Develop the Design Principles for Demand-Responsive Railway Station Areas

Abstract

Some station areas suffer from overcrowding and emptiness **issues** due to the fluctuation caused by events. This paper aims to develop design principles that help create demand-responsive station areas and establish a methodology for discovering similar principles. It develops a multi-step **methodological** framework that includes establishing design objectives and spatial dimensions, collecting data from literature and cases, processing data through systematic examination and research-by-design, evaluating initial findings, and reflecting the final findings through expert interviews. Applying this framework, using 12 papers and multiple cases (including Beijing West Railway Station, Shanghai Railway Station, Rotterdam Central Station, Utrecht Central Station, Bijlmer Arena Station, and so on) as the sources of heuristics for research-by-design, **resulted** in the discovery of 26 design principles, which can be viewed from various perspectives.

Keywords: Overcrowding, Emptiness, Urban design, Pattern language

1 Introduction

In some railway stations, overcrowding and emptiness (Fig. 1), which are two extremes of passenger fluctuation (Section 1.1), are tricky issues causing economic and experiential losses. Overcrowding is unpleasant for users and, more importantly, is a safety concern of stampedes (ChinaDaily, 2008; de Almeida and von Schreeb, 2019). Emptiness is a waste of space as resources for society, especially in high-density urban areas or cities; It is a waste of maintenance for railway companies; It causes economic loss, as stores or real estate property owners get less commercial revenue due to lack of customer patronage; It decreases users' experience, as spaces being empty makes people feel dangerous, especially at night. All these negative effects necessitate solutions to address overcrowding and emptiness in railway stations.

Addressing overcrowding and emptiness is relevant for many stations as they are challenged by various types of events. Such as spring festivals in China, Vietnam, and South Korea; and beer festivals, carnivals, and sports events in European cities (CityR). As events are ever-growing in cities (Tallieu) enriching the city dynamics, it is necessary to build stations that are capable of facilitating this. Also, addressing the after-event emptiness of space and making full use of space as a resource is helpful in promoting sustainability, especially in high-density cities where space is scarce.

(a) (b)

Figure 1: Overcrowding and emptiness in railway station areas. (Image source: [a] - 163.com; [b] - Sohu.com)

1.1 The nature of overcrowding and emptiness

1.1.1 Viewing stations from the pedestrian flow perspective

A basic unit of pedestrian movement can be seen as pedestrians transfer from their origins to their destinations through some spaces/passages/connections, and possibly **bottlenecks** (i.e., station components that have a limited capacity to handle the passenger flow, due to various reasons such as security/ticket checks, level changes, narrow passages, a limited number of trains, and disruptions on the railway lines) (Fig. 2 a). This basic unit can be repeatedly seen in various forms (Fig. 2 a-1, a-2) in the station area (Fig. 3). Station components that are working well during normal times can still become bottlenecks during big events (e.g., national holidays and football matches) when there are surging passengers. To accommodate the detained passengers, 'redundant' spaces are needed. These redundant spaces can be overcrowded during peak times while empty during non-peak times. Therefore, overcrowding and emptiness, which may seem two opposite phenomena, actually result from the same reason - fluctuated passenger flow due to events.

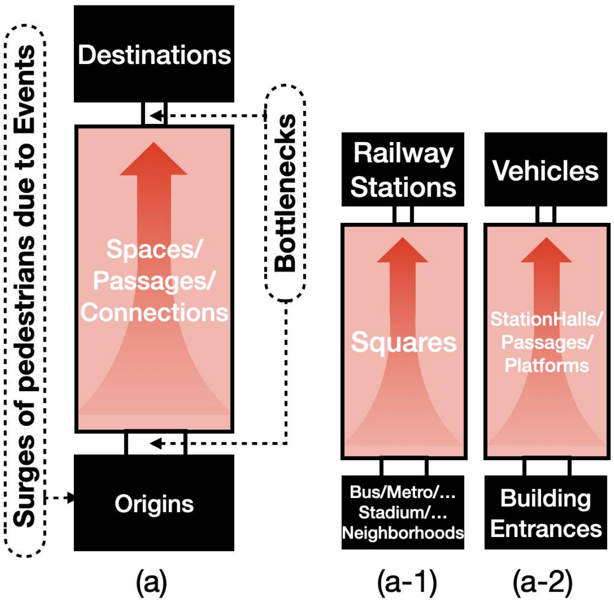

Figure 2: A conceptual basic unit of passenger flow (a) and its variations (a-1, a-2). (Image source: by authors. Inspired by (Fruin, 1971))

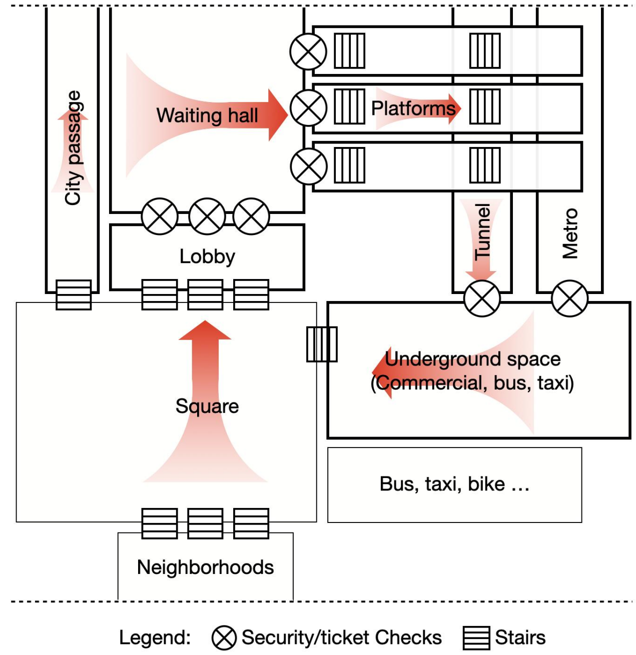

Figure 3: The mechanism of overcrowding and emptiness in Beijing West Railway Station area. (Image source: by authors)

1.1.2 Spatial relevance of the problems

With professional backgrounds in architecture and urban design, we saw the spatial relevance of overcrowding and emptiness to spatial configurations. The spatial considerations in these two fields usually include the form of space, layout of elements, accessibility, visibility, and so on, on building and district levels. In cases like Beijing West Railway Station (Fig. 4 a, b), overcrowding and emptiness are associated with the poor connection with the neighborhood, the gigantic non-human size of buildings, messy facilities on the square blocking view, and deteriorating space qualities, a lack of visibility from eye level to see the sunken plaza and atriums, traffic separate the use of walkable spaces, and so on. The station is relatively isolated from the neighboring city areas, and spaces within the station areas are separated by bottlenecks, which decrease the peak time capacity and make the station less attractive for non-transport use during non-peak times.

