(4) Scattered layouts for [peak/disruption time] high capacity or [normal time] vibrancy	(D2 – D3) (B1 – B3)	[Peak time] crowd density; [Disruption time] accommodating capacity for stranded passengers; [Normal time] visibility of stores/installations, visual experience, transfer distance
(5) Human-centered spaces	(D3 – D4)	[Normal time] possibility of organizing events, visual experience

Note: When building-level proposals are compared (proposals about the main station building), they are all set within the environment of district-level proposal D1. When district-level proposals are compared, all proposals’ main station buildings are set as building-level proposal B1.

2.3.2. The digital tools for simulation

The digital tools this study uses include Rhino, MassMotion, and Python scripts. Rhino is used to model spatial design proposals, with details including sky, buildings, trees, walkable areas, and stairs/ramps. The Rhino 3D models are then imported to MassMotion (a software program for movement simulation), followed by setting the OD matrices and running the movement simulation. MassMotion generates agent trajectories and facilitates movement analysis. The trajectories are then imported into Rhino, where visual analysis is conducted with Python scripts.

2.3.3. Temporal scenarios associated with flexible uses

This study sets three temporal scenarios associated with flexible uses: normal time (weekday non-rush hours), peak times (after a football match when massive stadium spectators come to the station), and disruption time (when the railway has disruptions and trains are delayed). These time scenarios are denoted as [Normal time], [Peak time], and [Disruption time] in this study. In different temporal scenarios, different numbers of agents are used (Table 4), and different types of user experiences are examined (Table 5).

2.3.4. Origin–destination (OD) matrix

This study deduces the Origin-Destination (OD) matrix (Table 4) based on the data published on the NS website [30]. This website documents all the stations in the Netherlands with their number of overall passengers, passengers of transfer, and modal split. The number of passengers transferring between the new stadium and the station during peak times is derived by referencing data from Amsterdam Bijlmer Arena Station. The OD matrices also incorporate temporal fluctuations.

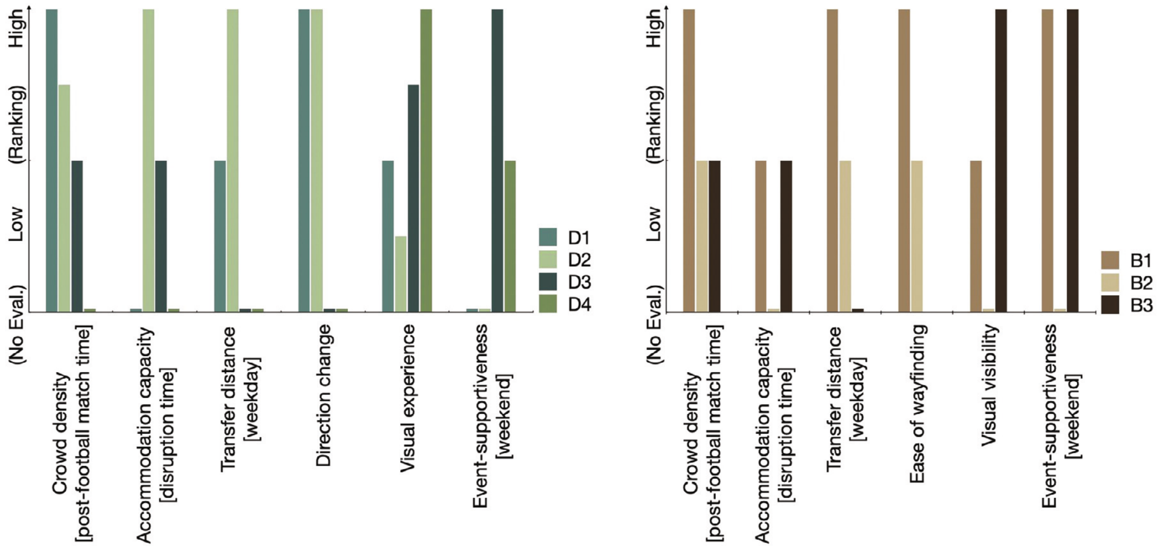

Fig. 6. Proposals' performance (the vertical axis denotes each proposal's relative ranking among all related proposals).

2.3.5. Agent parameters

The agent characteristic parameters are defined in two ways: The first is the agent behavioral parameters being defined in MassMotion's default setting, based on various scientific research works [31]. These parameters include individual optimum moving speed, direction preference, height, etc. The second is the agent's visual perceptual ability being defined by Enshan et al. [24], based on a series of technical work extracting data from street images and comparing with human ratings.

2.4. Make comparisons between design proposals

This study compares the design proposals, observing their corresponding performance differences, to investigate the effects of principles on station performances (Table 5). The performance examination considers several aspects: spatial scales and spatial scopes, time, people, and experiences. For example, when analyzing transfer distances, these aspects are specified. Different people have different sensitivities to the transfer distance in the station area. Stadium spectators are less sensitive to distance, while railway travelers are more sensitive to distance. Therefore, when analyzing transfer distance, this paper differentiates the groups of agents that represent these people. Building-level proposals only influence the journeys that happen within the station buildings, while district-level proposals affect the journeys that happen on the district level. Therefore, when analyzing transfer distance, this paper specifies the spatial scope of journeys.

3. Results

This section presents the simulation results. In general, the results show that every proposal has some strengths and limitations (Fig. 6). D2 and B1 excel the most in the performances. The following subsections explain each design principle's effects on the related proposals.

