Evaluate user satisfaction for urban design of railway station areas
An assessment framework using agent-based simulation

Enshan, Chen; van der Spek, Stefan; van der Hoeven, Frank; Triggianese, Manuela

DOI
10.1016/j.eiar.2024.107685

Publication date
2025

Document Version
Final published version

Published in
Environmental Impact Assessment Review

Environmental Impact Assessment Review 110 (2025) 107685

Contents lists available at ScienceDirect

Environmental Impact Assessment Review

journal homepage: www.elsevier.com/locate/eiar

Evaluate user satisfaction for urban design of railway station areas: An assessment framework using agent-based simulation

Chen Enshan [a,*], Stefan van de Spek [a], Frank van der Hoeven [a], Manuela Triggianese [b]

[a] *Department of Urbanism, Faculty of Architecture, Delft University of Technology, the Netherlands*
[b] *Department of Architecture, Faculty of Architecture, Delft University of Technology, the Netherlands*

ARTICLE INFO

Keywords:
Mapping
Environmental psychology
Crowd simulation
Vision analysis

ABSTRACT

Aims: Railway station areas can play a crucial role in promoting sustainable development if integrated with cities and be fluctuation-responsive through effective urban design. However, during the design stage, assessing the station areas' performance, of which user satisfaction is indicative, is challenging due to methodological limitations. Agent-based simulation (ABS) is promising as it can link spatial features with agents' behavior features. This research questions to what extent ABS can help assess the urban design of station areas.
Methods: This paper adopts the user pyramid as the theoretical framework, which outlines five types of user needs: safety, speed, ease, comfort, and experience. The paper selects indicators linking satisfaction and spatial features at the district and building levels. These indicators are measured in the simulation of the station system using digital tools, including MassMotion and Python scripts. The theory, indicators, and tools, in combination, serve as an assessment framework. Rotterdam Central Station is used as a case to demonstrate how the framework works.
Results: The framework is capable of assessing design alternatives by identifying changes in user satisfaction. It can be applied on the district level (at a scale of 250 m) with substantial details to inform design decision-making, and it is useful during the design stage when only limited data is available. This paper strengthens the scientific knowledge of railway station areas through the multidisciplinary literature review that translates user needs for urban design use, and it advances the digital means to visualize user satisfaction affected by design.

1. Introduction

Railway stations play a crucial role in promoting sustainable development. Rail transport is more energy-efficient than any other motorized traffic means on the ground (Newman and Kenworthy, 1999; Loo and Comtois, 2016). To increase the use of rail transport, stations should be able to attract passengers (Kasraian et al., 2016). Also, compact development around railway stations provides cities with larger growth potential and curbs urban sprawl (Shikata et al., 2013). If railway stations are well-integrated into the structure of the cities and their direct surroundings, then they can contribute to making the city competitive, realizing economic potential from real estate development, and so on (Bertolini, 2008; Ibraeva et al., 2020; Priemus, 2008; Peters and Novy, 2012; Dai et al., 2019; Cheng et al., 2021). With these motives, a research topic, namely 'station-city integration', has long been discussed.

Stations have been studied in engineering, architecture, urban planning, and management. Engineering design efforts have been made for optimizations of scheduling and assignment of resources (Shafahi and Khani, 2010); Architecture can contribute by making stations visually attractive as gateways to city centers (Richards and MacKenzie, 1986); While management and urban planning deal with the positioning of station sites during decision-making and making stations more accessible to passengers (Yin et al., 2015; Wang, 2022; Borghetti et al., 2021). Besides these traditional fields for station design research, urban design in practice is shown to be critical for station-city integration (Peters and Tolkoff, 2016; Triggianese, 2015; da Conceição, 2015). Urban design, which primarily deals with public space and users (Carmona et al., 2010; de Jonge and van der Voordt, 2002), is even more relevant for stations considering the past decades' planning paradigm shift from vehicle-oriented to human-oriented (Bertolini, 2020).

* Corresponding author at: Building 8, Julianalaan 134, 2628 BL Delft, the Netherlands.
E-mail address: e.chen@tudelft.nl (C. Enshan).

https://doi.org/10.1016/j.eiar.2024.107685
Received 26 March 2024; Received in revised form 20 September 2024; Accepted 23 September 2024
Available online 30 September 2024

1.1. Assess urban design toward station-city integration and fluctuation-responsive

An ongoing PhD project, including this study, is being conducted to explore the contribution of urban design to station-city integration. This project consists of a problem statement, an assessment framework, and design principles (Fig. 1). This project found a particular issue with stations, which is the fluctuation in use, and it requires stations to be fluctuation-responsive.

The use of stations typically fluctuates, especially during events. Events across different temporal scales (Carmona et al., 2010) can cause overcrowding during peak times and emptiness during non-peak times. These events include daily rush-hour commuting, multi-weekly sports events, and yearly holidays. Overcrowding is a safety concern, and emptiness is a waste of space resources, both of which decrease user experience. Therefore stations should be fluctuation-responsive. Overcrowding and emptiness can either be reduced or exacerbated during station-city integration. This is because cities can positively bring stations with more accommodating capacities and more users. Cities can also negatively bring more conflicting use and empty space. Therefore, assessment of design proposals during the design stage is necessary to ensure design solutions take advantage of the positive impact while avoiding the negative.

Spatial and human aspects are inseparably considered during urban design. Spatial configuration facilitates users' needs, and user satisfaction indicates spatial performance (Fig. 2). However, evaluating user satisfaction in urban design proposals for railway station areas remains challenging due to the limitations of existing digital tools, as described in the following two sections.

1.2. Existing methods in the urban design field

Various digital methods and tools are available in the field of urban design (Fig. 3). For example, space syntax, accessibility analysis, connectivity analysis, proximity analysis, resilience analysis, isovist, visibility analysis, eye-tracking, computer vision, vision analysis, movement simulation, virtual reality, statistical index analysis (Jehle et al., 2022; Stojanovski, 2020; Lu et al., 2022; Benedikt, 1979; Chen et al., 2021; Hollander et al., 2023; Liu, 2020; Zhang et al., 2023; Hillier, 2015; Yu et al., 2021; Piga and Morello, 2015). They vary in modeling strategies, content being addressed, and data dependencies.

These methods use different modeling strategies to represent real-world systems. Network-based methods treat systems as networks consisting of lines and nodes, such as railway networks and city street networks. Space-based methods treat systems as the sum of space units or grids. For example, a plaza can be seen as a plane with hundreds of 1 m × 1 m space units combined. Agent-based methods treat systems as being composed of agents that interact with each other and with their environment. For example, a plaza can be seen as a physical plane with human users upon it, where these users interact with each other and can interact with the environment by moving and seeing (Fig. 4).

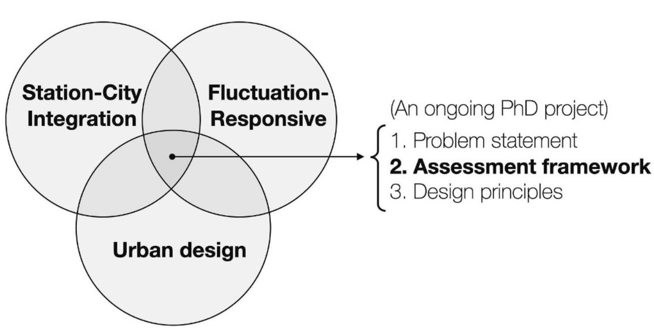

Fig. 1. This paper is part of a PhD project at the intersection of three topics.

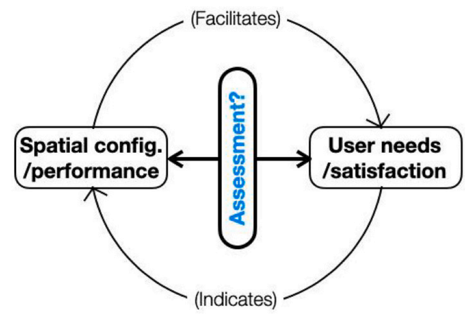

Fig. 2. Space and users are interrelated in urban design.

In terms of the content being dealt with, some primarily address spatial aspects, while others can also address human aspects. For example, connectivity analysis investigates purely the physical structure of a network. In contrast, movement simulation builds not only the physical environment but also the human-like agents moving in the environment.

These methods have different data dependencies. Some methods require real-world data from the investigated projects. For example, when eye tracking is used to analyze a project, photos of the project are typically needed, or alternatively, participants are put into the project environment for experiments. Participants' eye attention is influenced by the detailed elements of the real-world scene. In contrast, some other methods do not require real-world data from the investigated projects. This is possible because these methods use universal data from other projects or universal laws. For example, a visibility analysis can simply use (unbuilt) 3D models instead of photos of the investigated projects. Because whether sight lines are blocked or not follows the universal physical law of light (Fig. 5).

1.3. Agent-based simulation

Among the above methods, agent-based simulation (ABS) is the most promising approach for assessing user satisfaction in designing railway station areas.

Thanks to its modeling strategy, ABS provides high-resolution results and links spatial and human aspects better. For research of railway station areas on a spatial scale as "small" as several hundred meters, agent-based simulation can specifically show qualities of certain spaces (or space units) that are actually used by agents (Fig. 4). In contrast, the network-based methods abstract much of the reality into lines and hence barely provide any insights; space-based methods show the qualities of all space units regardless of whether they are being used or not (Fig. 4). Beyond the high-resolution modeling of space, ABS, with agents' parameter settings, better represents human features than other methods.

Agent-based simulation (ABS) does not require real-world data from the investigated projects, making it suitable during the design stage. Project-specific real-world data does not exist during the design stage as design proposals are not yet built. ABS takes the 3D models of design proposals as input and the set parameters of agents using data, scientific evidence, or knowledge developed in other projects or research fields, such as environmental psychology and behavior (Gifford, 2001).

Despite the promising potential, Agent-based simulation (ABS) is limitedly used in the design practice of railway stations. It has been used to assess safety with movement simulation in basic scenarios such as overcrowding and evacuation (Dubroca-Voisin et al., 2019; Pu et al., 2022). Other diverse user perceptual and spatial aspects remain unexplored by ABS. In fact, in design practice, other user perceptual aspects are largely evaluated by designers' manual analysis based on their personal hypotheses.

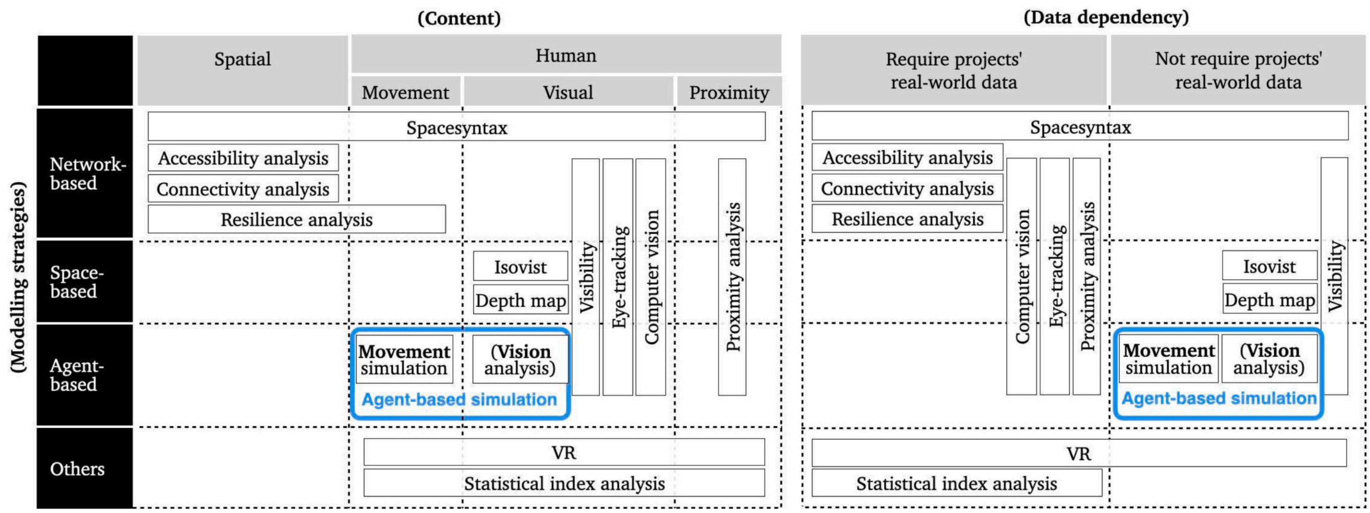

Fig. 3. Some common methods used in urban design field.