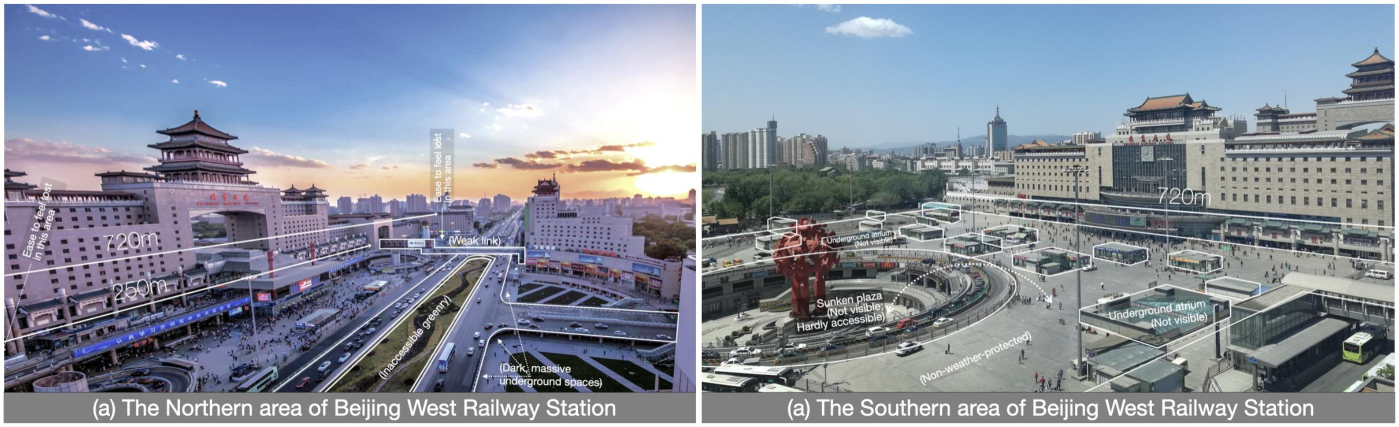

Figure 4: Spatial relevance shown by an example case of Beijing West Railway Station. (Image source: [a] - Meipian.cn; [b] - Wikimedia.org. Redrawn by the authors)

1.1.3 Temporal scales of the problem-causing events

Various events on different temporal scales (Carmona et al., 2010) can influence stations (Fig. 5), such as daily and weekly commuting, multi-weekly sports events, yearly holidays, and multi-decennially Olympics. However, daily and weekly commuting is more of a topic for metro stations than railway stations and is commonly investigated in research on 'TOD (Transit Oriented Development)' (Ibraeva et al., 2020). Low-frequency events such as the Olympics are too rare to find patterns (Alexander, 1977). In contrast, multi-weekly to yearly events are peculiar because they result in relatively drastic pedestrian fluctuation, and it is feasible to find patterns. They are of particular concern to railway stations and have barely been studied.

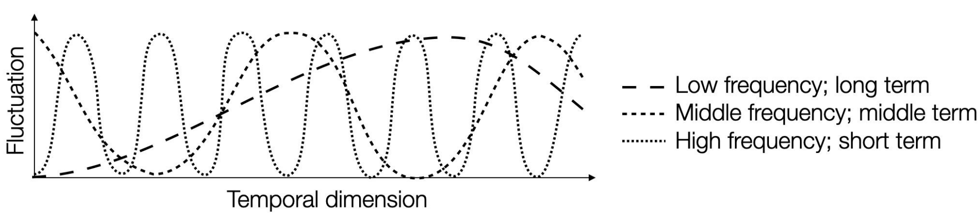

Figure 5: Temporal scales. (Image source: drawn by the authors, inspired by fig. 130, on p. 38 of (de Jonge and van der Voordt, 2002))

1.2 Demand-responsive as an objective

The overcrowding and emptiness issues urge relevant station areas to be 'demand-responsive.' Since this paper studies the particular issues - overcrowding and emptiness- which are barely addressed by existing spatial design research, there are no corresponding termed solution packages. Therefore, this paper needs to name a term for possible solutions and enrich the meaning of the term. One ideal term this paper found is 'demand-responsive' inspired by the word 'demand-responsive transport,' which is a practice ideal (Enoch et al., 2006) used in the transport service field, describing a flexible mode of transportation that adapts to the demands of its user groups (Hunkin and Krell, 2018). This paper transfers the meaning of 'demand-responsive' to the station context regarding **spatial design** perspective, defining it as **a quality of station areas that can address the use fluctuation caused by events, reduce potential overcrowding and emptiness, make spaces sufficiently be used during non-peak and peak time, and satisfy users' needs**. (See also Section 2.5.2 Literature, and Supplementary materials)

1.3 Spatial solutions as a research objective

This research hypothesizes that spatial solutions (on district and building levels) can contribute to demand-responsive solutions. Firstly, overcrowding and emptiness sometimes result from poor spatial configuration (Section 1.1.2), spatial relevance of the problems). Therefore, good spatial solutions will make a change, and in cases like the Rotterdam Central Station (CS) and Utrecht CS areas, through proper spatial design, great improvement has been achieved during the latest redevelopments. Secondly, it is common for spatial solutions to resolve non-spatial issues or to enhance non-spatial solutions. Indeed, "a pattern of events cannot be separated from the space where it occurs" (Alexander, 1979, p. 73). Overcrowding and emptiness in stations are often a mixture of spatial and non-spatial issues, and possible solutions can come from spatial design, among other fields such as transportation engineering, management, and planning. For example, a (spatially) well-designed plaza can serve as a basis for (managerially) organizing leisure events, hence reducing emptiness.

1.3.1 Address both overcrowding and emptiness

Spatial solutions should be able to address both overcrowding and emptiness and should not ignore one of them. If only overcrowding or emptiness were considered, there could easily be a paradox of 'larger' or 'smaller' spaces for railway station areas. For example, to reduce overcrowding, stations can be designed with 'larger' redundant spaces, but then the emptiness issue during non-peak time will be exacerbated; to reduce emptiness, stations can be designed with 'smaller' redundant spaces, but they will be more overcrowded during peak time. To avoid the paradox, design solutions should be able to reduce both overcrowding and emptiness. That is to say, solutions should 1) increase transport (i.e., transfer/waiting) capacity without significantly enlarging spaces that are prone to be empty or 2) increase the leisure use of space without significantly reducing transport capacity.

Traditionally, overcrowding issue is addressed by research on crowd management in the civil engineering field, where fundamental concerns such as safety and evacuations related (Schadschneider et al., 2012; Yang et al., 2020). Spatial emptiness - or the opposite - spatial vibrancy - is investigated by research on public space in the urban design field (Gehl, 1987; Whyte, 2001). The knowledge that addresses both overcrowding and emptiness is yet lacking. Research regarding 'resilience' - the concept addresses risks in fluctuations - and research on 'flexibility' has shown some general possibilities for demand-responsive solutions (such as the research by Mehmood (2016); Ardeshiri et al. (2016); Geraedts (2008)), yet much more is needed.

1.3.2 Spatial scales of concern: the district and building levels (within 250m radius)

For issues related to railway stations, typically, there are potential solutions across different spatial scales, and spatial solutions at the district level are less studied (Fig. 6). On regional or city levels, many studies have investigated planning interventions to improve stations' performance (Yin et al., 2015; van den Berg et al., 1998; Borghetti et al., 2021). In these studies, stations are simplified as nodes within networks. These nodes (station areas) are usually defined with a range **around 500-1000m** (Zhang et al., 2019; Borghetti et al., 2021). At these levels, overcrowding can potentially be solved by the shared capacity from other stations (Bešinović, 2020; Lu et al., 2022) or other mobilities (Martins et al., 2019), and emptiness can potentially be solved by better accessibility (Borghetti et al., 2021; Jehle et al., 2022) that promotes more use.

However, interventions at these higher levels are usually non-spatial, missing the complexity of overcrowding and emptiness relating to 3D and configurations (Section 1.1.2). In contrast, district-level interventions can take district structures and 3D urban forms into consideration. And yet, little is known about district-level interventions.

In this research, we investigate station areas with a range within approximately 250-300m, smaller than the typical 500m range in planning-oriented research. This is because we take user perception into consideration. As noted by Peek and van Hagen (2002), in practice, a 300m radius for the so-called "station environment" is used. This smaller range serves this study's explorative nature to investigate spatial configurations that lie in urban design (and architecture, as explained in the following paragraph) domains. During field visits of selected cases, we found that the stations are usually visually perceivable around the maximum 250m range (see Supplementary Materials, figs. 47, 48, and 49, depicting areas of different stations).