3.1. The effects of principle 1 (event visibility)

Fig. 7 shows the simulation results of proposals B1 and B3 during weekends when an event is going on. In B1, the event is located in the central area, while in B3, the event is located near the main entrance. The event in B3 is visible to 47.47% agents during their journeys, while the event in B1 is only visible to 21.23% agents during their journeys. This is because more agents pass by the main entrance area. This shows that when adopting design principle one, the location of events matters. The event location should be considered with respect to pedestrians' routes.

3.2. The effects of principle 2 (reconfiguration-supportiveness)

During the stadium peak times, in D2, when massive passengers move towards stations, some paths (see paths 9 and 10 in Fig. 9 - top) can be closed to avoid overcrowding. In D1, on-site staff can even guide pedestrians to the normally redundant paths (i.e., the path colored in yellow in Fig. 8, or the path 11 in Fig. 9 - bottom) to reduce the crowd density further. D1 enables lower crowd density than D2.

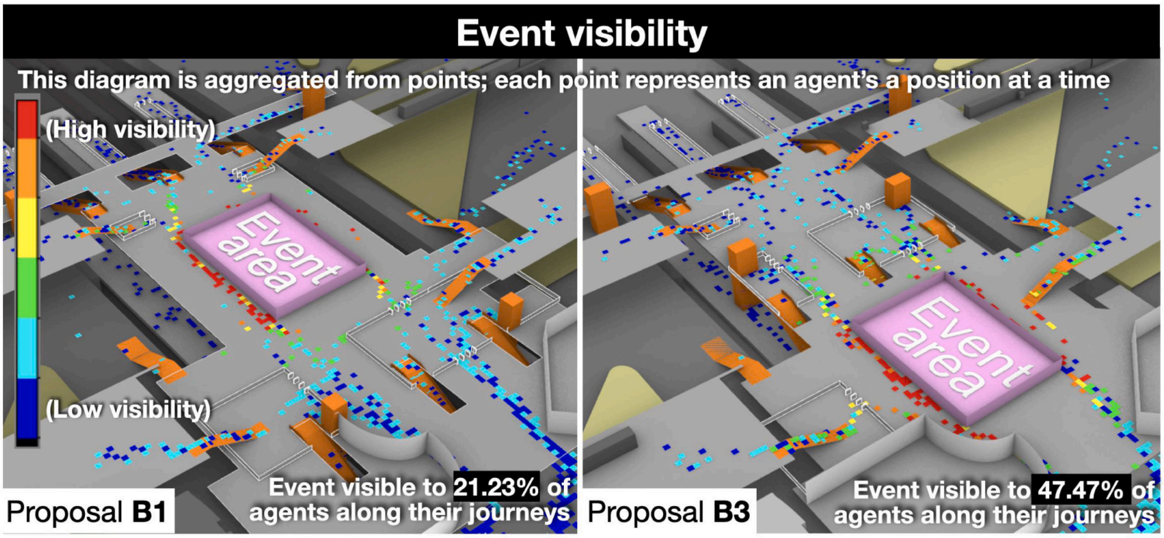

Fig. 7. Simulation results of proposals during weekends.

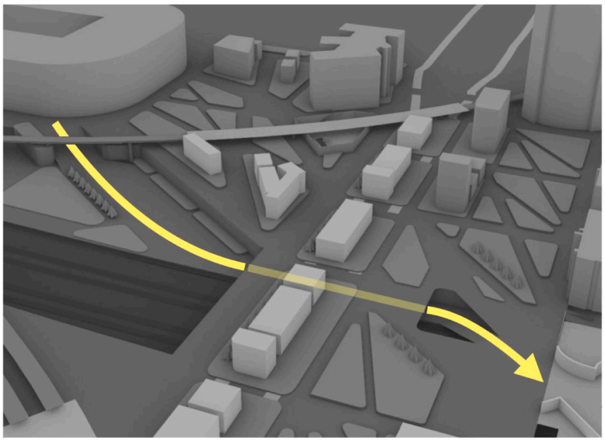

Fig. 8. The shortcut path in proposal D1.

Proposal D1 is more reconfiguration-supportive in terms of paths. Hypothetically, in D1, when the main path needs maintenance (e.g., when repairing streets or digging to fix pipelines), pedestrians can alternatively use the redundant paths. In D2, however, as there is only one main path, there will be no such alternative. One option for D2 is to widen the main street to avoid overcrowding during maintenance, but that could lower the visual experience as the street becomes wide and visually boring.

3.3. The effects of principle 3 (quality connections)

Proposal D1 has many walkable paths (connections) and emphasizes the quantity of connections, while D2 has fewer connections and emphasizes the quality of connections. D1 has more connections and supports more configurations, enabling it to have a lower crowd density during peak times (see Section 3.2, Fig. 9). With a dense, walkable network, D1 also provides more route choices. Some routes are comparatively shorter in D1 than in D2 (see routes 5 vs 5'). However, the many connections in D1 come with some costs. As cut by a dense pedestrian street network, D1 has less suitable plots for large-sized buildings (see the new buildings in Fig. 10 - middle, colored in white), and less green space (see the green areas in Fig. 10 - middle).