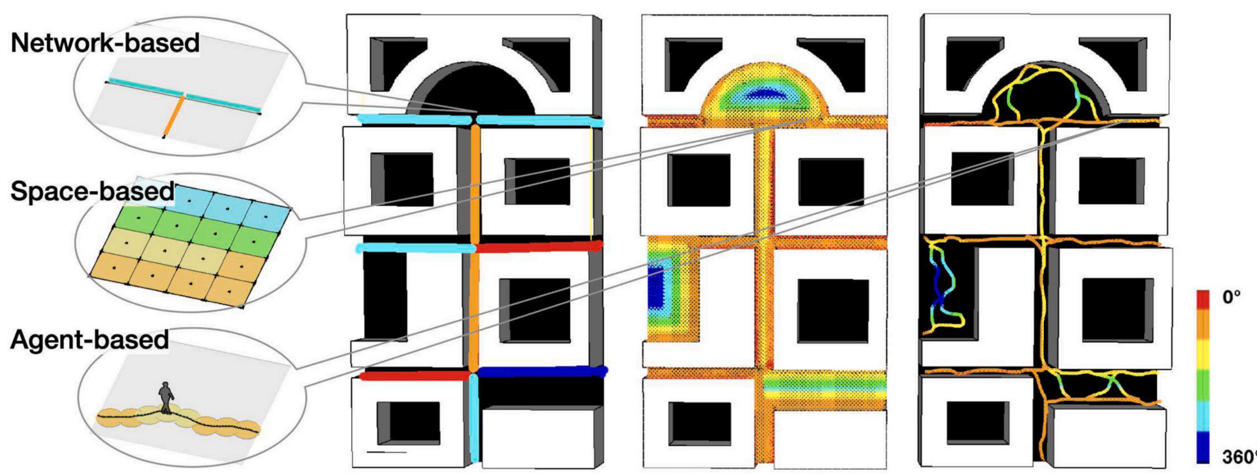

Fig. 4. Exemplary eveluation of spactial openess using different approaches.

Fig. 5. The structure of this study.

1.4. Research gap and research questions

The above introduces a research gap through an extensive overview. Assessing urban design alternatives is critical for ensuring the positive effects of station-city integration and making station fluctuation-responsive. To facilitate this assessment, agent-based simulation is the most promising among many existing analytical methods. However, it is currently limitedly used only for safety evaluation, without considering other diverse human and spatial aspects.

Aiming to fill this research gap, we set the research question: To what extent can agent-based simulation help assess user satisfaction to facilitate the urban design of stations and station areas (that are integrated with cities and fluctuation-responsive to events) (Fig. 6)? The expected outcome of this research is an assessment framework, and two sub-questions are proposed: 1) Is the developed assessment framework effective in identifying the user satisfaction changes caused by different design alternatives? 2) What is the usage of this framework in practice?

This paper constructs the assessment framework by integrating theory, indicators, and digital tools. During this construction, the paper does a multidisciplinary literature review that translates user needs for urban design use, strengthening the scientific knowledge of railway station areas. The paper also does software development, advancing existing digital tools besides their existing functionality.

The remainder of the paper is organized as follows: Chapter 2 describes the methods. It defines the station area, user needs, and indicators. Chapters 3 and 4 apply these methods in Rotterdam Central Station and analyze the results. Chapter 5 discusses the implications of the research findings, and Chapter 6 concludes (Fig. 7).

2. Methodology

This chapter develops the assessment framework, which consists of a theoretical framework, indicators, and digital tools. In the whole assessment process, the theoretical framework and indicators are the settings of the agent-based simulation, spatial design proposals are the inputs, and the user satisfaction mappings are the outputs (Fig. 8).

2.1. Theoretical framework

Based on a reoccurring survey of all Dutch rail stations, Mark Van Hagen (2015) outlined a pyramid of customer needs with five types of user needs of railway passengers: safety, speed, ease, comfort, and experience (Fig. 9). There are managerial interventions to satisfy these needs, such as music, colored light, and infotainment (Van Hagen, 2011). While this user pyramid is currently only used to inspire management interventions, it can also be linked with urban design. Various kinds of knowledge make it possible to link user perceptions with spatial qualities, as detailed in Sections 2.3 and 2.4. Before establishing the spatial link, it is necessary to articulate the spatial scale of the railway station area, as described in the following Section 2.2.

2.2. The spatial scale (250 m) of railway station areas

The 'railway station area' is a concept with different meanings on various spatial scales for different people. To some people, the most important are the station buildings; to some people, their perception of the stations includes the surrounding city areas, while to others; stations are embedded in local city mobility networks and the regional railway networks. To some extent, 'station buildings', 'station areas', and 'railway networks' are inevitably inter-influenced by each other. These

Fig. 6. The position of the research question.

different kinds of understanding are all true depending on the spatial level at which stations are analyzed (Du et al., 2021). Research on different levels typically addresses different aspects of railway stations, such as strategical synergy on the regional level (Yin et al., 2015), programming competition against old centers in the city (van den Berg et al., 1998), accessibility on the district level (Borghetti et al., 2021), and model integration on the building level (Shikata et al., 2013) (Fig. 10, left). As an urban design study, this research deals with station areas on the district level.

Even specifically on the district level, there are various existing approaches to define the range of station areas, such basing on walkable radius, functional-historical elements, topographic, and a development perimeter (Bertolini and Spit, 1998). The walkable radius approach is possibly the most popular because it is simple and can be applied across different cases. With a slight variance in different literature, this radius value typically lies between 500 and 700 m distance or a 5- to 10-min walk (Calthorpe and Poticha, 1993; Bertolini, 2008).

However, based on several considerations, we adopt a radius of around 250-300 m maximum as the station area, about half of the typical walkable radius value (Fig. 10, right). First, the paper studies user satisfaction in railway stations, and perception instead of walking ability is prioritized. In practice, a 300 m radius for the so-called "station environment" is recommended (Peek and van Hagen, 2002). During field visits, we also found that the stations are usually perceivable around the maximum 250 m range (see supplementary materials section S10). Secondly, considering station areas as public spaces, research on other types of public space is referenceable. Studies of green parks suggest a maximum of 300 m walking distance (Konijnendijk, 2023) from residents' homes to green spaces. Thirdly, this smaller range serves this study's explorative nature to investigate spatial configurations that lie in urban design and architecture domains. This range is barely investigated in existing assessment literature compared to a larger area, around 500 m, for at least two reasons. Firstly, it is hard to find a positive relationship between the station's proximity and economic performance when it is too close to the station buildings due to railway noise and pollutants. Secondly, considering the circle area size formula (Area $= \pi r^2$), a radius increase (e.g., 250 m) in a peripheral part, compared with the same radius increase in a core area, results in a much larger area size, which emphasizes the importance of the catchment area. Nevertheless, we see the unique importance of the core area. For example, if it is unsafe, a piece of area located in the core part, compared with its counterpart located in the catchment area, will have a larger influence since more passengers go through it (Fig. 10, right).

2.3. Literature review and selection of user satisfaction indicators

This paper adopts the user pyramid (Van Hagen, 2011), which consists of five user needs: safety, speed, ease, comfort, and experience. To operationalize these concepts for urban design, we link them to spatial-related indicators based on a literature review. Using Web Of Science, a topic search (title abstract, author keywords, keywords plus) is conducted. The topic words include all the five needs, "qualities," combined with "measure*" (* denotes fuzzy search), "evaluation*," "assessment*," "station," and "public space." The search for papers was conducted in all the publications of the Environmental Impact Assessment Review, Journal of Urban Design, Journal of Environmental Psychology, and Environment and Planning B: Urban Analytics and City Science. Among the resultant papers, those of top citations are examined. Commonly references shown in these papers are further searched and reviewed. Besides the academic publications, relevant building codes, industry standards, and design guidelines are examined based on the authors' knowledge.

2.3.1. Safety

Indicators for safety. Safety in public space has been described as

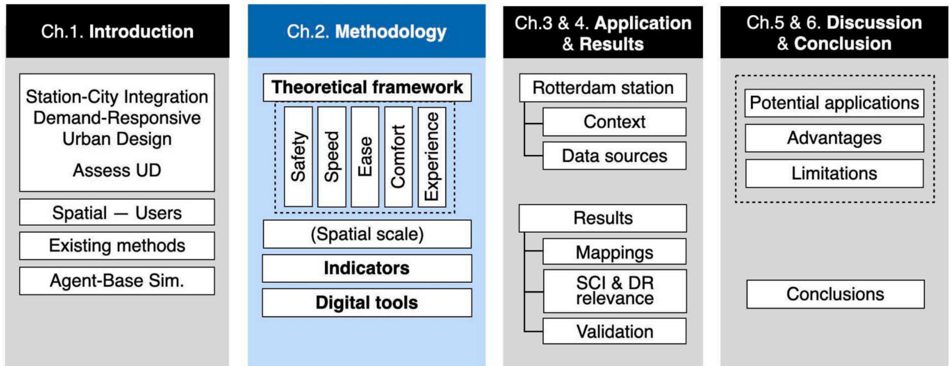

Fig. 7. The structure of this study.

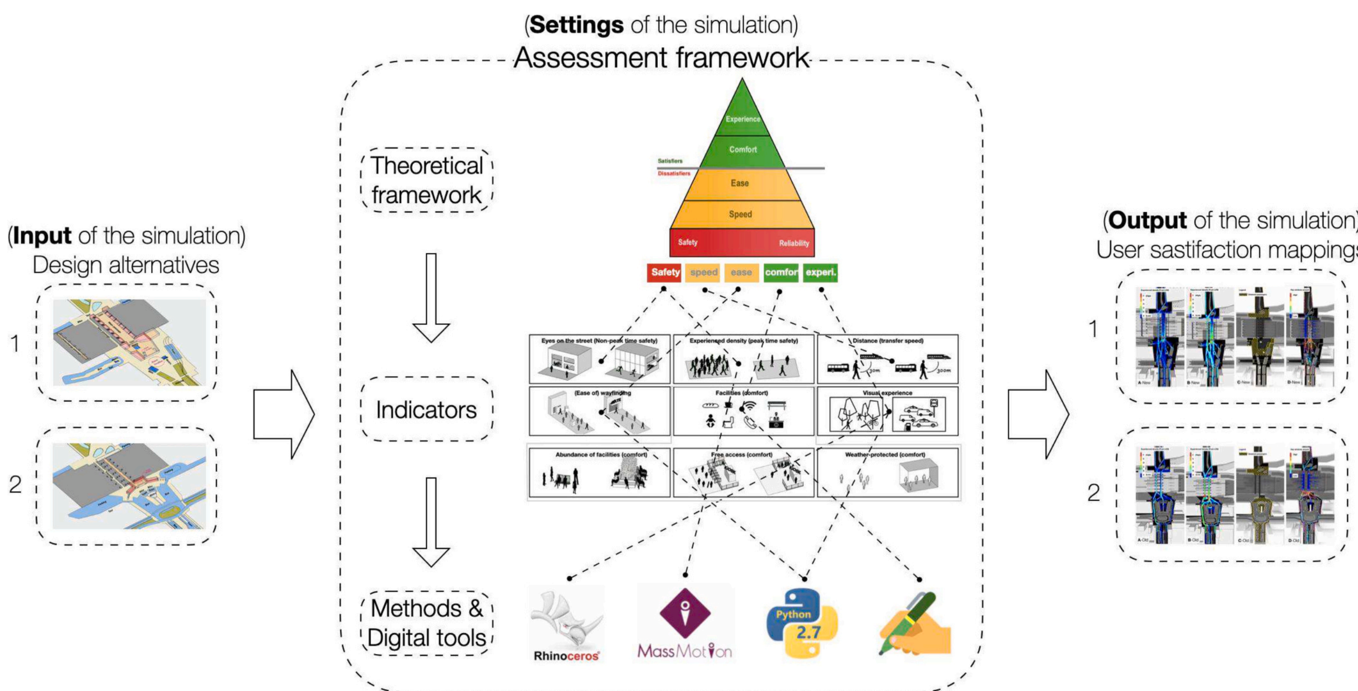

Fig. 8. The assessment framework in the assessment process.

related to many non-spatial, usually equipment and managerial aspects, such as CCTV, sufficient lighting, security signages, cleanliness, familiarity (Larimian and Sadeghi, 2021; Van Melik et al., 2007; Mehta, 2014; Kong and Pojani, 2017), upkeep (De Silva et al., 2017), separation from vehicles, and proper pavement (Hebbert, 2005; Movahed et al., 2012). Some research also linked safety to high-level, large-scale spatial planning patterns (Stoker et al., 2015). This paper chooses two concepts to operationalize safety: "eyes on the street" and flow density. "Eyes on the Street" is introduced by (Jacobs, 1961), describing the surveillance provided by residents and shopkeepers, which deters criminal activities in public spaces. This implies that spaces enclosed by more building facades with windows will be safer, as people living inside watching through the windows provide surveillance (Chen et al., 2021). Some railway station areas are too empty during non-peak times, making pedestrians feel unsafe; thereby, "eyes upon the street" are needed. On the other hand, during peak times, high density in pedestrian flow is a safety concern as it may lead to overcrowding and even stampedes (de Almeida and von Schreeb, 2019). To measure the density as well as related aspects, including speed and flow volume, the concept of "level-of-service" (from A to F level, with low to high density) articulated by (Fruin, 1971) is commonly used in the practice of flow management.

2.3.2. (Transfer) speed

Indicators for transfer speed. Transfer speed is a clear-cut concept. The measurable indicators include the transfer time and the transfer distance. For measuring transfer time, there are more advanced indicators such as "Generalized Journey Time" and "Social Cost" (Office, 2017). They incorporate influences of journey quality by assigning different weights to the original journey time segments regarding different motions (walking, waiting, or climbing stairs) and congestion statuses.