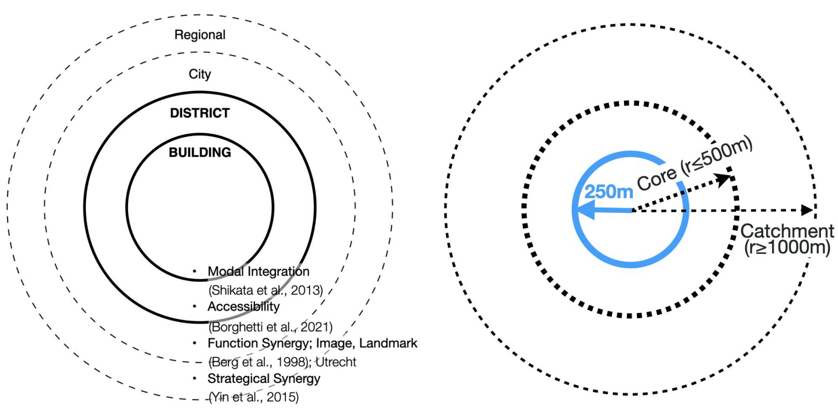

Figure 6: Spatial scales of station areas. (Image source: (Chen et al., 2024))

Besides the district level, the building level (at which we analyze the station building) should also be considered. In railway development, urban design schemes at the district level are commonly determined by the layouts of station buildings at the building level. For example, in Utrecht Central Station and Rotterdam Central Station, the large structure - a city axis, is much determined by the qualities of city passages embedded in the station buildings.

1.4 Relevance with station-city integration

Demand-responsive is interconnected with the research topic of '**station-city integration (SCI)**,' as they can interchangeably be the context or solutions for each other. SCI is a research topic that aims to get various possible benefits by integrating stations and cities. It has a relatively long history of rich academic conversations across multiple fields (Cheng et al., 2021; Yin et al., 2015), including spatial design (Calthorpe and Poticha, 1993; De Wilde, 2006; Shikata et al., 2013; Zemp et al., 2011; Du et al., 2021; da Conceição, 2015). Spatial interpretations for integration typically include mode integration, mixed use of land, high-density development, the stack of building floors, and so on.

SCI brings potential as well as risks for demand-responsive solutions. When stations and cities are 'integrated,' it is possible for stations to benefit from an enlarged accommodation capacity and increased user numbers, therefore relieving the overcrowding and emptiness issues. The opposite side effect is also possible, though; stations may be more overcrowded in peak time due to the increased number of passengers or more empty if the city areas are mostly empty by themselves. The city users may even cause flow conflicts for transport passengers. The city areas can benefit from stations' massive passengers, a vibrant environment, and increased commercial revenue; it is also possible to have side effects such as being rendered into chaotic areas due to traffic elements. Developing city areas beyond pure stations may require a heavy initial investment, resulting in high maintenance costs after development. The dual possibilities of benefits and side effects make SCI a fruitful and challenging topic for demand-responsive solutions. To reduce overcrowding and emptiness, stations should be integrated with cities carefully, possibly with the help of a systematic assessment of design interventions. **Despite** the high relevance of station-city integration, existing research on this topic does not address the demand-responsive railway station.

1.5 Knowledge Gap and Research Question

The above introduction explains the nature of overcrowding and emptiness (O&E) as related to events, and reveals the research objective: spatial solutions for demand-responsive (DR) station areas, which should maximize the benefits and avoid risks of station-city integration (SCI). **However**, this research objective is still a knowledge gap considering the existing research from several perspectives: Firstly, the specific temporal scale of events (between multi-weekly to yearly) and the spatial scale of station areas(at the district level within 250m) are hardly explored by existing research (Sections 1.1.3, 1.3.2); Secondly, overcrowding and emptiness should be addressed together (otherwise there will be a spatial dilemma), while existing research about crowd management in civil engineering field only addresses overcrowding, and research of public space in urban design filed only address emptiness (Section 1.3.1). With the essence of addressing fluctuation - the 'demand-responsive' concept - initial developed in the transportation service field, is still a practice ideal with purely managerial interventions, missing the spatial relevance (Section 1.2); Thirdly, demand-responsive solution is not yet established in the highly-related research topic - station-city integration (Section 1.4).

Aimed at filling the knowledge gap, an ongoing Ph.D project is being conducted, which 1) articulates the overcrowding & emptiness problems from the spatial design perspective, 2) establishes an assessment framework for design evaluation, and 3) develops **design principles** (fig. 7). This paper is part of the project and specifically addresses the design principles. The main research question of this paper is: **What are the design principles for demand-responsive railway station areas?** A subsequent question is: **What is a practical way to develop design principles?** The remainder of this paper is structured as follows: Chapter 2 describes the methodology, Chapter 3 reports the results, Chapter 4 discusses the whole research and results, and Chapter 5 draws conclusions.

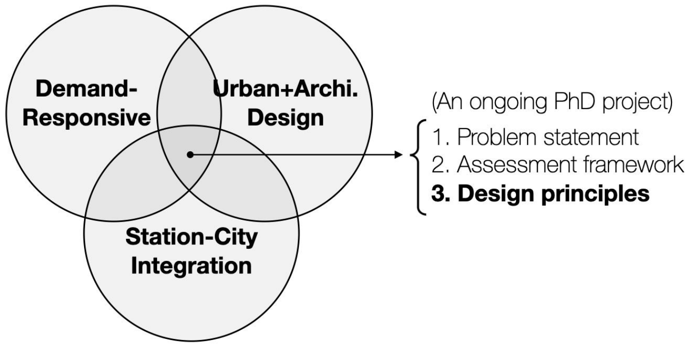

Figure 7: This paper is part of a PhD project at the intersection of three topics. (Image source: by authors)

2 Methodology

In this section, we first define what a 'design principle' is, and then describe the methodology for developing it.

2.1 What is a design principle?

Design principles/guidelines are commonly used in the design field. Their meanings vary in different research or design projects, from vague to more specific (Liu, 2020; van der Hoeven and Juchnevic, 2016). We adopt the well-defined concept called 'patterns' from Alexander (1979, 1977) as what we mean by 'design principles.' In the following two paragraphs, we briefly describe the related concept of 'patterns' and how we make use of them.

"*Each **pattern** is a three-part rule, which expresses a relation between a certain **context, a problem, and a solution**. Each pattern depends both on the smaller patterns it contains, and on the larger patterns within which it is contained*" (Alexander, 1979, pp. 247, 312). Following these ideas, in this research, we treat the design principles as 'solutions' for 'problems' within 'contexts' (Section 3.2). In chapter 1 Introduction, we already describe the general context and problems. In chapter 3 Results, Section 3.2 Design principles, some design principles aimed at their own and more specific problems within certain contexts; we describe these problems and contexts whenever necessary in the description of each principle.

Alexander organizes different patterns in a scalar hierarchical **network**, in which the relationships between patterns are illustrated (and the network is indeed the structure of the **pattern language**) (Alexander, 1979, p. 314). Similarly, we organize all our design principles in a network (fig. 43).

2.2 A seven-step methodology framework for developing design principles

To systematically discover and evaluate design principles, we propose a methodology seven-step framework (Fig. 8), which includes (S1) developing design objectives and design dimensions, (S2) collecting data from cases and literature, (S3) data processing, (S4) proposing hypotheses, (S5) evaluation of hypotheses, and (S6) presenting final results. Iteration, as a typical procedure in design-related research (Nijhuis and Bobbink, 2012), is also embedded as Step 7 (S7) and as a sub-step within Step 3. The following sections describe some key components of the framework.