In the simulation, counter-intuitively, agents in D1 walk longer distances. This may be due to the algorithm used in the simulations. The simulation is based on the social forces algorithm [32], which has a force that models attractive effects (e.g., pedestrians stay close to friends, or are attracted by interesting objects). As D1 has more routes, agents may sometimes be 'attracted' to some routes that are not necessarily the shortest.

The street visual quality and route direction changes are similar in the two proposals. Only in a few spots, D1 has higher visual quality values (see locations 3, 4, 3', 4' in Fig. 10 - bottom). In summary, the district-level dense walkable network enables lower

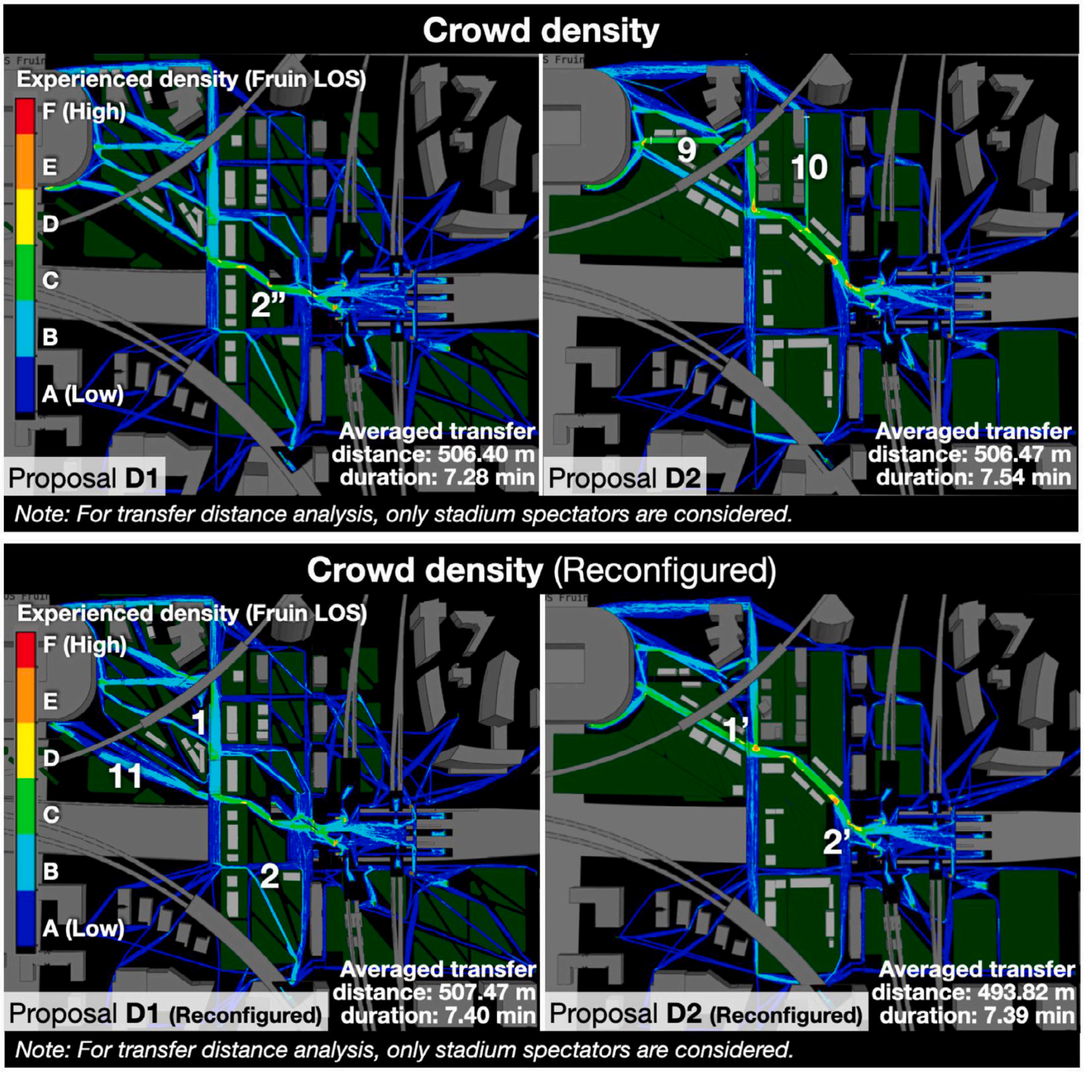

Fig. 9. The crowd density in proposals D3 and D4.

crowd density during peak times, makes negligible differences in the direction changes and visual perception of agents, and does not necessarily lower the agents' walking distance.

Building-level proposal B1 has more connections (as it supports more route choices in the hall area) than proposal B2. The crowd density is similar in both proposals (Fig. 11 - top). In B1, thanks to the direct routes (see routes 6 and 7) in the large hall spaces in B1, the transfer distance (measured within the station buildings, including platforms) is shorter, and the direction change is less (Fig. 11 - middle and bottom).

3.4. The effects of principle 4 (scattered layouts)

Regarding the railway station building(s), proposal D2 is designed in a scattered layout (with three station buildings at three locations), while D3 is designed in a concentrated layout (with only one station building). During peak times, the crowd density in D2 is lower than in D3 at some points (see locations 17 and 17' in Fig. 12 - top). The density difference is not significant because the passenger volume shared by the two small stations is not significant (the small stations in D2 only add three extra tracks to the main stations' 10 tracks). During disruptions, D2 also has a better accommodating capacity for stranded passengers (see crowding accumulated at locations 15 vs 15' in Fig. 12 - middle). The averaged visual quality is slightly higher in D2 than in D3 (Fig. 12 - bottom). This may be due to the higher proportion of agents going through the high-quality main path in D2. Another drawback of the scattered layout is that it adds to the difficulty of wayfinding. When people have to choose one among three stations, they may mistakenly go on the wrong paths.