2.3.3. Ease (of wayfinding)

Indicators for ease (of wayfinding). In the initial search using "ease" as the topic word, no paper shows up. Therefore, we further interpret the meaning of "ease." According to van Hagen's initial expression: "…then the traveler wants the change to be easy, i.e. convenient and with little hassle. Travel information and signposting are a help and must be seen as logical and unambiguous…" (Van Hagen, 2011), we interpret ease as "easiness of wayfinding". Wayfinding is a complicated issue, determined by numerous socio-demographics, motility, urban environment, navigational preferences, and daily travel behavior factors (Zomer et al., 2019). Some common factors include journey distance, time, angles,

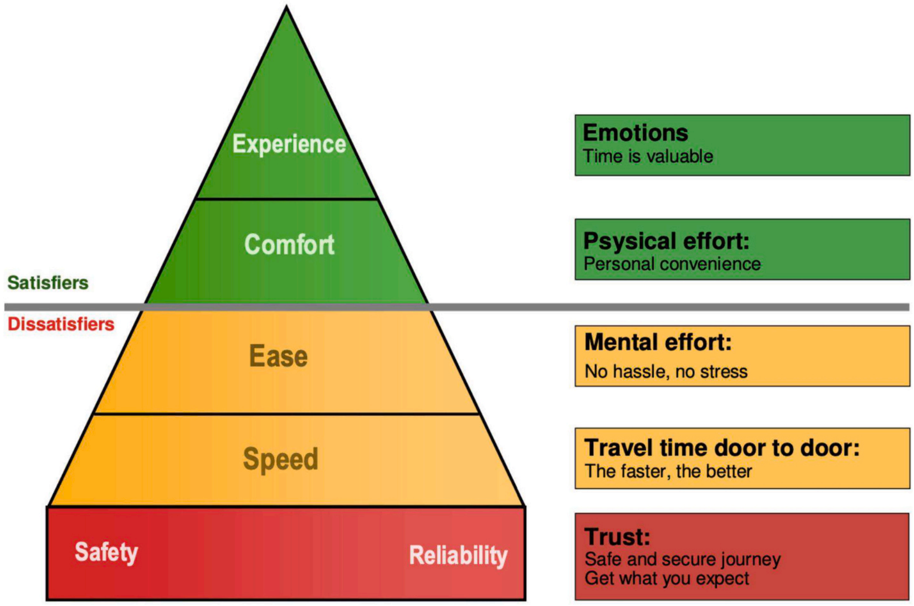

Fig. 9. Pyramid of (railway station) customer needs [Source: (Mark Van Hagen, 2015)].

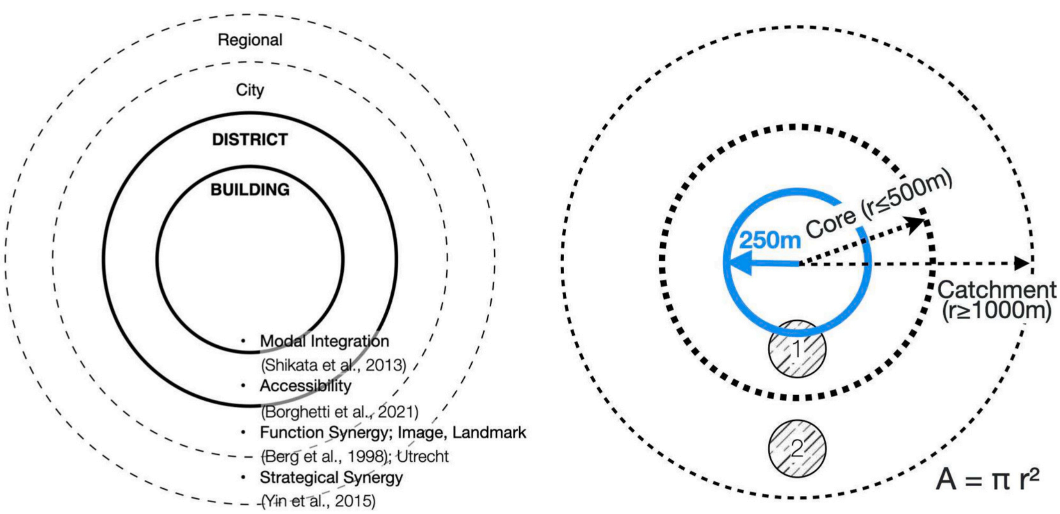

Fig. 10. Various spatial scales of station areas addressing different research issues.

turns, length of the first leg (a leg means a route segment) and decision points (Golledge, 1999), enclosure familiarity, social interaction, environmental information, spatial orientation, exit selection (Veeraswamy, 2011), and signage (Arthur and Passini, 1989).

2.3.4. Comfort

Indicators for comfort. Comfort (Van Hagen, 2011) is interpreted as the comfortable use of facilities in this study. In railway station areas, facilities include free toilets, ticket office, seating, food retail, other retail, weather-protected areas) (Anthony and Frank, 2021), travel information, parent room for baby change, police office, lost and found, and so on (Brons and Rietveld, 2009). For the comfort of non-passengers, such as neighborhood city users, free-access passages also matter.

In common sense, the more abundant (e.g., more chairs, larger weather-protected area), freer (e.g., free toilet outside gated areas), and closer (e.g., closer convenience stores) the facilities are, the more comfortable passengers can be. These factors are not hard to mimic using agent-based simulation (e.g., enable area detection to calculate the abundance, proximity analysis to evaluate distance, and set the token status to check access). However, no research has yet quantitatively linked these factors with comfort value. This paper made a limited contribution by calculating comfort statistically using the AHP method (Section 2.4.4). The paper also chooses the proximity of stores as an example for mapping. The spatial linkage between comfort and spatial aspects is a direction for future research to explore.

2.3.5. (Visual) experience

Indicators for experience. Experience (Van Hagen, 2011) is interpreted as visual experience in this study. Ewing and Handy (2009) related many visual elements of the built environment to some commonly used urban design qualities, including imageability, enclosure, human scale, transparency, and complexity. The visual indicators used by Ewing and Handy (2009) include factors that urban design typically can intervene in, such as buildings with non-rectangular silhouettes, building proportion, dominant building colors, accent colors, sight lines, building height, planters, landscape, etc. The measurement of these elements is done manually in Ewing & Handy's work. With the recent years' development of image segmentation in the computer science field, it is possible to measure visual elements by machine (Nagata et al., 2020). Visual elements can be quantified with qualities using open datasets like Place Pulse, in which street images are scored for qualities including safe, lively, boring, depressing, wealthy, and beautiful (Salesses, 2012). This paper chooses 'lively' in Place Pulse as the experience quality for further analysis. 'Lively' is a critical experience quality in the station area because station areas can be easily rendered lifeless due to the many traffic elements that discourage people from staying.

2.3.6. Final selection of indicators

The final inclusion of indicators considers several criteria. First, indicators should have relevance to spatial-morphological implications. Second, they should be measurable based on the typical design proposals (usually containing cartoon-like 3D models) as input and not rely on real-world data. Third, overlapping is reduced as much as possible between different categories of indicators. Fourth, knowledge of collective experience based on the general population instead of special populations is preferred. Lastly, indicators that can reflect the peak times and normal times differences are incorporated. The indicators selected are listed in Table 1 (Fig. 11). These indicators are measured in the simulation (Section 2.5). The values of user needs are calculated based on these measured indicator values (Section 2.4).

2.3.7. Summary

The above literature review translates the five types of user needs into many indicators. These indicators come from multiple disciplines or fields, including urban design, transport, environmental psychology, and computer science. The further selection of indicators ensures that they can link spatial aspects with human features and are practical for use in agent-based simulation. These indicators play a central role in linking different parts of the assessment framework (Fig. 12).

2.4. Define measurement formulas

Based on the selected indicators, the following formulas are proposed. They calculate different indicators to measure the five user needs quantitatively.

2.4.1. Safety (regarding overcrowding during peak time and 'eyes upon streets' during non-peak time)

Eq. (1) calculates safety during peak time. Eq. (2) calculates safety during non-peak time. d denotes agent experienced density. P_f denotes the proportion of building facades in an agent's vision.

$$V_{\text{safe1}} = d \tag{1}$$

$$V_{safe2} = P_f \tag{2}$$

Table 1
Indicators selected.

User Needs	Selected Indicators	Key Reference	Spatial-Morphological Configuration Relevance
Safety	(Peak time) Flow density; (Non-peak time) Visibility of windows	(Fruin, 1971; Chen et al., 2021)	Shape of spaces, enclosure of facades; Building location and shape
Speed	Transfer time & distance	(Office, 2017)	Constellations of mobility sites, location of passage
Ease	Direction change	(Conroy, 2001)	Constellations of mobility sites, layouts and paths
Comfort	Various types of facilities, weather protected areas	(Anthony and Frank, 2021)	Outdoor and indoor spaces
Experience	Various types of visual elements	(Ewing and Handy, 2009)	Locations of artworks & activities, diversity of elements

2.4.2. (Transfer) speed

Eq. (3) calculates the speed value, i.e. how fast a passenger can finish his transfer journey. Given the same walking ability of the general population, the "speed" of finishing the transfer journey is inversely proportional to the travel distance. L represents an agent's travel distance from origin to destination.

$$V_{speed} = 1/L \tag{3}$$

2.4.3. Ease (of wayfinding)

Eq. (4) calculates the ease of wayfinding for passengers in railway station transfer. It equals an agent's accumulated heading direction change for its whole movement journey. $\Delta\theta$ denotes the direction change at a given time interval, which is set as 1 s in this study. is the whole time that an agent uses to finish his journey.

$$V_{ease} = \sum_{t=0}^{T} \Delta\theta \tag{4}$$

2.4.4. Comfort (regarding facilities and weather-protected areas)

Eq. (5) calculates the comfort value. f_i denotes facilities, including toilets & parent rooms for baby change, ticket offices/machines, seating, kiosk & retail, travel information points, lost and found services & station police offices, and weather-protected areas. The weight of each type of facility is obtained based on experts' ratings ($n = 11$) using the Analytic Hierarchy Process (AHP) method (Table 2).

$$V_{comf} = \sum_{i=1}^{n} f_i \tag{5}$$

2.4.5. (Visual) experience

Eq. (6) is a linear regression model (see supplementary material Section 3.5 for why choosing this model) that calculates the experience value based on visual elements. Two visual features of the visual elements are used: 1) the visual (pixel) proportions of elements and 2) the number of elements (using semantic segmentation and instance segmentation, correspondingly. Fig. 13). These two visual features are feasible to be extracted from photos, but more importantly, are also possible to be extracted from cartoon-like design renderings or 3D models (Fig. 5). (In comparison, there are many features used in the computer vision field that are not usable since they are based on photos - real-world data, like the eight features used in the work of (Naik et al., 2014)). The variables' weights are extracted from the Place Pulse 2.0 dataset (consisting of human-rated street view images) (Salesses, 2012). The statistically significant (p-value < 0.05) and spatial-related variables include the proportions of sky, buildings, water, and trees, and the number of people. Besides the direct effects of these variables, a significant and positive effect of the Shannon index on 'lively' is also found (Table 3). The Shannon index is a common index used for diversity measurement (Zhong et al., 2020), which in this study is calculated based on the visual proportions of buildings, sky, trees, grass, and sidewalks. Including the Shannon index as an extra variable in the linear regression model helps improve the model's accuracy (See more details in supplementary materials 3.1–3.5).

$$V_{expe} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_m x_m + e \tag{6}$$

2.5. Methods and tools

Among the five needs, four can be measured when two types of agent features are simulated - movement and vision (Fig. 14, left). The other one, comfort, is manually analyzed due to a lack of scientific data to support quantitative simulation. MassMotion is used for movement simulation, generating movement trajectories and relevant information. We write Python scripts for vision simulation based on the linear regression model. Rhino is used for modeling and rendering. More

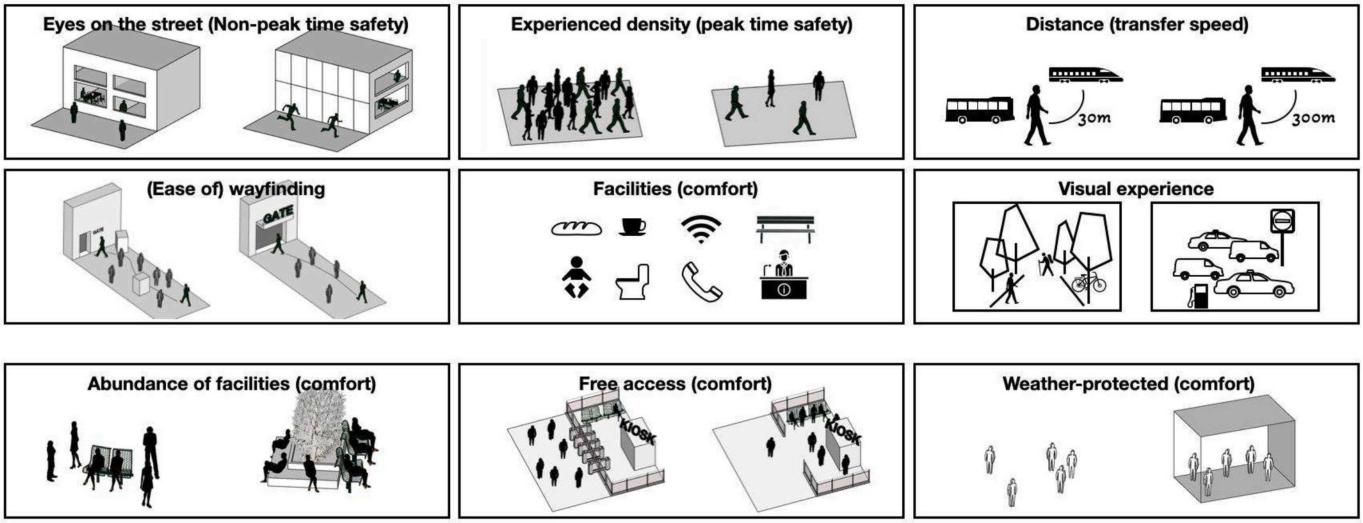

Fig. 11. Various indicators of user needs (source: by authors).