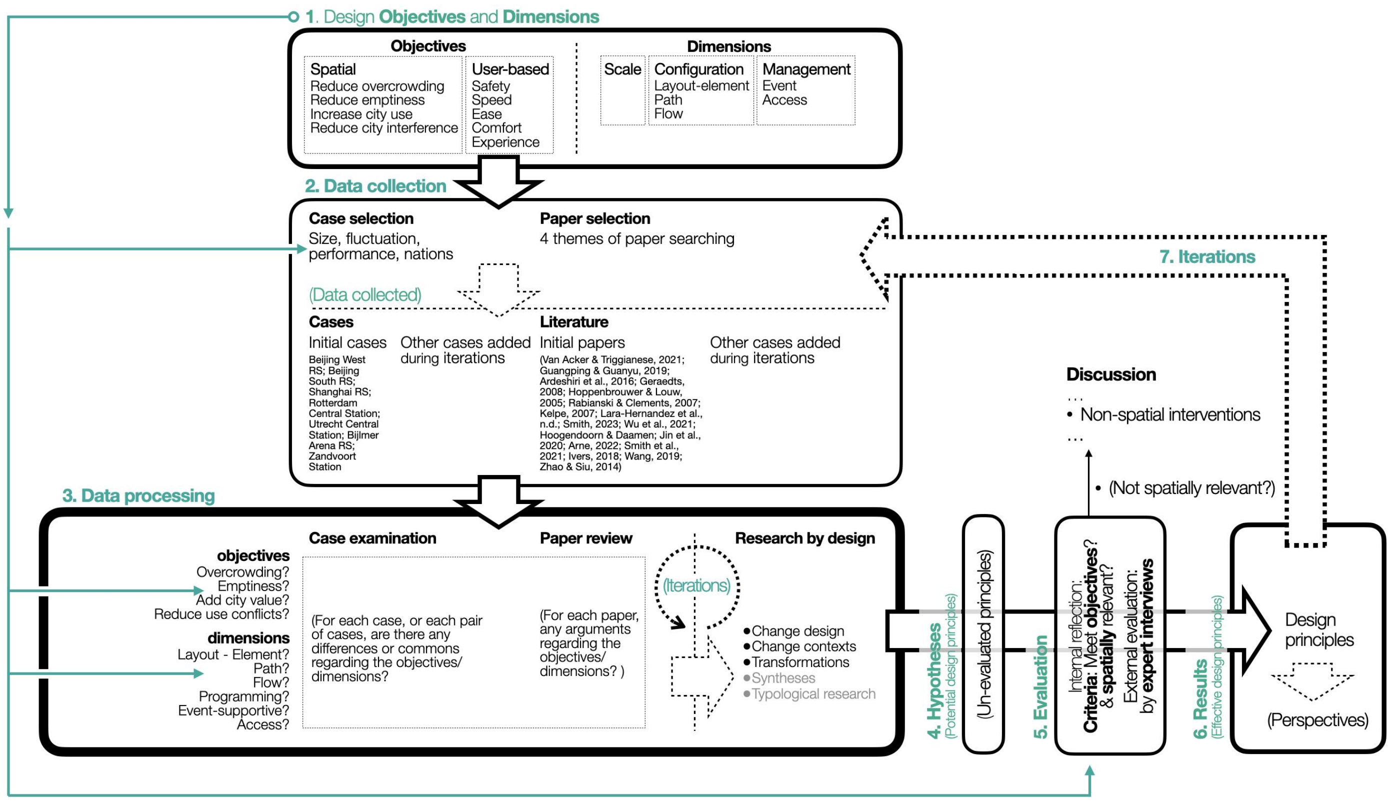

Figure 8: The process of developing design principles. (Image source: by authors)

2.3 Design objectives

Multiple design objectives are established in this paper, which are categorized into a) problem-solving and value-creating and b) user-based. The objectives in the first category are more relevant to stakeholders' interests, and the objectives in the second are more relevant to users' experiences.

2.3.1 Problem-solving and value-creating objectives

Four design objectives are defined in this category. The initial problems this paper investigates are overcrowding and emptiness, so 1) reducing overcrowding and 2) reducing emptiness naturally becomes the two primary objectives. Since this research is also embedded in the station-city integration topic, it considers beyond the station, setting two extra objectives for the city: 3) adding value to the city and 4) reducing interference to the city. Objectives 1) and 2) are the added values to stations, and 3) and 4) are the added values to cities. In this sense, these objectives contribute to station-city integration. These design objectives serve as guidance for collecting relevant data (in Step 2. Data collection), guide the examination of input data (in Step 3. Data processing), and function as criteria to evaluate the initial results (in Step 5. Evaluation, fig. 8).

2.3.2 User-based objectives

Various user-based design objectives are set. As transport infrastructure, stations have their primary users as transport passengers; While stations are also promoted as places in the city (Bertolini and Spit, 1998), they should also consider the non-passengers (e.g., neighborhood residents) as users. For passengers, according to van Hagen (2011), there are five types of needs: safety, speed, ease, comfort, and experience. A further study by Chen et al. (2024) translated these needs into quantifiable spatial and behavioral/perceptual features. For non-passengers, since they are diverse in nature, it is hard to define their universal needs; One attempt by Carr et al. (1992) specifies the general public space users' needs as comfort, relaxation, passive engagement with the environment, active engagement with the environment, and discovery. This paper therefore set corresponding design objectives as: 5) enhancing the five types of passengers' needs, and 6) enhancing the multiple general public space needs.

2.4 Dimensions of spatial and managerial interventions

This paper examines spatial interventions relevant to design and management. Railway station development is a complex topic addressed by different practice fields, including planning, design, management, and so on. These fields typically have interventions taken on certain temporal scales. Design and engineering renewals may happen every few years, and management interventions can be taken on a daily basis (Carmona et al., 2010). As design research, this paper primarily investigates spatial design solutions; and it also investigates managerial solutions (that have spatial implications) because events (both as problems and solutions) are closely related to management. Planning strategies usually address spatially much broader and temporally long-term issues, which is less relevant to the issues this paper addresses and, therefore, is left out.

2.4.1 The configuration of station areas

This paper views the configuration of station areas from four perspectives to encompass a comprehensive understanding of this complex system. Firstly, in the introduction part (Section 1.1), this paper already explained the station configuration as it facilitates pedestrian flow transfer from origins to destinations (Fig. 2, 3). Secondly, similar to the general flow analysis, designers in design practice often examine specific paths of users to gain experiential/perceptual understandings of space (Fig. 10 c) (Arne, 2022). Thirdly, design is also commonly treated as the study of elements and layout (de Jonge and van der Voordt, 2002; Liu, 2020). For station areas at the district level, elements include the station building, squares, city passage, urban furniture, and so on; and the layout is about the composition/constellation/organization/network of these elements. at the building level, the layout is about the organization of various mobility sites (railway, metro, bus, tram, bike, taxi/car) and building components (gates, indoor public spaces, hall, escalators, and so on) (Fig. 10 b; Fig. 9 b). Fourthly, the station areas can also be seen as things that belong to either the station or the neighboring city (Fig. 10 a). The configuration analyses from these four perspectives can be conducted at the district and the building levels.