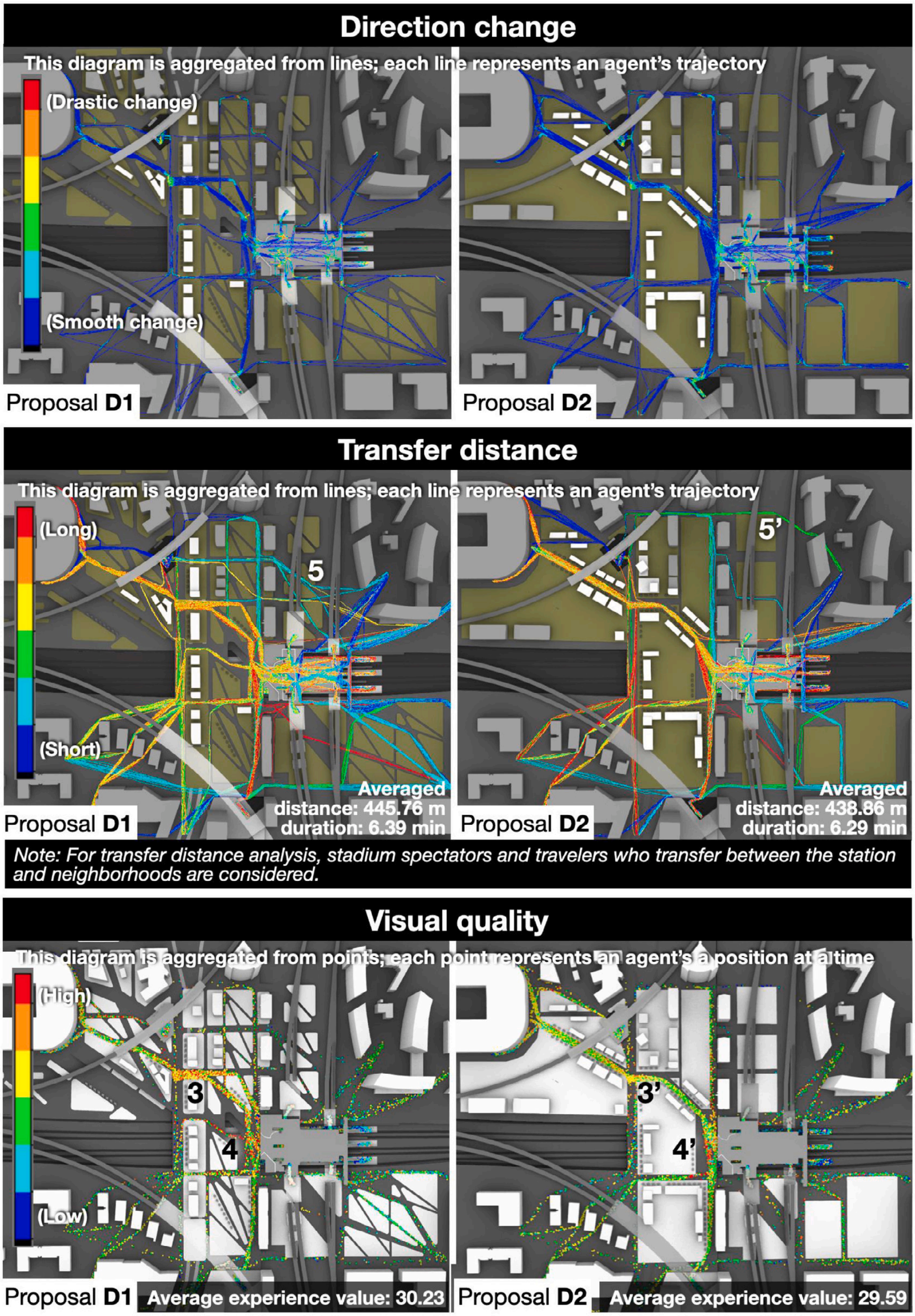

Fig. 10. The direction change, transfer distance, and visual quality in proposals D1 and D2.