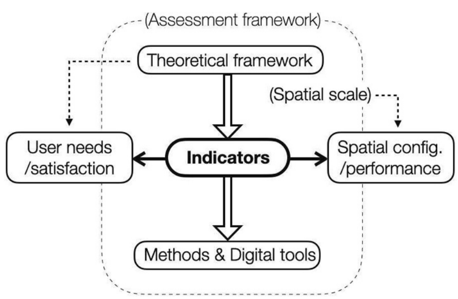

Fig. 12. The indicators' critical role within the assess framework.

Table 2
Importance of different facilities regarding comfort.

Indicators	Weight
Weather protected areas	0.200
Toilets and Parent rooms	0.193
Ticket offices/machines	0.180
Travel information points	0.156
Seats	0.122
Kiosk/Retail	0.090
Lost found and Police offices	0.059

Consistency ratio: 0.053.

Pythons scripts are written for various supporting works, including image segmentation (to get the linear regression model), data analysis, visualization, and so on (Fig. 14, right).

In this paragraph, we describe the practical software operations in detail, explaining how the indicators (Tables 1, 2, and 3) are applied in the simulation. Firstly, we build 3D Rhino models of the station cases, with necessary scene elements, including the sky, buildings (specifying window areas), water bodies, and trees. These scene elements are assigned in different colors. Secondly, we import the Rhino models into Massmotion, set the origins and destinations of passengers, set the OD (Origin-Destination) matrix defining the numbers of passengers, and run the movement simulation. Then, the flow density, transfer time, and transfer distance can be retrieved. Thirdly, from Massmotion, we export the movement trajectories as CSV files, then analyze these files using Python scripts to get the direction changes of each passenger. Fifthly, in Rhino 3D models, through the Rhino built-in Python plugin, with Python scripts, import passengers' (every 5 s) positions, set people figures on these positions, set camera on these positions to mimic passengers' views, and export screenshots (.png images) from the camera positions. Sixthly, we process the .png images using Python scripts to analyze the proportions and numbers of different elements (i.e., windows; sky, buildings, people, water, trees) by telling the different colors of pixels or using instance segmentation, respectively. Seventhly, we calculate the values of user needs based on all the indicators' values, and use Python scripts to map the values into different colored points on the passengers' positions in Rhino models.

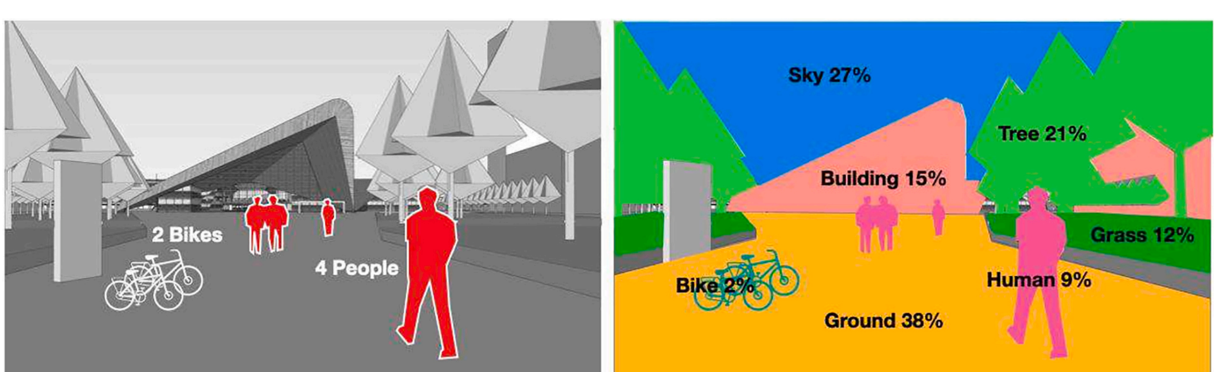

Fig. 13. Instance segmentation (left) and semantic segmentation (right).

Table 3
Importance of different facilities regarding comfort.

Indicators	Unstandardized Coefficients (B)	95 % Confidence Interval		Standardized Coefficients	P-value
		Lower Bound	Upper Bound		
(Constant)	22.388	20.457	24.320		<0.001
Sky	−6.554	−11.685	−1.422	−0.127	0.012
Building	8.457	5.135	11.780	0.257	<0.001
Person_No.	0.539	0.272	0.807	0.174	<0.001
Water	39.143	16.241	62.044	0.141	<0.001
Tree	4.596	1.421	7.771	0.145	0.005
Shannon index	2.202	0.656	3.747	0.124	0.005

Note: a) Dependent variable: 'lively' score. b) $R^2 = 0.167$, adjusted $R^2 = 0.156$. c) The Shannon index is calculated based on the proportions of buildings, sky, trees, grass, and sidewalks.

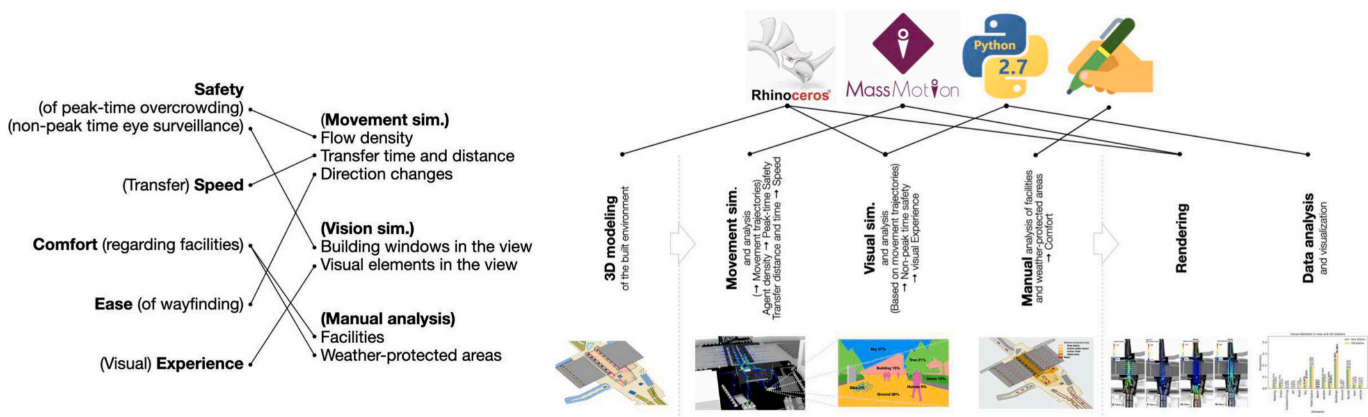

Fig. 14. Methods and tools used.

3. Case study

To demonstrate the new assessment framework's usage, we applied it to the Rotterdam Central Station (RCS) ('Rotterdam Centraal' in Dutch) case. The significant changes in user satisfaction before and after the redevelopment of RCS provide a great opportunity to see whether a new assessment framework can identify such changes. Also, this case's physical accessibility allows the authors to take field trips to collect data and reflect on the methods and findings.

3.1. The context of Rotterdam Central Station

Rotterdam Central Station has been redeveloped, leading to significant changes in user experience. The old Rotterdam Central Station (RCS), built in 1957, was designed for a smaller number of passengers. It became increasingly congested with the growing passenger flow before being redeveloped. Pedestrians also felt unsafe as vehicles were running all over the place (Fig. 15, left). The station no longer served as the city's gateway, and companies were unwilling to invest there. Since 2014, the station and surrounding area have been redeveloped. A new station opened in 2014. According to annual passenger surveys, it maintains top rankings among nearly 400 stations in the Netherlands (e.g., 6th in 2022). It has also received many design awards (Fig. 15, right).

3.2. Research design

Regarding spatial scale, the stations and surrounding areas are modeled on the building and district levels. The maximum range of station area is defined as roughly 250 m, where the more specific analyzed areas cover mobility sites (i.e. bus station, tram station, bike parking sites) and walkable outdoor spaces (Figs. 16, 18, 19. See also section 2.2)).

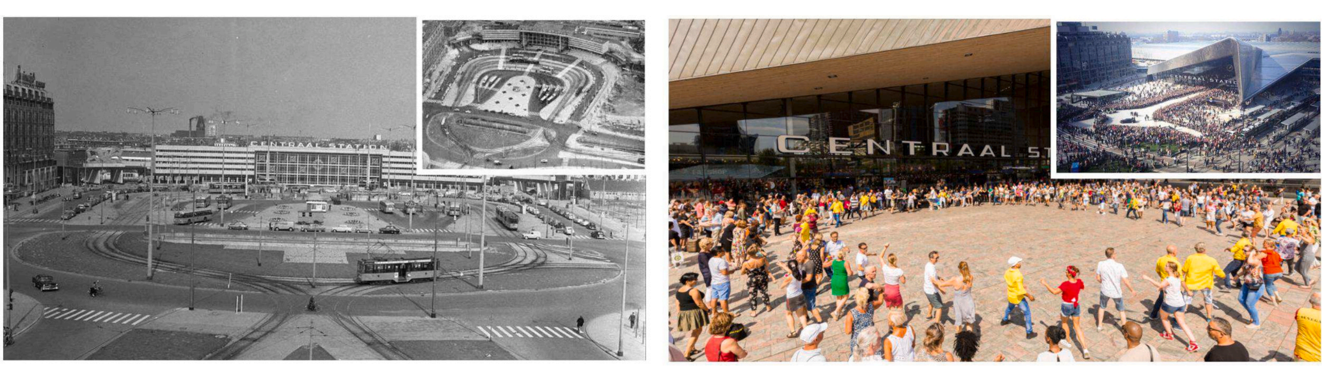

Fig. 15. The old and the new Rotterdam Central Stations (img. Sources: alamy.com; indebuurt.nl).

Regarding the temporal dimension (Carmona et al., 2010), this research sets simulation scenarios for weekday peak, weekday non-peak, weekends, disruption, and summer carnival times. It then compares these scenarios (Fig. 17).

3.3. Data sources

As outlined in Figs. 8 and 30, the simulation process has different components, including inputs (design proposals), settings (agents, flow, events), and outputs (user satisfaction mappings). Various data from multiple sources are used for these components.

The design proposals are basically 3D models of the station area. We built these models based on satellite images, floor drawings, and historical photos from the internet.

For movement-related agent parameters, we adopted the default values in MassMotion. These default values come from multiple sources, such as Fruin's work (Fruin, 1971) and data from the London railway system (Office, 2017). Vision-related agent parameters are actually the coefficients of the linear regression model. The model was built based on the Place Pulse 2.0 dataset (section 2.4.5), which consists of human-scored street images. For agent flow, we use Origin-Destination matrixes with the same mode split (to make the flow the same 'controlled variable') for the old and the new scenarios. This mode split is based on our on-site pedestrian counting and the Dutch railway company's flow data (NS) (see detailed explanation in supplementary materials section S2). For simulating Summer Carnival events, we observed the locations of crowds on the station plaza and in the station building during the carnival time in 2023.

When the simulation outputs, i.e., user satisfaction mappings, are generated, we compare them with the real-world user satisfaction changes and interpret them with design interventions. The real-world user satisfaction data comes from the annual survey named Station Experience Monitor ('Stationsbelevingsmonitor' in Dutch) by the Dutch railway company. The design interventions are documented in a paper by Peters and Tolkoff (2016), in which user experience improvement is described from the experts' perspective.

4. Application results

4.1. Mappings of user satisfaction

The mapping results are shown as follows:

4.1.1. Safety (regarding overcrowding during peak time and 'eyes upon streets' during non-peak time)

Fig. 20-A. shows the peak time safety perception, represented by the flow density. In the old station areas, the area in front of the station

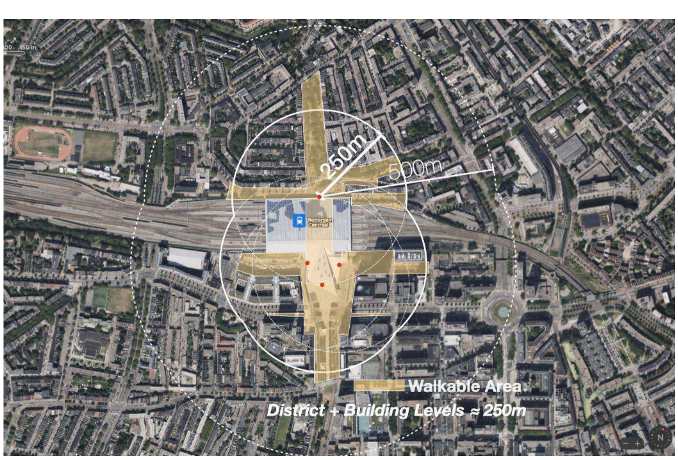

Fig. 16. The study area of Rotterdam Central.

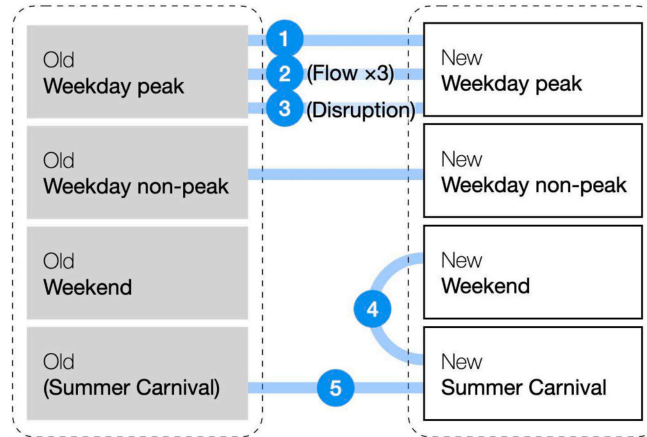

Fig. 17. Compare different scenarios.

building (location 1 in the diagrams) is crowded, and passengers may face the danger of being hit by vehicles. This area forms a bottleneck to the passenger pedestrian flows. This issue is solved in the new station, where pedestrian flows are more evenly distributed. In the hypothetical scenarios when pedestrian numbers are increased (Fig. 20-B, 22, locations 1 and 12), the old station can have severe congestion (level-of-service F) while the new station can still handle the increased pedestrian numbers. Therefore, the new station has a better peak time safety performance.