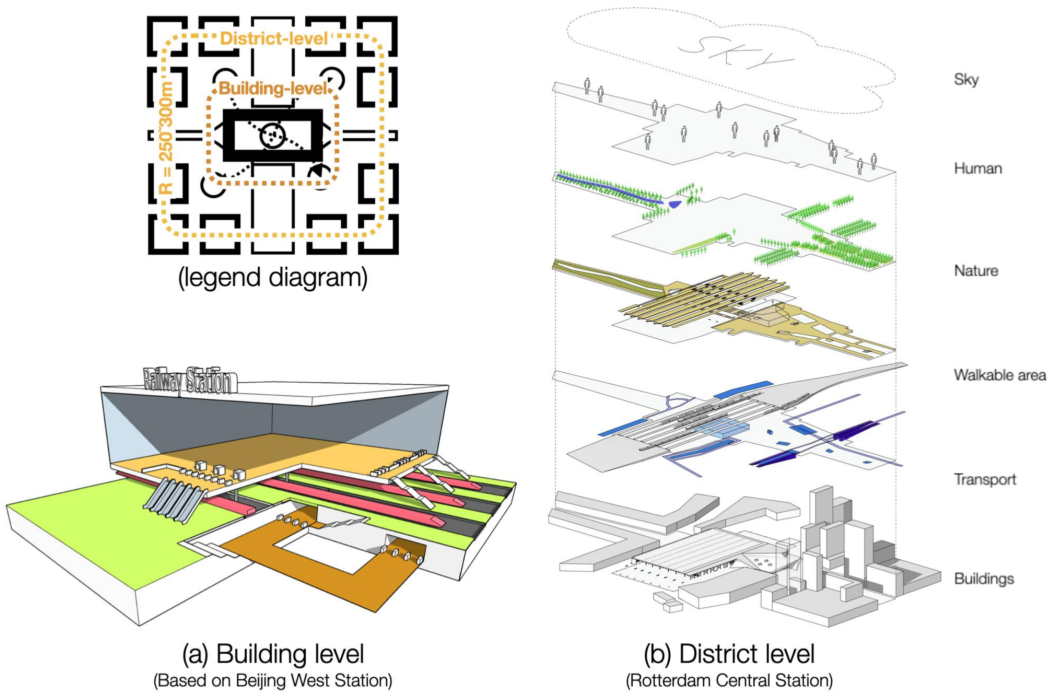

Figure 9: The station at the district and building levels. (Image source: by authors)

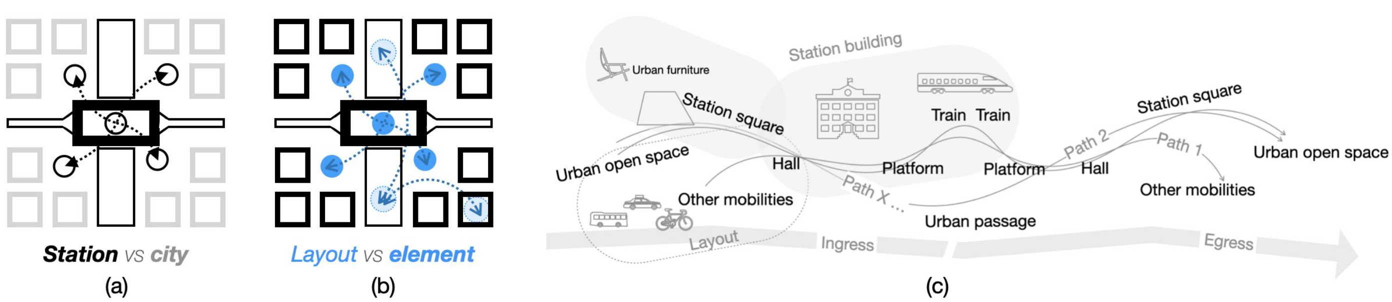

Figure 10: The configuration of the station. (Image source: by authors)

2.4.2 Managerial interventions

This paper considers two types of managerial interventions: organizing events and regulating access. According to Carr et al. (1992), there are several types of rights in public space, including access, claim, change, ownership and disposition, and so on. Management interventions can regulate these rights. Inspired by this, the paper realizes at least two types of managerial interventions - organizing events and regulating access (or routes and paths), can help to address overcrowding and emptiness. Firstly, although some (problem-causing) events affecting transport are the sources of the overcrowding and emptiness issues (Section 1.1), some other leisure events can be part of the solutions;

When the redundant spaces in station areas are empty during normal times, (solution-oriented) leisure events can be organized to reduce emptiness, such as exhibitions in station buildings, and markets or crowd dancing on station plazas (van Nieuwenhuize, 2023). Secondly, regulating access/route/path is commonly seen in crowd management practices to (re-)distribute the pedestrians and avoid overcrowding.

2.5 Data sources

This paper uses real-world cases and literature as data sources to discover initial relevant solutions (that already exist in practice). It uses 'research by design (RbD) (12)' to further develop new solutions (that do not exist in practice (Nijhuis and Bobbink, 2012)). Combining literature and cases with RbD enables us to find solutions from the past and for the future and to leverage both theoretical and practical knowledge (Fig. 11).

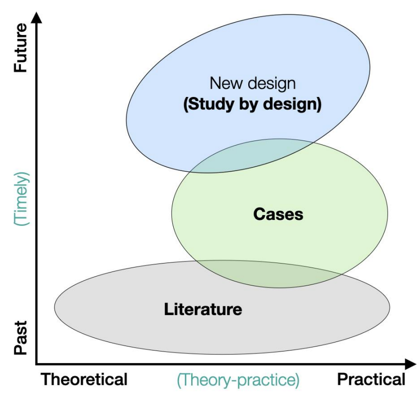

Figure 11: Data sources. (Image source: by authors)

2.5.1 Cases

The cases used in this paper include seven initial station cases, multiple extended station cases, and non-station cases. Seven initial station cases are selected, including Beijing West Railway Station (RS), Beijing South RS, Shanghai RS, Rotterdam Central Station (CS), Utrecht CS, Bijlmer Arena RS, and Zandvoort RS. They differ in 1) fluctuation contexts and/or 2) performance addressing fluctuation. Some of them - 'poor' examples (Beijing West RS and Beijing South RS) - have overcrowding and emptiness phenomena yet not solved, while others - 'good' examples - potentially solved these phenomena. Most of them are major stations of the cities (see Supplementary Materials, Table 1; Section 4.3 Station typology implied by the cases). These initial cases are also chosen due to our physical vicinity to the cases, which enables us to do site visits and get experiential/perceptual heuristics.

Extended station cases and non-station cases are also added in several situations: 1) When initial station cases are not enough to illustrate the discovered solutions, 2) When extra cases extend the generalizability of the design principles. The non-station cases are primarily selected from airports, shopping malls, and stadiums because they, like stations, are also large infrastructures that deal with massive users.

2.5.2 Literature

Literature is searched through four themes. 12 papers are finally selected and used for providing heuristics for research-by-design (see Supplementary Materials, fig. 46). The first theme of searching is demand-responsive related concepts (Section 1.2), including 'resilience,' 'flexible,' 'dynamic,' 'adaptive,' 'robust,' 'movable,' 'reconfigurable,' 'multi-functional,' 'temporary,' and so on (see Section 6.1.1 in Supplementary Materials for more explanations). The second theme is specifically for searching heuristics that deal with overcrowding: pedestrian simulations of railway stations. The third theme is specifically for searching heuristics that deal with emptiness: events (or activities) in public spaces (or urban/open spaces,' 'places,' and 'landscapes'). The fourth theme includes the station-city consideration: station-city integration from the urban design perspective. Google Scholar was used as the database for searching, considering its diverse range of literature types, making it suitable for design-related content beyond typical scientific knowledge.

2.6 Data processing

We examine each case and literature paper regarding its relevance to design objectives and dimensions, compare various pairs of cases to see evident commons or differences, and then use the findings for research-by-design (See Supplementary Materials, fig. 50, and Sections 2.3, 2.4). The research-by-design method is explained below:

2.6.1 Research by design

Research by design (RbD) is a research method that uses design to develop knowledge. We adopt the definition of RbD proposed by de Jonge and van der Voordt (2002), in which RbD is defined as **changing the design itself or its context** and studying the **effects** of the transformations (Fig. 8).

More specifically, in this research, the changes/transformations we made include transferring strategies between different types of buildings/spaces; transferring strategies between different scales; testing with different shapes, sizes, positions, directions, and so on (DADFT, 1991); making novel combinations/syntheses of different objectives and measures. Fig. 12 is an example of using RbD to study the relationship between event typology and the positioning of city passages. (See also Supplementary Materials explaining the validity of research by design.)