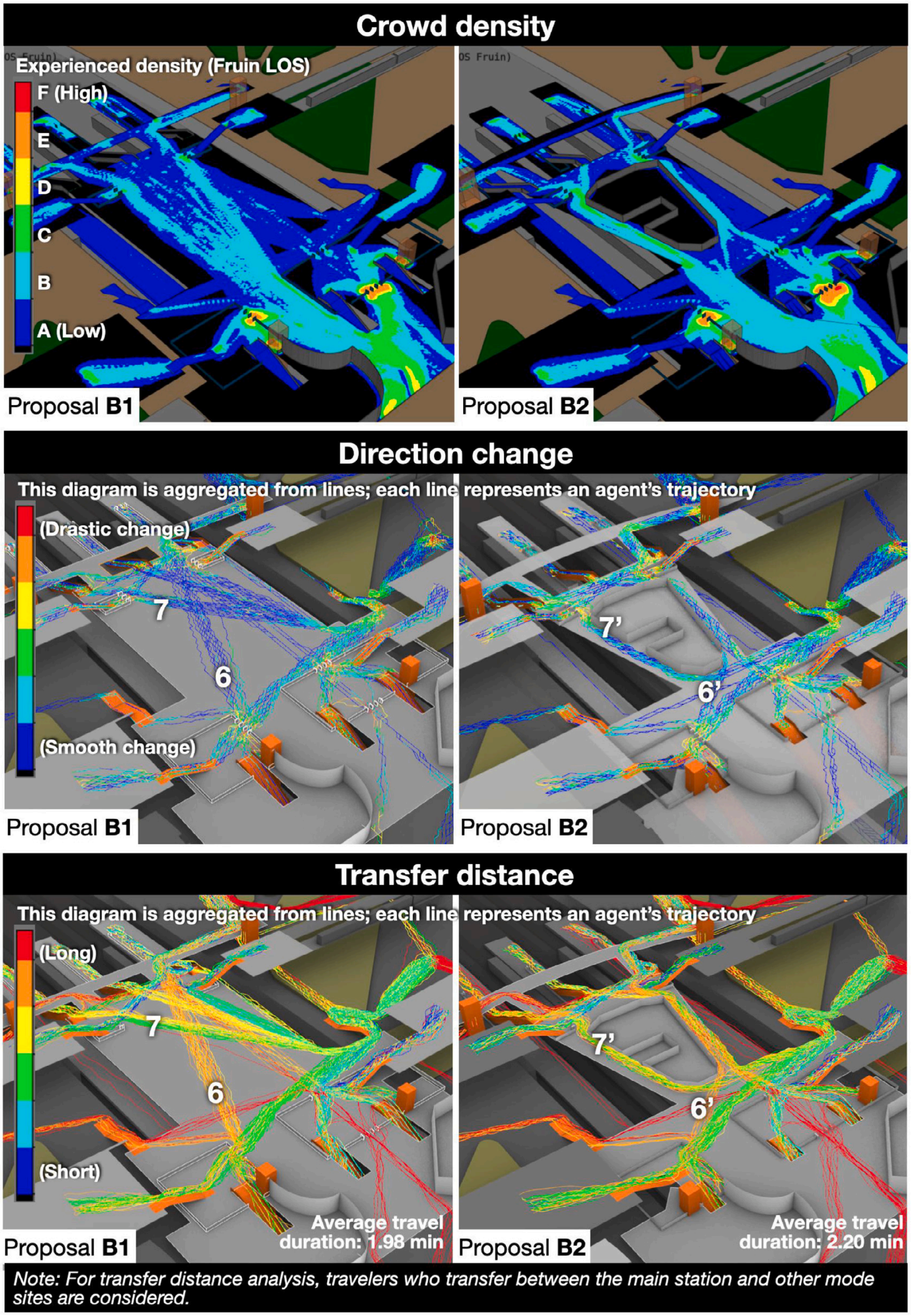

Fig. 11. The crowd density, direction change, and transfer distance in proposals B1 and B2.