Fig. 20-D shows non-peak time safety perception in the station. In the old station, the main passage across the building under railway tracks (location 2) receives little eye surveillance. While in the new station, it receives much more eye surveillance thanks to the newly added retails under the track. This means a safer environment during non-peak time, especially at night.

4.1.2. (Transfer) speed

Fig. 21-E and Fig. 23 show the passengers' transfer speed (This transfer speed analysis is conducted only for passengers and not for leisure users as the former care about it while the latter hardly do). The average passenger transfer distance and time in the new scenario is just slightly shorter than that in the old scenario. In the old station areas, most mobility sites are directly located in front of the station building (location 3), which makes the transfer distance quite short for the majority of passengers. Different from most passengers, those who come from the bus and tram stations that are located in the far south (location 4) need to take much longer transfer journeys in the scenario. They also need to take the detours caused by the motorway Weena (location 5) during their transfer journey. In the new station, passengers transferring from various modes of transportation have more equitable experiences.

4.1.3. Ease (of wayfinding)

Fig. 21-F and Fig. 24 show the ease of wayfinding, indicated by the direction change (This analysis is only conducted on transport passengers and not for leisure users, as the former care about it, while the latter do not necessarily). In the old situation, when moving in the high density of people in front of the station building (location 6), passengers need to constantly change heading directions to avoid collisions with others; People who come from the far south bus/tram stations need to take many detours. In the new station, passengers have more direct trajectories and would feel much more at ease.

4.1.4. Comfort (regarding facilities and weather-protected areas)

The comfort need in general is better satisfied in the new than in the old station. The old station has limited retail stores in the station hall, while the new station has plenty of stores located in the hall and in the main passage under the tracks (Fig. 19), which provide convenient

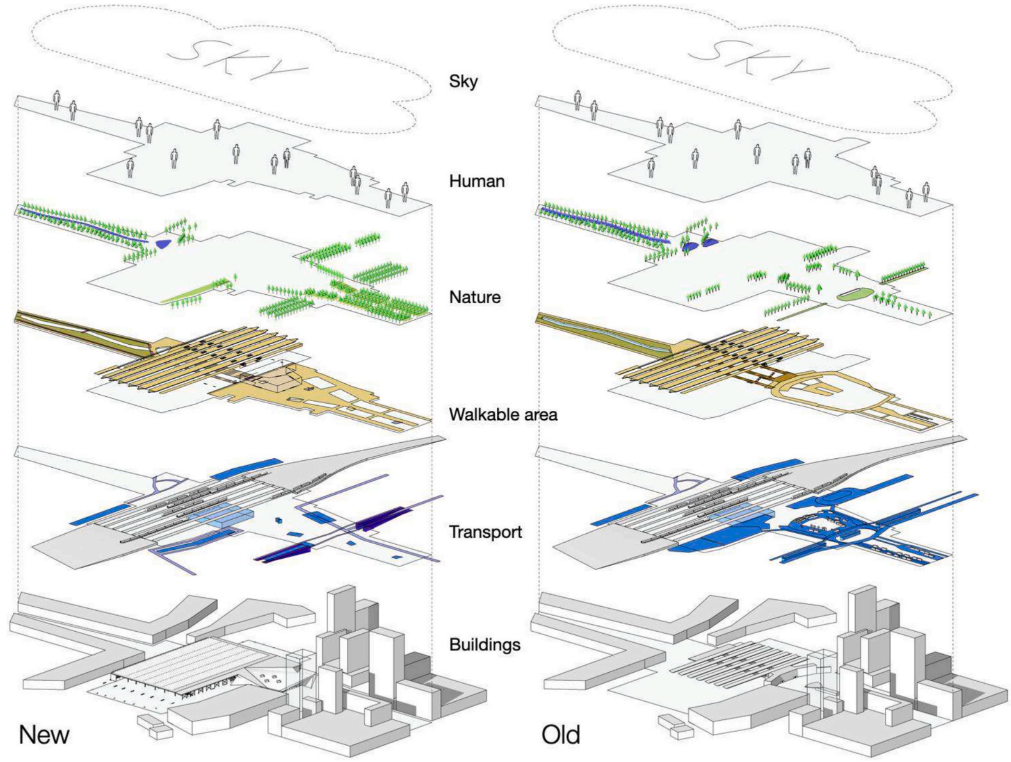

Fig. 18. The stations on the district level.

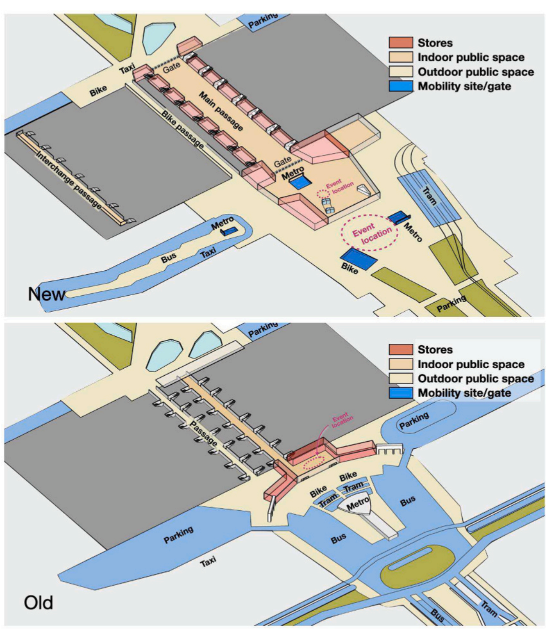

Fig. 19. The stations on the building level.

consumption choices for users (e.g., Fig. 21-G, location 7, where stores are near in the new station than the old). In the old station, seats are largely missing. The new station provides several types of seating options: several clusters of seats in the station hall; seats in the coffee shop; and in the outside space, the marble edges surrounding the flowerbeds can be used as benches (Fig. 25). The new station has much larger weather-protected spaces, including indoor spaces and the gray spaces covered by the big canopy. However, there are gates for ticket checking in the new station which reduces its comfort use than the old, as the latter was totally free-access (Fig. 25). Sales of retail located within the gated area have dropped by 25 % after the installation of ticket gates (Peters and Tolkoff, 2016, p. 7).

4.1.5. (Visual) experience

Fig. 21-H shows visual experience in the station. In the station plaza area, the visual perception is more positive in the new scenario than in the old scenario. This is because, in the old scenario, when people stand in the plaza area (location 1), their sight lines toward positive environmental elements (including buildings, trees, and humans) are pretty much blocked by vehicles. In the summed visual perception of all agents (Fig. 26), more building proportion is presented in the view in the old scenario. This is because the old paths from the neighborhood were mainly located alongside the building (locations 9 and 10), while in the new station areas, the paths are evenly located in the open spaces (location 11).

4.1.6. Performance during events and disruptions

The new station is supportive of large events, while the old station is not. In the new station area, the plaza can be used for big events, and smaller events or installations can be set in the station hall (Figs. 15, 19). A further simulation shows that adding events in the new station has negligible impacts on the flow density, transfer distance, and transfer time (Fig. 27). In contrast, in the old station, no major event can be organized at the plaza as it was occupied by transport facilities (Figs. 15, 19) unless all the transport function stops to give way to events.

The new station is more resilient to disruption than the old station. Railway lines and stations can be affected by different disruptions (https://www.rijdendetreinen.nl/en/statistics) leading to stations sometimes being shut down. In such a situation, the passengers will not be able to board and will be detained in the spaces around the station. The summed area of outdoor spaces around the new station is doubled; therefore, it will have a double capacity to accommodate the detained passengers during extreme disruptions (Fig. 20-C).

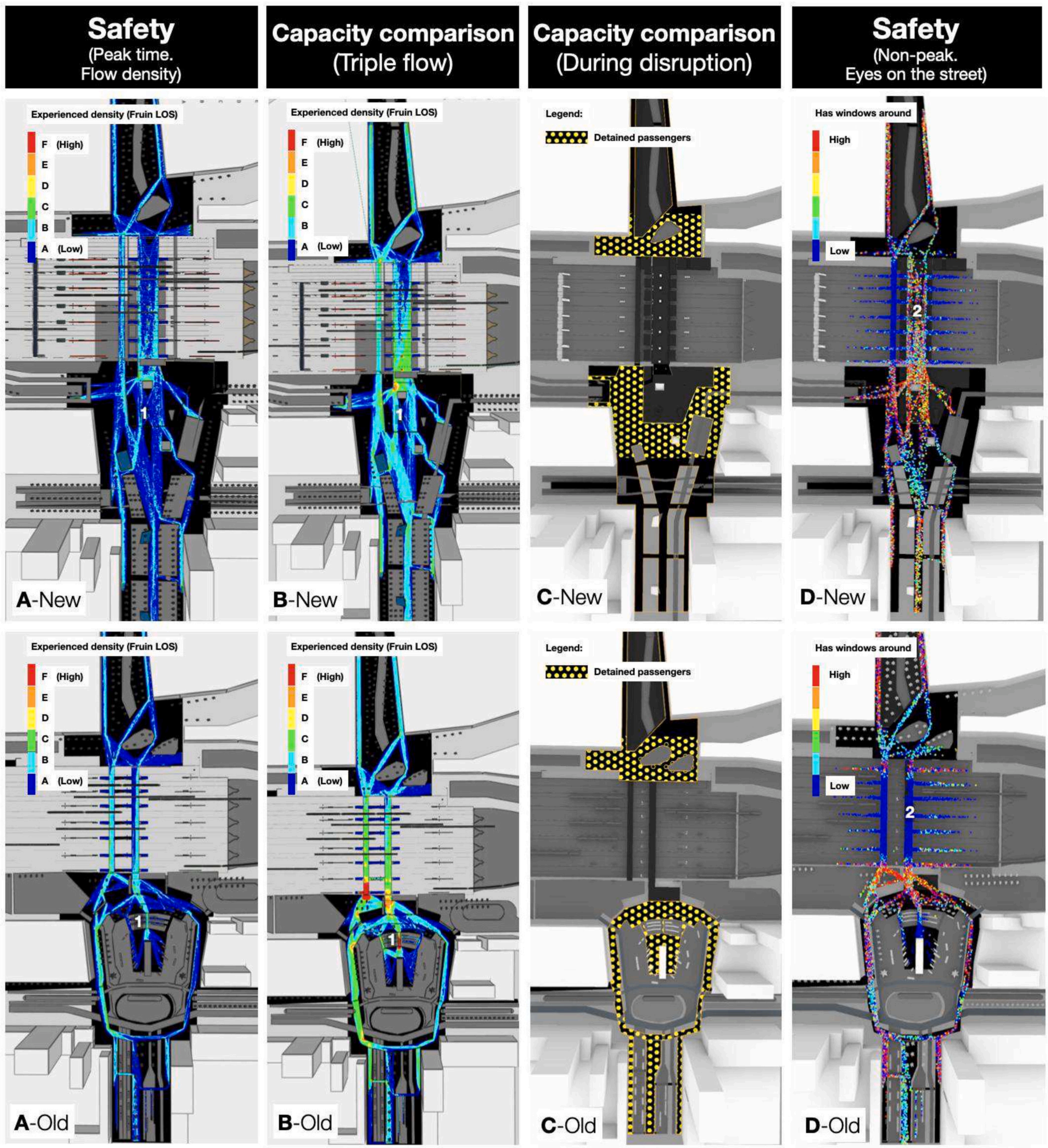

Fig. 20. A) flow density as peak-time safety. B) capacity comparison with triple times of passenger numbers. C) capacity comparison during a hypothetic disruption. D) 'eyes on the street' as non-peak-time safety.

4.2. Relates to station-city integration and fluctuation-responsive

Various design interventions, whose impacts are reflected by agents' satisfaction during the above application, are relevant to station-city integration (SCI) and fluctuation-responsive (DR). Some of these design interventions are primarily about the spatial layout and others are about the elements of stations. Regarding SCI, these design interventions promote high-quality connections, provide the station with city function and environment, and reduce interference between the station and the city. Regarding DR, these interventions reduce overcrowding, build events-supportive space, and promote quality during non-peak (Fig. 28, see also Fig. 1).