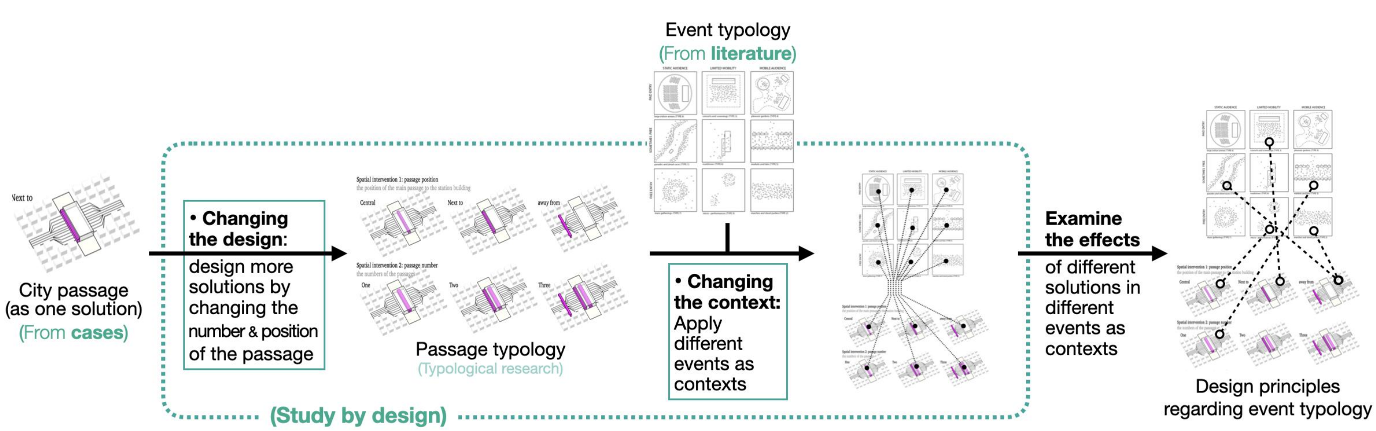

Figure 12: An example of research by design. (Image source: by authors)

2.7 Criteria for evaluation

We evaluate the design principles with two criteria: 1) whether the findings meet design objectives (Section 2.3); 2) how practical they can be used in practice (Nijhuis and Bobbink, 2012). Firstly, we check the design solutions by ourselves using a table where design objectives are listed against principles (See Supplementary Materials, fig. 51). Secondly, we do interviews with field experts to reflect on the design principles.

3 Results

3.1 Overview of the design principles

Within the time frame of this research, more than twenty design principles are developed. It is evident that more potential design principles can be found in future research following the same methodology. Literature, cases, and research-by-design all provide substantial heuristics for the final result (fig. 13). Different design principles have their varying strengths and limitations (Supplementary Materials, fig. 51).

Design principles	Source of heuristics				Reflections from experts
	Cases (station)	(non-station)	Literature	Research by design	
1. Flexible use	-	Paris beaches (Paris Plages)	(Hoppenbrouwer & Louw, 2005)	-	-
2. Suitable general layouts of the station and city	-	-	(Guangping & guanyu, 2019; Shikata et al., 2013)	Apply different layouts as contexts	-
3. Set apart non-transport function	Utrecht new vs old;	-	-	-	-
4. Vibrate city environment by scattered mobility nodes	-	-	-	Transformed from DP5 to a larger scale	-
5. Increase accommodating capacity by scattered mobility nodes	Beijing West vs Shanghai	-	-	-	-
6. Make events visible by aligning main paths and open spaces	Beijing West; Rotterdam new vs old	-	-	Virtually add events to see the effects	-
7. Human-oriented spaces	Rotterdam new vs old	-		Virtually add events to see the effects	-
8. Connect with neighborhoods	Beijing West; Rotterdam; Utrecht	-	(Peters & Tolkoff, 2016)	-	√
9. Smooth level changes by landscape design (District level)	Jiaxing	-	-	Transformed from DP10 to a larger scale	-
10. Smooth level changes by landscape design (Building level)	Arnhem	-	-	-	√
11. Adaptive redundant spaces with path regulation	Shanghai	(Path regulations in) Airports; Shopping malls	-	Transformed from non-station case experience	√
12. Programming considering the time dimension	Guangzhou	TOD mixed-use practice	(Calthorpe & Poticha, 1993)	Transformed from higher-frequency events	-
13. Shortcuts or optimizing paths	Beijing West	-	-	Design shortcuts as a new solution	√
14. Flexible buildings	-	The Shed; Stadium 974	(Ivers, 2018; Smith, 2023)	-	√
15. Flexible building components	-	-	-	Transformed from DP14 to a smaller scale	-
16. Add installations and facilities	Antwerpen	-	(Ivers, 2018; Kelpe, 2007)	Transformed from non-station cases	√
17. Reconfigurable elements	-	-	(Ivers, 2018)	Transformed from non-station cases	-
18. Redundant spaces	-	Allianz Arena	-	Transformed from non-station cases	-
19. Setting apart bottlenecks	-	-	(Hoogendoorn & Daamen, 2004)	-	-
20. City passages	Rotterdam; Utrecht; Bijlmer	-	-	-	-
21. Position city passages	Rotterdam; Utrecht; Amsterdam	-	-	Apply this as a context for DP20	-
22. Reduce barriers to ease flow (District level)	Beijing West; Rotterdaam; Utrecht	-	-	Design	-
23. Reduce barriers to ease flow (Building level)	Beijng West	-	-	Transformed from DP22 to a smaller scale	-
24. Stairs as stages or seats	Utrecht; Cologne; Antwerp	-	-	-	√
25. City axes	Rotterdaam; Utrecht	-	-	-	-
26. Reconfigurable spaces	-	-	(Ivers, 2018)	Transformed from non-station cases	√

Figure 13: Sources of heuristics. (Image source: by authors)

3.2 Design principles

In this section, we present the individual design principles in the form of **Context-Problems(/Potentials)-Solutions-Examples-Limitations(/Reflections)** whenever possible. All principles are aimed at addressing the general overcrowding and/or emptiness problems (see Chapter 1 Introduction), while some individual principles also address their own specific problems, which are detailed in their corresponding description texts. For validation, each principle is reviewed by field experts during expert interviews, and the feedback comments are incorporated into the corresponding descriptions. In this paper, due to the word limit, we report the principles with only brief descriptions. The full descriptions can be browsed on our interactive website (`http://c1309928130.pythonanywhere.com/`). Each principle is indexed with a number in a full bracket, such as '(1)'.

(1) Flexible use

Two types of spaces in station areas can potentially be flexibly used, including stations' own spaces and the nearby neighborhoods' spaces. These spaces can be used to accommodate passengers during peak times and for leisure activities during non-peak times. This requires stations to be Connected with neighborhoods (8). For non-peak-time leisure use, it is necessary to further Reduce barriers to ease flow (22) & (23), provide Human-oriented spaces, with leisure events and Make events visible by aligning main paths and open spaces (6). Station areas also need to be Programmed considering the time dimension (12). Stations can even be designed as Flexible buildings or building components (14) & (15), to have a responsive capacity for accommodating passengers. However, flexible use also has its **limitations**, as it can potentially add to the management efforts for stakeholders of stations and cities (e.g., see the chaos in Bijlmer Arena station when the management capacity is surpassed (Aseniya, 2019)).