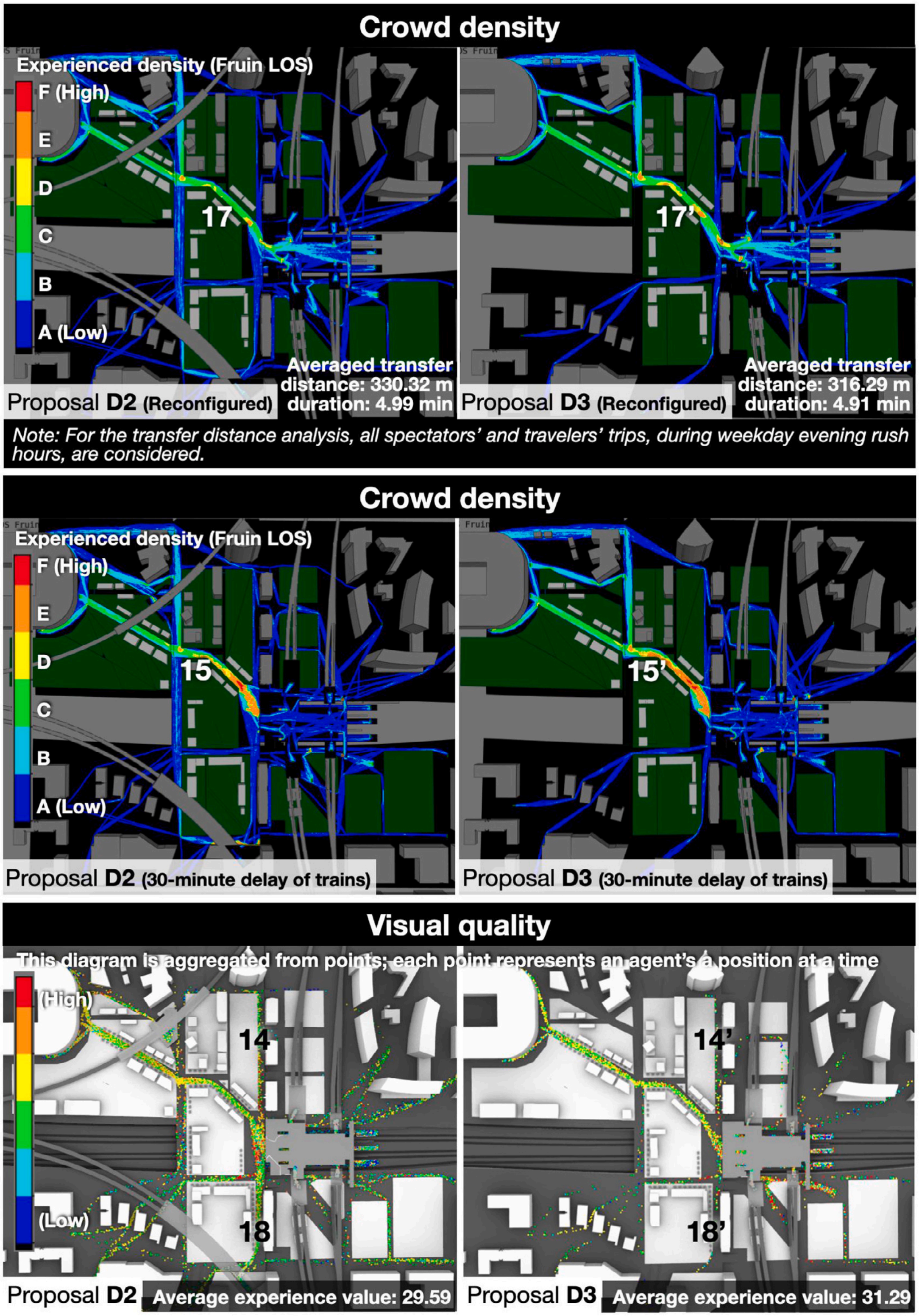

Fig. 12. The crowd density (during rush hours and disruption times) and visual quality in proposals D2 and D3.

Regarding the stairs and gates, proposal B1 is designed in a scattered layout, while B3 is designed in a concentrated layout. However, locally, B1 also has an area where three stairs are concentratedly located (area 12 in Fig. 13 - middle). In general, the crowd density in B3 is higher during peak times (see locations 14' in Fig. 13 - top). However, the crowd density is not a big issue for B3 during peak time, as the bottlenecks occur at the gates for both proposals B1 and B3.

During disruption times, the stranded agents aggregate in the area where stairs are concentrated (location 13' in proposal B3, location 12 in proposal B1). B1 needs less managerial effort to redistribute the aggregated passengers in area 12. B3 needs more managerial effort to redistribute the more aggregated passengers in area 13' (Fig. 13 - middle). In this sense, B1 has a higher capacity to accommodate stranded passengers.

Surprisingly, B3, with a more concentrated layout of stairs—which would intuitively lead to an assumption of shorter transfer distances, actually results in longer average transfer distances (of agents switching between platforms). After further analysis, it is observed that in B1, stairs are more scattered and evenly positioned, so agents can switch between platforms using the nearby stairs. In B3, some agents need to take longer routes to the stairs further away (see Fig. 13 - bottom). This suggests that the initial assumption was based on a limited understanding of layout, considering only the stairs and missing the platforms. When platforms are considered, the initially 'concentrated' layout – regarding only stairs – turns out to be actually 'scattered.'

In summary, the above results and reflections show that scattered layouts ease the crowd density during peak times and increase the accommodating capacity during disruption time, but potentially decrease the district-level experience of visual quality, and add to the difficulty of wayfinding.

3.5. The effects of principle 5 (human-centered spaces)

Proposal D3 is relatively more human-oriented, while D4 is more vehicle-oriented. D3 has human-scale buildings and streets, and it supports large events (to be held in front of the station) to enliven the environment. In contrast, D4 has wide streets and large parking spaces for vehicles; it does not support large events (unless all the transport activities stop, i.e., no buses, trams, and cars come and go to stations, which is practically not feasible). Therefore, during non-peak times, the environment in D4 will be emptier and lifeless (Fig. 14). In summary, the results show that human-centered design provides more opportunities to enliven the environment.

Surprisingly, according to the simulation, the average visual quality value is slightly higher in D4 (=31.65) than in D3 (=31.29). This count-intuitive result may be due to the limitations of the current simulation approach, which does not include perceived distance. In reality, humans are able to visually perceive the distance of objects or the depth of space, so a space with buildings far away is less lively than a space with buildings nearby. Additionally, when crossing the wide streets in D4, people generally have negative feelings of fearing being hit by vehicles. These patterns are not captured by the current simulation approach. This necessitates improving the simulation approach in the future.

4. Discussions

4.1. Research implications

According to Alexander, design principles (what he calls patterns) are essentially *solutions* for *problems* under certain *contexts* [33, p.314]. In the design practice, the contexts, problems, and solutions are often not linearly one-directionally developed; rather, they usually iterate and accumulate during design [1]. Even commonly for designers, creating solutions helps uncover and define the problems or contexts they address [17, p.455]. This study also provides this kind of knowledge accumulation. With the design principles being assessed, their suitable specific contexts become clearer. For example, considering proposals D1 and D2, reconfiguration-supportiveness is a highly relevant station quality in the context where flow bottlenecks exist (without bottlenecks, reconfiguration is not necessary) (Fig. 15). With the design principles being assessed, their interrelationships also become clearer. For example, considering proposals D1 and D2, 'quality connections' enable 'reconfiguration-supportiveness'; in Proposals B1 and B3, making stations 'reconfiguration-supportive' enables 'making event visible' (Fig. 15).