4.3. Validation of the assessment framework

In general, as shown in the Rotterdam Central Station (RCS) case, the

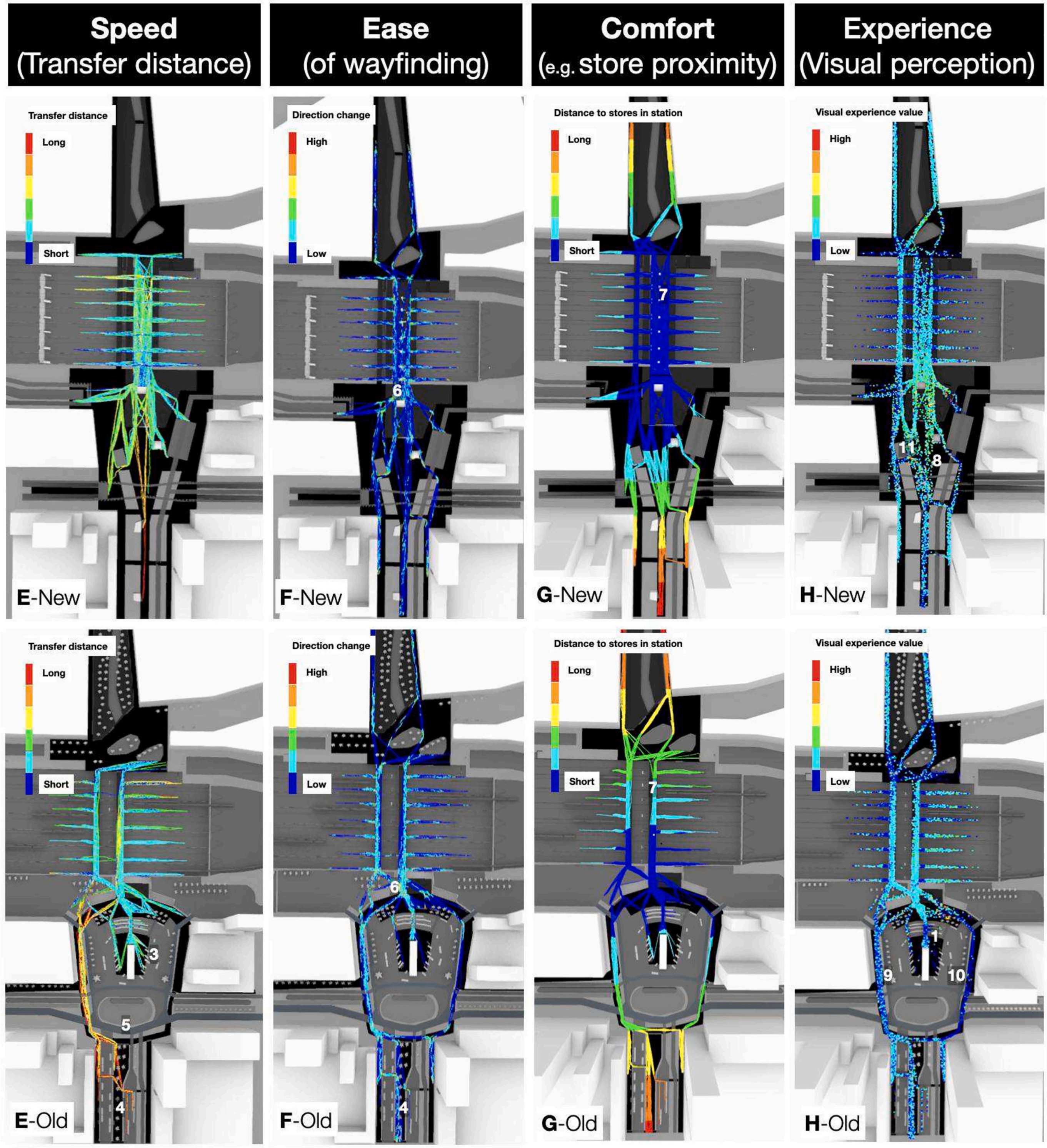

Fig. 21. E) transfer distance. F) ease of wayfinding. G) store proximity as comfort. H) visual experience.

whole framework successfully reflects the impact of design alternatives on agents' satisfaction. This aligns with the'Stationsbelevingsmonitor' passenger surveys and qualitative observations by Peters and Tolkoff (2016). For each specific need, the simulation's validity varies. Peak-time safety, (transfer) speed, and ease (of wayfinding), non-peak-time safety values are measured based on physical quantities derived from agents' movement trajectories, so their validity is determined by the movement simulation algorithm in MassMotion (namely 'social forces'). MassMotion is a validated commercial software program (Kinsey et al., 2015). The comfort and experience values are less accurate due to subjective factors involved (i.e. the variables' weights). The comfort value calculated through the AHP method has a consistency ratio = 0.053, suggesting that the judgments made by different experts are reasonably consistent. The linear regression model for experience value has a, indicating an acceptable accuracy in social science (according to Ozili (2023), should be greater than 0.1).

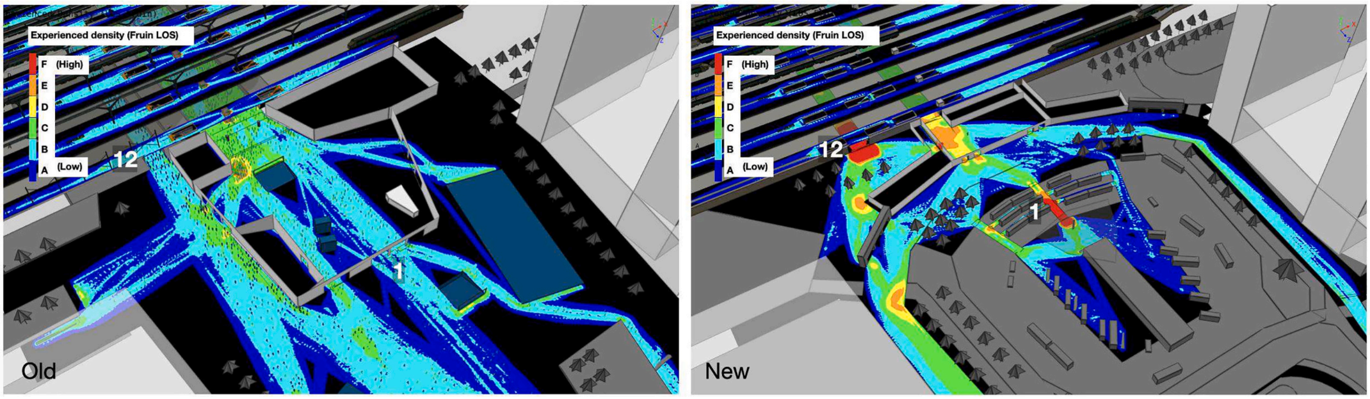

Fig. 22. Flow density with three times of agent numbers.

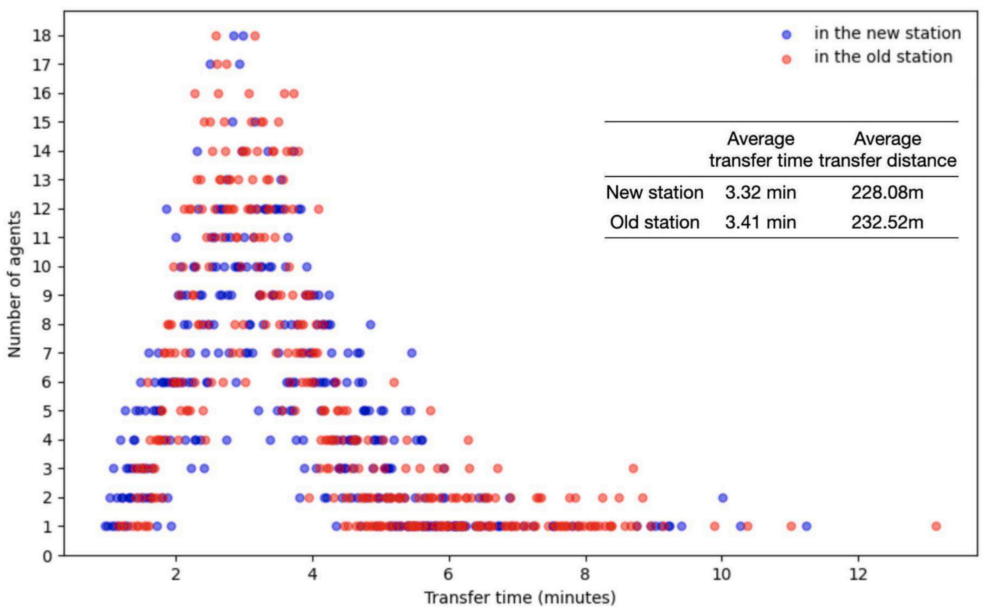

Fig. 23. Agents' transfer time and transfer distance.

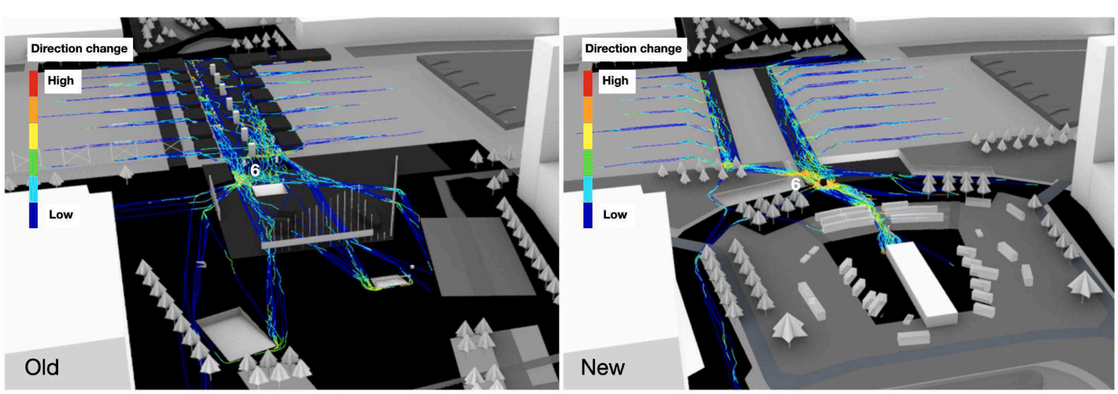

Fig. 24. Direction changes in trajectories.

5. Discussions

5.1. Potential applications of the assessment framework

During the design stage, the assessment framework facilitates the evaluations during design iterations. This framework presents the user needs systematically for designers to check in case of neglecting certain aspects when dealing with the complexity of stations. The framework incorporates scientific knowledge to inspire evidence/knowledge-based design (Klaasen, 2016). Since applying this framework still needs some coding skills (while typical designers hardly have coding skills) and familiarity with MassMotion software, it would be easier for the

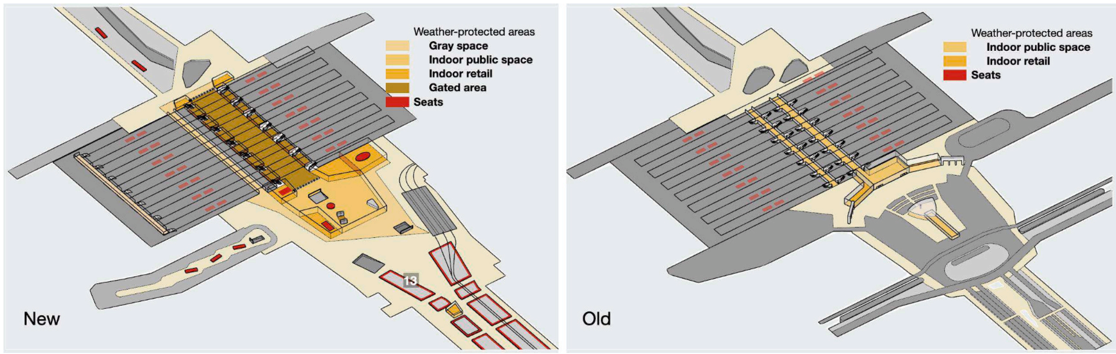

Fig. 25. Weather-procted areas and seats.

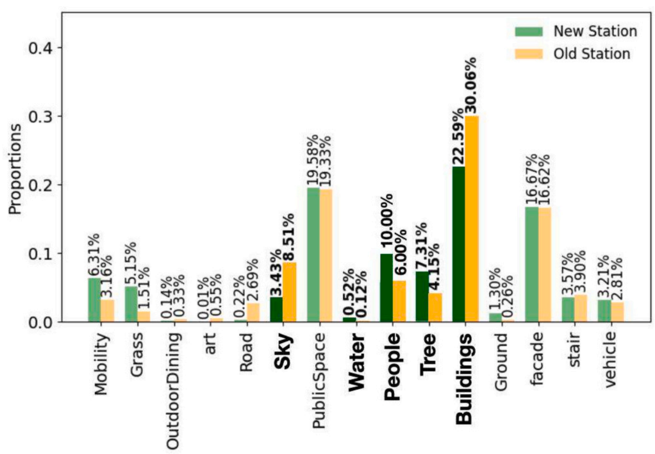

Fig. 26. Proportions of different elements in agents' view.

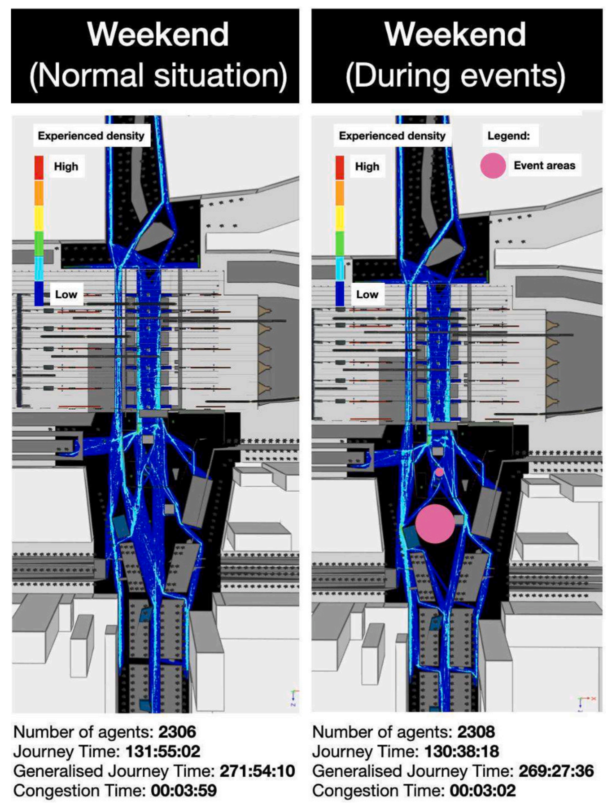

Fig. 27. Flow density and agents' transfer time in the new station during normal time and event time.

assessment provided by the design consultant service.