Notably, the term 'flexible use' intrinsically incorporates the 'time dimension,' while some similar terms do not necessarily incorporate it. To better emphasize the time dimension nature, terms like 'flexible,' 'temporary,' 'reconfigurable,' 'adaptive,' and 'changeable' are more appropriate than terms like 'mixed-use,' 'multi-functional,' 'all-in-one,' and 'sharing.' Because the latter can mean something has multiple functions working at the same time, not necessarily at different times.

Figure 14: Paris Beaches ('Paris Plages' in French) - Roads in Paris are flexibly used as beaches in the summer. (Image source: stadsstranden.nl)

(2) Suitable general layouts of the station and city and (3) Set apart non-transport function

Stations and cities can be seen as being composed of different elements, which can be arranged in a suitable general layout to make the spatial allocation more understandable and rational. These general layouts can be applied on different spatial scales. Mixing station transport functions with city non-transport functions can intensify land use, increase commercial revenue, vibrate the spaces, and so on. However, this also potentially causes conflicting use between the stations and cities, and between passengers and non-passengers. Therefore, sometimes it is necessary to Set apart non-transport function (3).

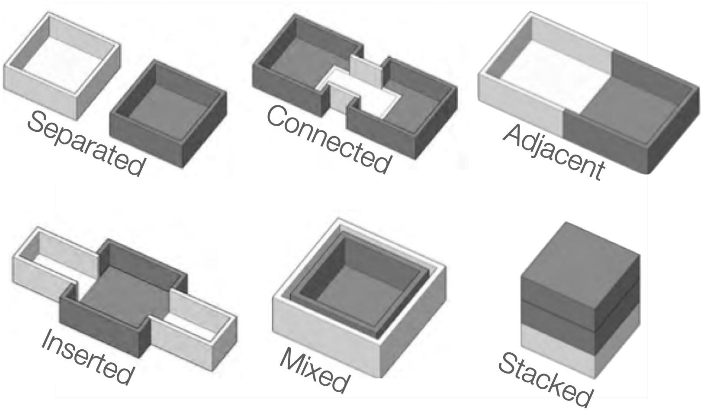

Figure 15: Different general layouts of the station and city. (Image source: (Qi and Lu, 2019)

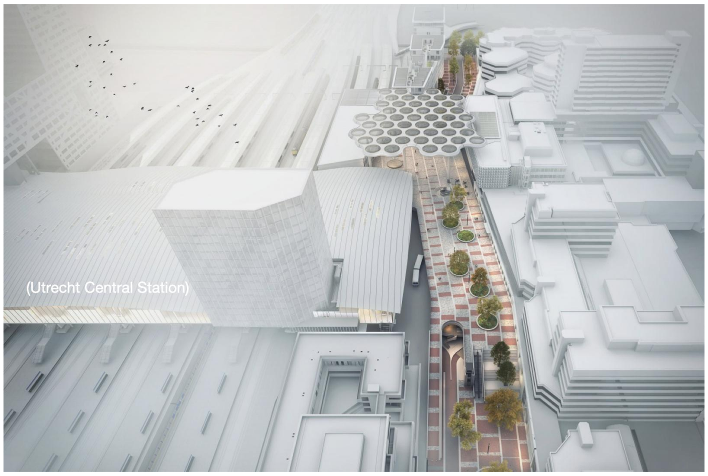

Figure 16: The east plaza at Utrecht Stations separates the station building from the shopping mall. (Image source: Santenco.nl)

(4) & (5) Vibrate city environment or increase accommodating capacity by scattered mobility nodes

Layouts of scattered mobility nodes are useful in two **contexts**. First, if a station is empty during non-peak times, scattered layouts let railway passengers, who are potential customers of city stores, go through city districts so that the city environment will be vibrant. Secondly, if a station has peak-time overcrowding, scattered layouts increase the accommodating capacity of the station during peak times. This is because passengers are more evenly dispersed to multiple sites instead of concentrating on a limited site, which reduces the probability of overcrowding/stampedes. However, scattered layouts may result in harder wayfinding and harder transferring between mobility sites, so it should be **limitedly** used for stations with light transfer loads between different mobilities.

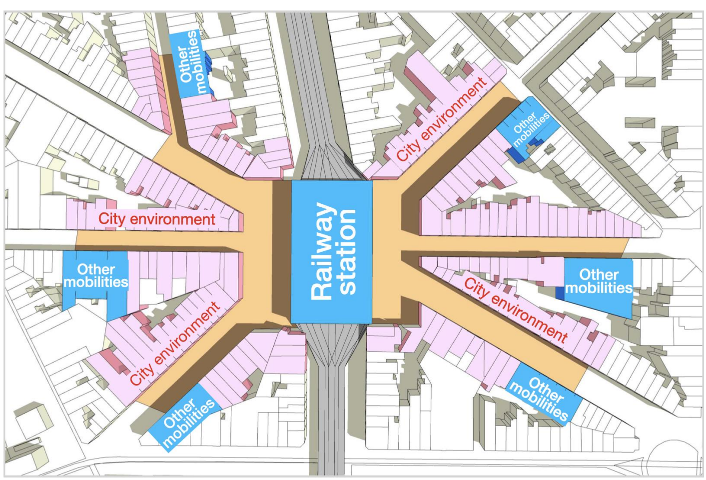

Figure 17: Vibrate city environment by scattered mobility nodes (at the district level)

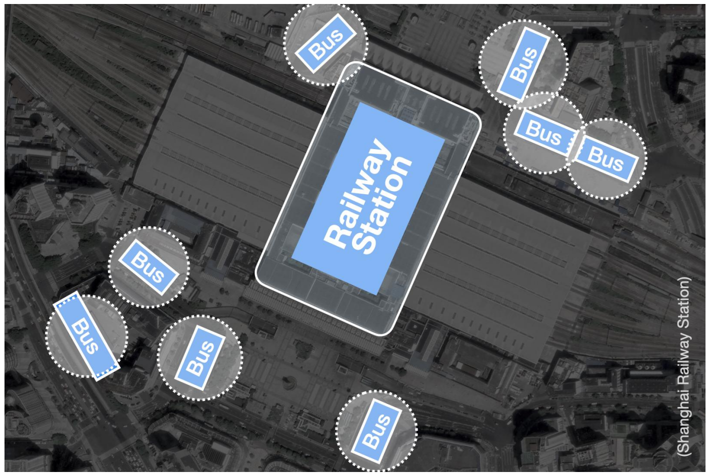

Figure 18: Increase transport capacity by scattered mobility nodes (at the building level)

(6) Make events visible by aligning main paths and open spaces

To create a vibrant environment and reduce emptiness, leisure events can be organized; But If the events happen in some spots that are invisible to pedestrians (e.g., due to level changes, street-level sight lines are blocked) or away from main pedestrian paths, then events can not easily attract people. Therefore, the alignment between open spaces and event-goers' (leisure users') paths should be well-designed -to make events visible or even accessible (for pedestrians to participate) - depending on the event types.

Many different types of events/activities can be held in station areas. For example, open markets, outdoor music festivals, carnivals, and so on. Events' visibility can be enhanced by using Stairs as stages or seats (24). Event-supportive spaces are usually Human-oriented spaces (7) that support Flexible use (1). The paths that event-goers (leisure users) are willing to walk through should be considered in a large network of paths, which can consist of Connections with neighborhoods (8) that (22 23) Reduced barriers to ease flow, and City passages and their positioning (20) & (21).