Negative correlations are also discovered. For example, in proposals D1 and D2, scattered layouts add to the managerial difficulty of reconfigurations (when different groups of people go to three different station buildings, it is hard to make path reconfigurations satisfying all the groups) and the difficulty of wayfinding (Fig. 15).

4.2. Research limitations and future directions

The station contexts/settings in this study are limited. Firstly, the modal split is set based on data from the existing case, while the modal split can change at different times. Modal split can influence the results. Secondly, each case in the built environment is situated in its particular spatial context, and transferring its experience to other cases requires considerable generalization efforts. More challenging is that stations are the type of buildings with the most diverse variants [34]. This study's case is just one representing its similar counterparts, and there are many other significantly different cases beyond.

The station performance considered in this study is limited. This study focuses on user experiences, which can be assessed with the advantage of agent-based simulation. However, in the development and daily operations of railway stations, there are many other types of performance that other actors (beyond users, i.e., developers, railway companies, governments, NGOs, etc.) care about. For example, the cost and return to build stations (financial performance), the programming adaptability to future changes, the managerial capacity needed to run stations, the vehicle transportation efficiency, and the reserved spaces for nature [35–39]. Acknowledging these limitations, this study outlines work for future research: expand studies on more station settings and performances.

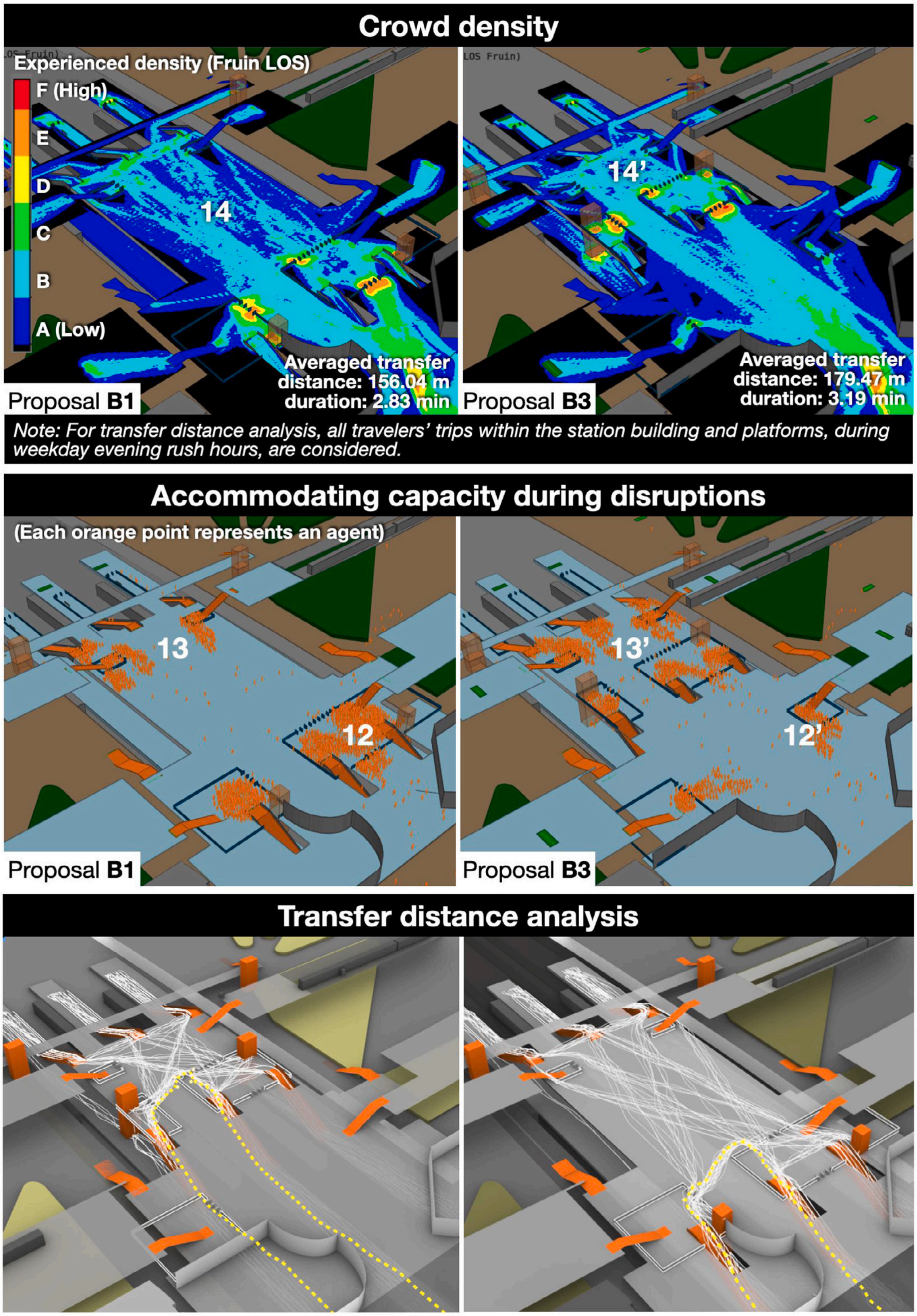

Fig. 13. The crowd density, accommodation capacity during disruptions, and transfer distance in proposals B1 and B3.