The framework also facilitates communication and collaboration with different actors involved in station area developments (Fig. 29). Since the results generated by this framework are vivid, they can be communicated to a broader audience, such as retailers, neighborhood residents, and the general public through different media platforms (Li et al., 2023), and increase the public participation (Gao, 2023).

Moreover, the framework can potentially be used for site assessment before design, for post-occupancy evaluation (Weimin and Mo, 2019) after design, and for non-design evaluation, such as estimating the impact of organizing events (Smith et al., 2021). With its future development, the more reality this framework can simulate (Fig. 30), the more usage it will have in different parts of the whole ecology of practice (Fig. 29).

5.2. Knowledge contributions

This study contributes to the knowledge body of station area design. This study's literature review of indicators bridges existing knowledge that scatteredly lay in multiple disciplines. New knowledge is also developed during the research for a complete framework, including the linear regression model for visual experience simulation and the weight values for comfort evaluation.

The research forms part of a larger PhD project that considers stations' temporal use feature, enriches the meanings of 'fluctuation-responsive,' 'resilience' (Shafiei Dastjerdi et al., 2021), 'flexible,' and 'temporary use' in railway station practice. These terms all convey a dynamic essence and contribute to a more sustainable way of space usage (Madanipour, 2018; Carr and Dionisio, 2017).

5.3. Limitations and future research directions

With a specific (urban design) domain-specific purpose to assess spatial configurations that user satisfaction is indicative of, this study only simulates a limited part of the station system (Fig. 30, content in colored texts). The station system, in its total reality, is a mixture of the station environment, users, and so on. The station environment has many spatial features on different spatial scales (Section 2.2) and many non-spatial features. Users are of many types, with features on collective and individual levels, and they are evolving/adaptive. The station system has different types of performance and can be approached from different professional fields. In acknowledging the broader picture depicted in Fig. 30, we outline a future research direction: integrate more aspects to expand the assessment framework.

In this research, the stations' performances are judged through comparisons between the new and old stations. A more ideal judgment is to compare the station's performance with standards. However, user

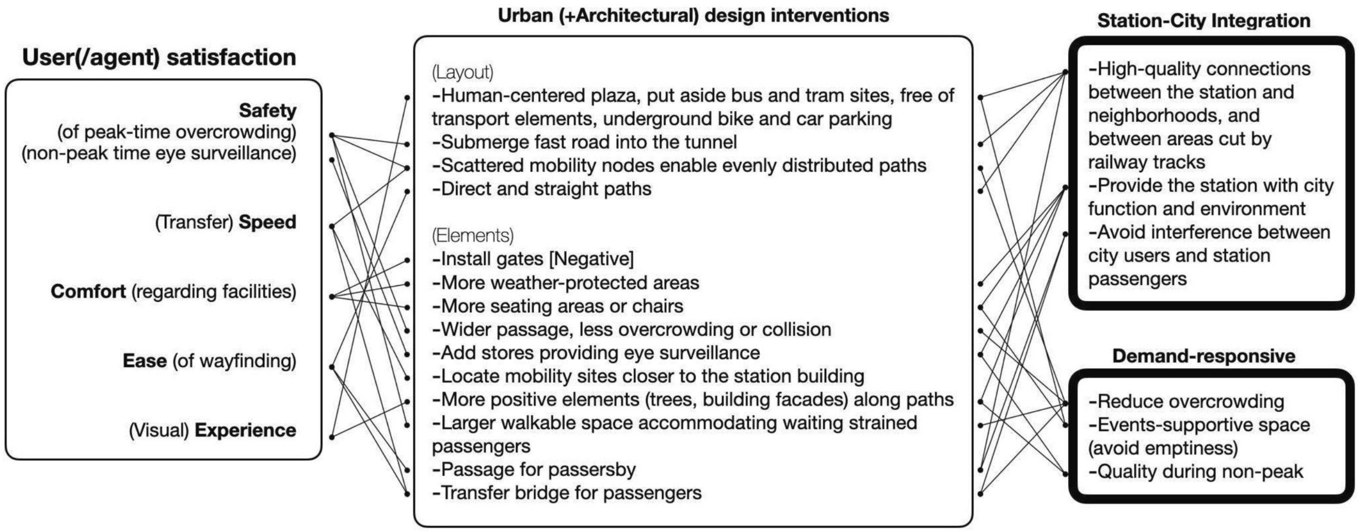

Fig. 28. Design interventions and their relevance to station-city integration and fluctuation-responsive.

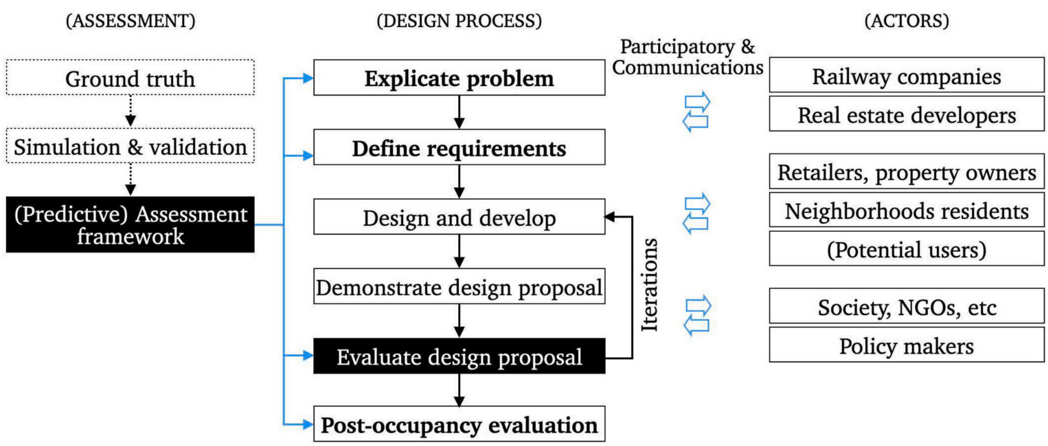

Fig. 29. The assessment framework's potential applications in practice.

satisfaction regarding the five user needs is a complex issue that relates to many factors, including national contexts, user preferences, and so on. The existing evidence we have is still far away from forming such standards. These standards are possible in the future with more scientific evidence or industrial standards, and our assessment framework being applied in more cases (See supplementary materials section S11. Referenceable values regarding user needs).

6. Conclusions

This paper addresses one main research question and two sub-questions: To what extent can agent-based simulation help assess user satisfaction to facilitate the urban design of stations and station areas (that are integrated with cities and fluctuation-responsive to events)? Is the developed assessment framework effective in telling the user satisfaction caused by different design alternatives? And what is the usage of this framework in practice? The results and discussion show positive answers as well as limitations to these questions:

1) Agent-based simulation (ABS) has proven useful in developing the new assessment framework. ABS makes it possible to integrate human perceptual knowledge and spatial quality knowledge. The simulation settings in this study include agent parameters, flow, and events, which reflect real-world station systems. We acknowledge that there are still many more factors to be simulated.
2) The assessment framework is shown to be effective when applied to the Rotterdam Central Station (RCS) case. Given the input of different design alternatives, the assessment framework outputs the agents' satisfaction mapping to show the impact. Besides the whole framework being effective, the separate quality value calculations are also valid with varying accuracy.
3) This assessment framework is applicable in design practice. It facilitates design proposal evaluation, promotes communication among different actors, and potentially helps assess non-design interventions.

Funding

This work was supported by the China Scholarship Council (CSC) [202106260022].

CRediT authorship contribution statement

Enshan Chen: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Stefan van de Spek:** Conceptualization, Methodology, Writing – review & editing,

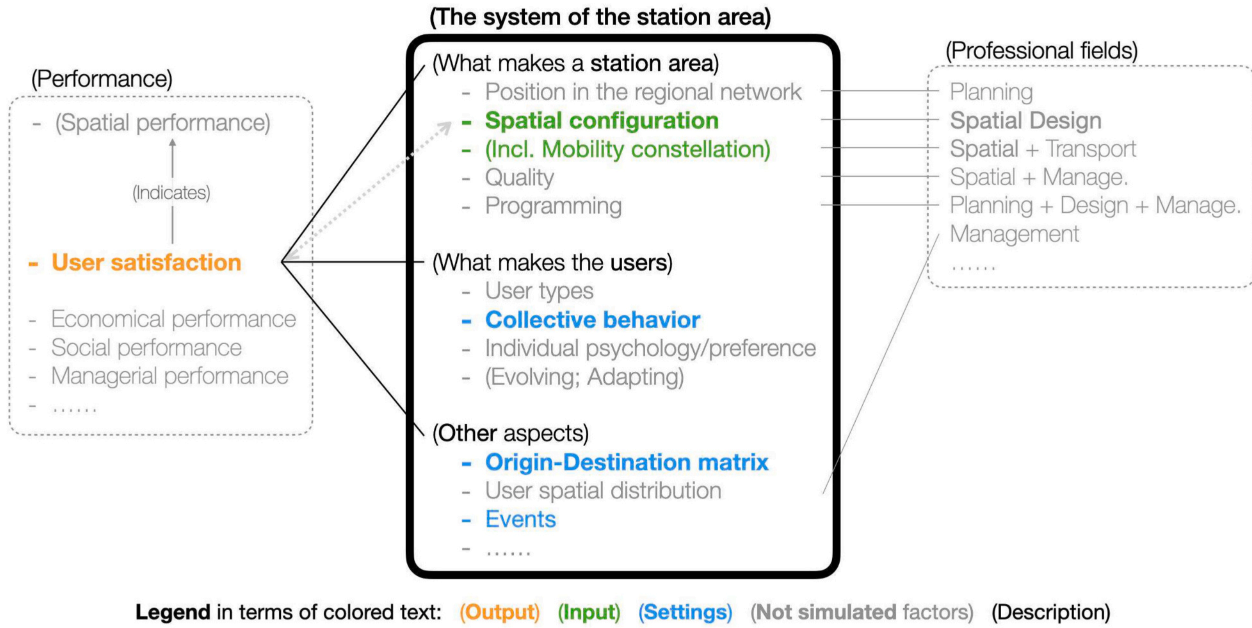

Fig. 30. Limited part of the reality be simulated.

Supervision, Project administration. **Frank van der Hoeven:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Manuela Triggianese:** Conceptualization, Methodology, Supervision.

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.

Acknowledgment

We would like to thank Minyu Cui for the on-site pedestrian data collection.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2024.107685.