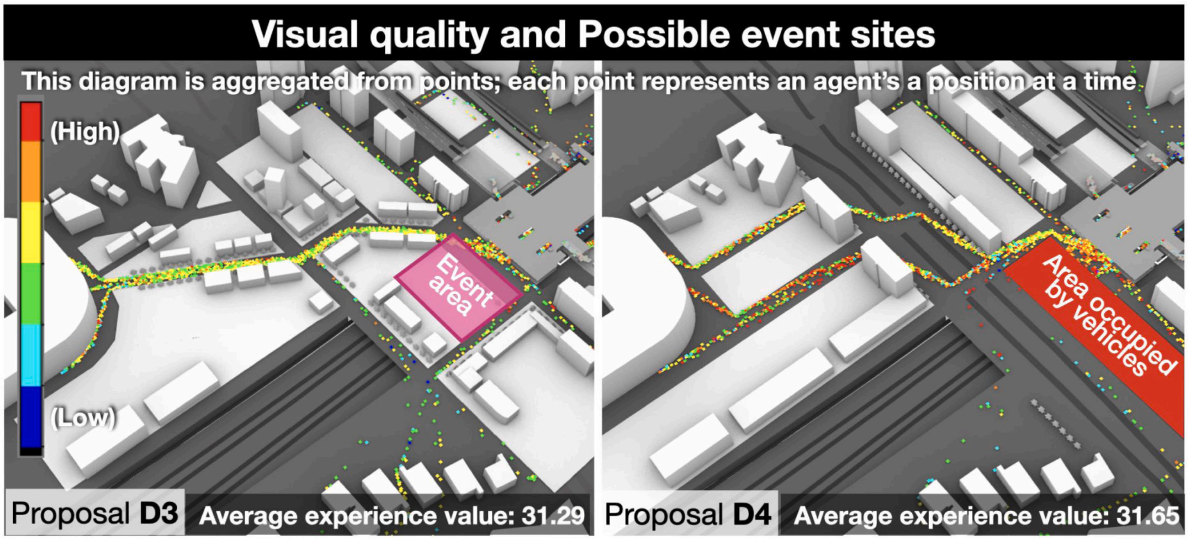

Fig. 14. Visual quality and potential event sites in proposals D3 and D4.

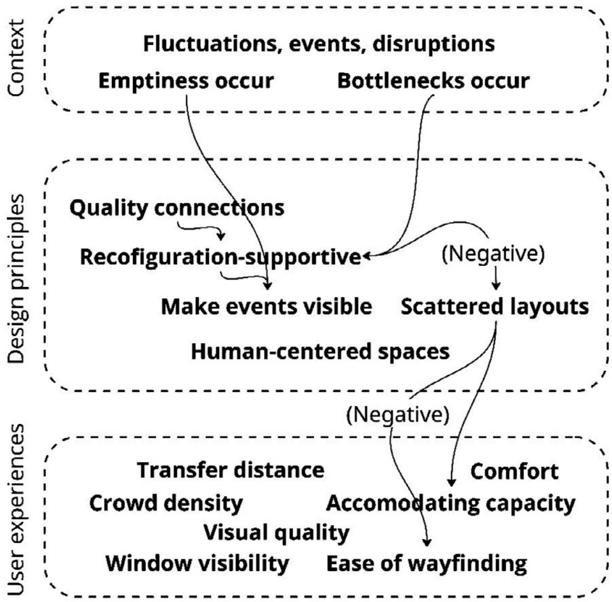

Fig. 15. The interrelationship between contexts, principles, and user experiences.

5. Conclusions

This study addresses one major question. In Section 1, regarding design principles for the flexible use of station areas, this study presented the major question: How effective are the design principles for flexible use of stations, as demonstrated through research-by-design and agent-based simulation? The results confirm that the principles are generally effective, each with its own strengths and limitations. For design and policy-makers, the following executive summary is provided:

(1) For addressing overcrowding and underutilization in railway stations, design proposals at both district and building levels can promote flexible use by incorporating the following features: event visibility, reconfiguration-supportiveness, quality connections, scattered layouts, and human-centered spaces.
(2) However, quality connections may require more investment to build and occupy more usable land; Scattered layouts may increase wayfinding difficulty and require greater managerial effort for reconfiguration (Fig. 15).

This study also addresses a minor question: What are the limitations of agent-based simulation (ABS) in assessing complex projects like railway stations? Reflecting on the results, this study argues that current ABS models have not yet incorporated more human abilities, including subjective feelings of safety, wayfinding capacity, and humans' ability to perceive spatial depth. These limitations of ABS highlight the usefulness of other traditional means for design assessment, such as expert evaluations and designers' analytical drawings.

By addressing the research questions, the study contributes to the accumulated design knowledge of the design principles of flexible use. Additionally, this study contributes to the methodology of design principles validation by its novel conceptual framework that integrates research-by-design and agent-based simulation (ABS) (Fig. 2). Although ABS cannot model abstract principles directly, this framework shows a viable route for translating principles into design proposals that can be tested. Originally developed to assess specific design principles, this framework is also transferable to similar studies of design principles.

CRediT authorship contribution statement

Chen Enshan: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Stefan van der Spek:** Supervision, Project administration, Methodology, Conceptualization. **Anan Tian:** Visualization, Data curation, Conceptualization. **Manuela Triggianese:** Supervision, Methodology, Conceptualization. **Frank van der Hoeven:** Supervision.

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Declaration of competing interest

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

Data availability

Data will be made available on request.

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