References

Anthony, D., Frank, A., 2021. Station Design Guidance Design Manual NR/GN/CIV/100/02.
Arthur, P., Passini, R., 1989. Wayfinding: People, Signs, and Architecture, 1st ed. McGraw-Hill, New York.
Benedikt, M.L., 1979. To take hold of space: Isovists and isovist fields. Environ. Plan. B: Planning Design 6, 47–65. https://doi.org/10.1068/b060047.
Bertolini, L., 2008. Station areas as nodes and places in urban networks: An analytical tool and alternative development strategies. In: Bruinsma, F., Pels, E., Rietveld, P., Priemus, H., van Wee, B. (Eds.), Railway Development: Impacts on Urban Dynamics. Physica-Verlag HD, Heidelberg, pp. 35–57. https://doi.org/10.1007/978-3-7908-1972-4_3.
Bertolini, L., 2020. From "streets for traffic" to "streets for people": can street experiments transform urban mobility? Transp. Rev. 40, 734–753. https://doi.org/10.1080/01441647.2020.1761907.
Bertolini, L., Spit, T., 1998. Cities on Rails: The Redevelopment of Railway Station Areas. E & FN Spon.
Borghetti, F., Colombo, C.G., Longo, M., Mazzoncini, R., Cesarini, L., Contestabile, L., Somaschini, C., 2021. 15-Min Station: a case study in North Italy City to evaluate the livability of an area. Sustainability 13, 10246. https://doi.org/10.3390/su131810246.
Brons, Martijn, Rietveld, Piet, 2009. Improving the quality of the door-to-door rail journey: a customer-oriented approach. Built Environ. (1978) 35, 122–135. https://doi.org/10.2148/benv.35.1.122 arXiv:23289648.
Calthorpe, P., Poticha, S., 1993. The Next American Metropolis: Ecology, Community, and the American Dream. Princeton Architectural Press.
Carmona, M., Heath, T., Oc, T., Tiesdell, S., 2010. Public Places Urban Spaces, Second Edition: The Dimensions of Urban Design, 2nd ed. Architectural Press, Amsterdam Heidelberg.
Carr, J., Dionisio, M.R., 2017. Flexible spaces as a "third way" forward for planning urban shared spaces. Cities 70, 73–82. https://doi.org/10.1016/j.cities.2017.06.009.
Chen, E., Yang, S., Zhuang, Y., 2021. Analysis of urban security based on visibility: taking Utrecht Railway Station area as an example. Architect. Technique 27, 121–123. https://doi.org/10.19953/j.at.2021.04.031.
Cheng, T., Zheng, J., Li, X. (Eds.), 2021. Symposium of the Forum on China "Station-City Integration Development". China Architecture & Building Press.
Conroy, R., 2001. Spatial Navigation in Immersive Virtual Environments. University of London, Doctoral.
da Conceição, A.L.M., 2015. From City's Station to Station City: An Integrative Spatial Approach to the (re)Development of Station Areas. Ph.D. thesis. Delft University of Technology.
Dai, Y., Cheng, T., Chen, P., 2019. Brief discussion about "integrated station-city development". Architect. Pract. 16–23.
de Almeida, M.M., von Schreeb, J., 2019. Human stampedes: an updated review of current literature. Prehosp. Disast. Med. 34, 82–88. https://doi.org/10.1017/S1049023X18001073.
de Jonge, T.M., van der Voordt, D.J.M., 2002. WAYS to Study and Research Urban, Architectural and Technical Design. DUP Science.
De Silva, C., Warusavitharana, E., Ratnayake, R., 2017. An examination of the temporal effects of environmental cues on pedestrians' feelings of safety. Comput. Environ. Urban. Syst. 64, 266–274. https://doi.org/10.1016/j.compenvurbsys.2017.03.006.
Du, J., Druta, O., Van Wesemael, P., 2021. Place quality in high-speed rail station areas: concept definition. J. Transp. Land Use 14, 1165–1186. https://doi.org/10.5198/jtlu.2021.1820.
Dubroca-Voisin, M., Kabalan, B., Leurent, F., 2019. On pedestrian traffic management in railway stations: simulation needs and model assessment. Transp. Res. Procedia 37, 3–10. https://doi.org/10.1016/j.trpro.2018.12.159.
Ewing, R., Handy, S., 2009. Measuring the unmeasurable: urban design qualities related to walkability. J. Urban Des. 14, 65–84. https://doi.org/10.1080/13574800802451155.
Fruin, J.J., 1971. Pedestrian Planning and Design. Metropolitan Association of Urban Designers and Environmental Planners.
Gao, Q., 2023. Retrospect and prospect: public participation in environmental impact assessment in China. Environ. Impact Assess. Rev. 101, 107146. https://doi.org/10.1016/j.eiar.2023.107146.
Gifford, R., 2001. Environmental Psychology: Principles and Practice, 3rd ed. Optimal Books, Colville, WA.
Golledge, R.G. (Ed.), 1999. Wayfinding Behavior: Cognitive Mapping and Other Spatial Processes, 1st ed. Johns Hopkins University Press, Baltimore.
Hebbert, M., 2005. Engineering, urbanism and the struggle for street design. J. Urban Des. 10, 39–59. https://doi.org/10.1080/13574800500062361.

Hillier, B., 2015. Space Is the Machine: A Configurational Theory of Architecture. CreateSpace Independent Publishing Platform, Place of Publication not Identified.
Hollander, J.B., Sussman, A., Lowitt, P., Angus, N., Situ, M., Magnuson, A., 2023. Insights into wayfinding: urban design exploration through the use of algorithmic eye-tracking software. J. Urban Des. 28, 274–295. https://doi.org/10.1080/13574809.2022.2118697.
Ibraeva, A., Correia, G.H.D.A., Silva, C., Antunes, A.P., 2020. Transit-oriented development: a review of research achievements and challenges. Transp. Res. A Policy Pract. 132, 110–130. https://doi.org/10.1016/j.tra.2019.10.018.
Jacobs, J., 1961. The Death and Life of Great American Cities, 1st ed. Random House, New York.
Jehle, U., Coetzee, C., Büttner, B., Pajares, E., Wulfhorst, G., 2022. Connecting people and places: analysis of perceived pedestrian accessibility to railway stations by Bavarian case studies. J. Urban Mobil. 2, 100025. https://doi.org/10.1016/j.urbmob.2022.100025.
Kasraian, D., Maat, K., Stead, D., van Wee, B., 2016. Long-term impacts of transport infrastructure networks on land-use change: an international review of empirical studies. Transp. Rev. 36, 772–792. https://doi.org/10.1080/01441647.2016.1168887.
Kinsey, M., Walker, G., Swailes, N., Butterworth, N., 2015. The Verification and Validation of MassMotion for Evacuation Modelling. ARUP, London, UK.
Klaasen, I., 2016. Knowledge-Based Design. https://doi.org/10.7480/isbn.9789040724794.
Kong, W., Pojani, D., 2017. Transit-oriented street design in Beijing. J. Urban Des. 22, 388–410. https://doi.org/10.1080/13574809.2016.1271700.
Konijnendijk, C.C., 2023. Evidence-based guidelines for greener, healthier, more resilient neighbourhoods: introducing the 3–30–300 rule. J. For. Res. 34, 821–830. https://doi.org/10.1007/s11676-022-01523-z.
Larimian, T., Sadeghi, A., 2021. Measuring urban social sustainability: scale development and validation. Environ. Plan. B: Urban Analyt. City Sci. 48, 621–637. https://doi.org/10.1177/2399808319882950.
Li, L., Du, Y., Ma, S., Ma, X., Zheng, Y., Han, X., 2023. Environmental disaster and public rescue: a social media perspective. Environ. Impact Assess. Rev. 100, 107093. https://doi.org/10.1016/j.eiar.2023.107093.
Liu, M., 2020. Mapping landscape spaces: understanding, interpretation, and the use of spatial-visual landscape characteristics in landscape design. A+BE Architect. Built Environ. 1–248. https://doi.org/10.7480/abe.2020.20.5403.
Loo, B.P.Y., Comtois, C., 2016. Sustainable Railway Futures: Issues and Challenges. Routledge.
Lu, Q.C., Xu, P., Cui, X., Li, J., 2022. 2 - Railway vulnerability and resilience. In: Calçada, R., Kaewunruen, S. (Eds.), Rail Infrastructure Resilience. Woodhead Publishing. Woodhead Publishing Series in Civil and Structural Engineering, pp. 5–35. https://doi.org/10.1016/B978-0-12-821042-0.00020-4.
Madanipour, A., 2018. Temporary use of space: urban processes between flexibility, opportunity and precarity. Urban Stud. 55, 1093–1110. https://doi.org/10.1177/0042098017705546.
Mehta, V., 2014. Evaluating public space. J. Urban Des. 19, 53–88. https://doi.org/10.1080/13574809.2013.854698.
Movahed, S., Azad, S.P., Zakeri, H., 2012. A safe pedestrian walkway; creation a safe public space based on pedestrian safety. Procedia Soc. Behav. Sci. 35, 572–585. https://doi.org/10.1016/j.sbspro.2012.02.124.
Nagata, S., Nakaya, T., Hanibuchi, T., Amagasa, S., Kikuchi, H., Inoue, S., 2020. Objective scoring of streetscape walkability related to leisure walking: statistical modeling approach with semantic segmentation of Google street view images. Health Place 66, 102428. https://doi.org/10.1016/j.healthplace.2020.102428.
Naik, N., Philipoom, J., Raskar, R., Hidalgo, C., 2014. Streetscore – Predicting the perceived safety of one million streetscapes. In: In: 2014 IEEE Conference on Computer Vision and Pattern Recognition Workshops. IEEE, Columbus, OH, USA, pp. 793–799. https://doi.org/10.1109/CVPRW.2014.121.
Newman, P., Kenworthy, J., 1999. Sustainability and Cities: Overcoming Automobile Dependence. Island Press, NS. Traveler Behavior | NS Dashboard. https://dashboards.nsjaarverslag.nl/reizigersgedrag/rotterdam-centraal.
Office, T.P.M., 2017. Business Case Development Manual. https://www.whatdotheyknow.com/request/197881/response/495035/attach/.
Ozili, P.K., 2023. The Acceptable R-Square in Empirical Modelling for Social Science Research. Munich Personal RePEc Archive.
Peek, G.J., van Hagen, M., 2002. Creating synergy in and around stations: three strategies for adding value. Transp. Res. Rec. 1793, 1–6. https://doi.org/10.3141/1793-01.
Peters, D., Novy, J., 2012. Train Station area development mega-projects in Europe: towards a typology. Built Environ. 38. https://doi.org/10.2148/benv.38.1.12.
Peters, D., Tolkoff, L., 2016. Lessons for Diridon: Rebuilding Rotterdam Centraal Station. SPUR. https://doi.org/10.13140/RG.2.2.34149.19681.
Piga, B., Morello, E., 2015. Environmental Design Studies on Perception and Simulation: An Urban Design Approach. Ambiances. Environnement Sensible, Architecture et espace Urbain. https://doi.org/10.4000/ambiances.647.
Priemus, H., 2008. Urban dynamics and transport infrastructure: Towards greater synergy. In: Bruinsma, F., Pels, E., Rietveld, P., Priemus, H., van Wee, B. (Eds.), Railway Development: Impacts on Urban Dynamics. Physica-Verlag HD, Heidelberg, pp. 15–33. https://doi.org/10.1007/978-3-7908-1972-4_2.
Pu, Y.S., Srikukenthiran, S., Morrow, E., Shalaby, A., Klumpenhouwer, W., 2022. Capacity analysis of a passenger rail hub using integrated railway and pedestrian simulation. Urban Rail. Transit. 8, 1–15. https://doi.org/10.1007/s40864-021-00162-7.
Richards, J., MacKenzie, J.M., 1986. The Railway Station: A Social History. Oxford [Oxfordshire]. Oxford University Press, New York.
Salesses, M.P., 2012. Place Pulse Measuring the Collaborative Image of the City. Ph.D. thesis. Massachusetts Institute of Technology.
Shafahi, Y., Khani, A., 2010. A practical model for transfer optimization in a transit network: model formulations and solutions. Transp. Res. A Policy Pract. 44, 377–389. https://doi.org/10.1016/j.tra.2010.03.007.
Shafiei Dastjerdi, M., Lak, A., Ghaffari, A., Sharifi, A., 2021. A conceptual framework for resilient place assessment based on spatial resilience approach: an integrative review. Urban Clim. 36, 100794. https://doi.org/10.1016/j.uclim.2021.100794.
Shikata, Y., Nikken Sekkei, K.K., Kenkyukai, Eki Machi Ittai Kaihatsu, 2013. Integrated Station-City Development: The Next Advances of TOD.
Smith, A., Vodicka, G., Colombo, A., McGillivray, D., Quinn, B., 2021. Staging city events in public spaces: an urban design perspective. Int J. Event Festiv. Manag. 12.
Stojanovski, T., 2020. Urban design and public transportation – public spaces, visual proximity and transit-oriented development (TOD). J. Urban Des. 25, 134–154. https://doi.org/10.1080/13574809.2019.1592665.
Stoker, P., Garfinkel-Castro, A., Khayesi, M., Odero, W., Mwangi, M.N., Peden, M., Ewing, R., 2015. Pedestrian safety and the built environment: a review of the risk factors. J. Plan. Lit. 30, 377–392. https://doi.org/10.1177/0885412215595438.
Triggianese, M., 2015. The Railway Station as a Centrepiece of Urban Design.
van den Berg, L., Pol, P., Research, E.I.f.C.U, 1998. The European High-Speed Train and Urban Development: Experiences in Fourteen European Urban Regions. Ashgate.
Van Hagen, M., 2011. Waiting Experience at Train Stations. Ph.D. thesis.. University of Twente, Delft.
Van Hagen, Mark, 2015. Effect of station improvement measures on customer satisfaction. J. Traffic Transp. Eng. 3. https://doi.org/10.17265/2328-2142/2015.01.002.
Van Melik, R., Van Aalst, I., Van Weesep, J., 2007. Fear and fantasy in the public domain: the development of secured and themed urban space. J. Urban Des. 12, 25–42. https://doi.org/10.1080/13574800601071170.
Veeraswamy, A., 2011. Computational Modelling of Agent Based Path Planning and the Representation of Human Wayfinding Behaviour within Egress Models. Ph.D. thesis.. University of Greenwich.
Wang, B., 2022. Integrating high-speed railway stations and urban areas in China: actors, processes and institutions. A+BE | architecture and the. Built Environ. 1–212. https://doi.org/10.7480/abe.2022.17.6828.
Weimin, Z., Mo, H., 2019. Post-occupancy evaluation a review of methods and state-of-the-art techniques. Time Architect. 46–51.
Yin, M., Bertolini, L., Duan, J., 2015. The effects of the high-speed railway on urban development: international experience and potential implications for China. Prog. Plan. 98, 1–52. https://doi.org/10.1016/j.progress.2013.11.001.
Yu, Y., Rong, H., Lingzhu, Z., 2021. Human-Oriented Urban Design with Support of Multi-Source Data and Deep Learning: A Case Study on Urban Greenway Planning of Suzhou Creek, Shanghai.
Zhang, H., Nijhuis, S., Newton, C., 2023. Advanced digital methods for Analysing and Optimising accessibility and visibility of water for designing sustainable healthy urban environments. Sustain. Cities Soc. 104804. https://doi.org/10.1016/j.scs.2023.104804.
Zhong, T., Lü, G., Zhong, X., Tang, H., Ye, Y., 2020. Measuring human-scale living convenience through multi-sourced urban data and a Geodesign approach: buildings as analytical units. Sustainability 12, 4712. https://doi.org/10.3390/su12114712.
Zomer, L.B., Schneider, F., Ton, D., Hoogendoorn-Lanser, S., Duives, D., Cats, O., Hoogendoorn, S., 2019. Determinants of urban wayfinding styles. Travel Behav. Soc. 17, 72–85. https://doi.org/10.1016/j.tbs.2019.07.002.