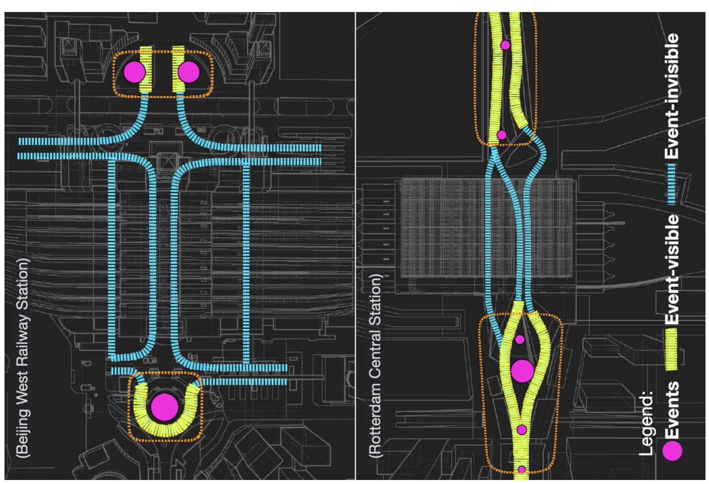

Figure 19: Alignment between open spaces and main paths. (Image source: by authors)

(7) Human-oriented spaces

Human-oriented spaces should support people to stay. In fig. 20-left, we try to illustrate some essential features of a human-centered space regarding the layout: it should be a coherent space at a core position in the station areas or the station buildings, free from traffic elements and intensive pass-by transport flow so that people would like to stay. In contrast, the layout in Fig. 20-right does not have these features.

Human-oriented spaces also need good spatial qualities that enhance the human experience as much as possible. It is impossible to exhaustively define all the qualities, which is perhaps why Alexander calls such qualities the 'quality without a name' (Alexander, 1979). Nevertheless, in the urban design field, scholars have explicated some common qualities (with spatial features), for instance: human scale; enclosed spaces with well-defined boundaries (Sitte, 1889); positives edges that promote social activities, urban life (Gehl, 1987; Whyte, 2001), and recognition/identity of different areas (Jacobs, 1961; Lynch, 1960); complexity/diversity of visual elements (Ewing and Handy, 2009).

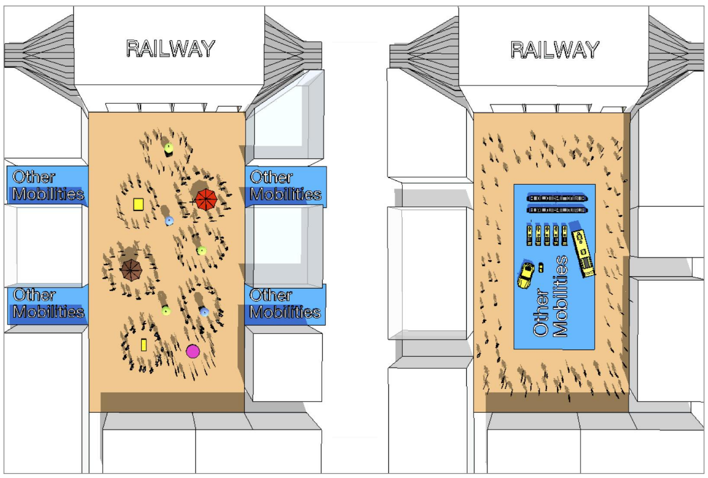

Figure 20: Human-oriented spaces versus vehicle-oriented spaces. (Image source: by authors)

Figure 21: The old and the new Rotterdam central stations. (Image source: Upper-left - Wikimedia.org; Upper-right - Internaathetposthuis.nl; Lower-left - Indebuurt.nl; Lower-right - MVSA Architects)

(8) Connect with neighborhoods, and (22) & (23) Reduce barriers to ease flow

Stations and cities can share each others' space for Flexible use (1), and in this **context**, they should first be connected (fig. 22). The connections/linkages between a station and its city neighborhoods can be pedestrian paths, footbridges/skywalks, tunnels, and so on. Typically, these connections are smaller parts of longer paths, and it is necessary to ensure they have enough capacity for passengers to pass during peak times. In addition, to avoid sudden changes/-variations in the width of the paths, which usually lead to a more significant bottleneck effect (Rzezonka et al., 2021), these connections can be designed in proper geometries with smooth width changing.

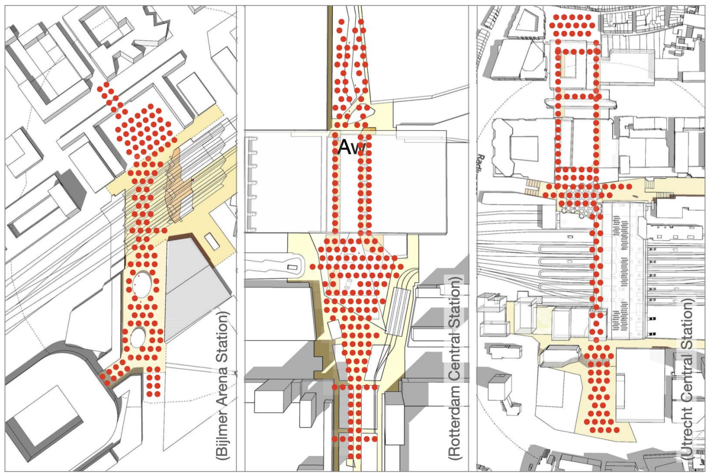

Figure 22: Connect with neighborhoods. (Image source: by authors)

If stations are already Connected with city neighborhoods (8) but due to poor connections' qualities, only passengers driven by strong motives would use the connections and leisure users are not willing to, then improving connection qualities is necessary. In other words, it is necessary to remove barriers to ease the flow.

Barriers to flow are usually in the following forms: 1) Stairs; 2) Lengthy, narrow, and boring paths; 3) Tunnels and skywalks/footbridges, which require effort to climb 4) Walking areas that are interfered with by intensive vehicle traffic; and 5) Strict security checking points or ticket gates.

Various **interventions** can be taken to reduce barriers to ease flow (figs. 23, 24), depending on the barrier types. Firstly, ground-level paths should be used as much as possible to avoid level changes and to maintain the street-level qualities of the overall environment. Secondly, Smooth level changes by landscape design (9) & (10). (This is particularly useful with small level changes; For large level changes, using escalators is usually more appropriate). Thirdly, for lengthy boring paths, design them like Human-oriented spaces (7), make them more pleasant with leisure facilities, otherwise use Shortcuts or optimizing paths (P13). Fourthly, if footbridges/skywalks are adopted, create street-like qualities. Fifthly, separate traffic roads from pedestrian paths, e.g., horizontally align the pedestrian paths and traffic roads or vertically submerge/elevate traffic roads to avoid overlapping. Sixthly, although security checks and ticket gates are primarily management issues, for spatial design considerations, Shortcuts or optimizing paths (P13) can possibly be adopted. Lastly, consider City passages and their positioning (20) & (21) if station areas are cut apart by railway tracks.

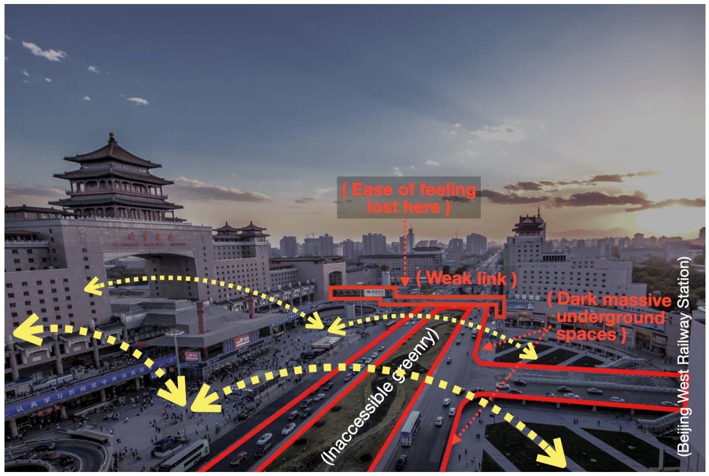

Figure 23: Reduce barriers to ease flow at the district level. (Image source: Analyzed and drawn by authors; Background image source: Meipian.cn)

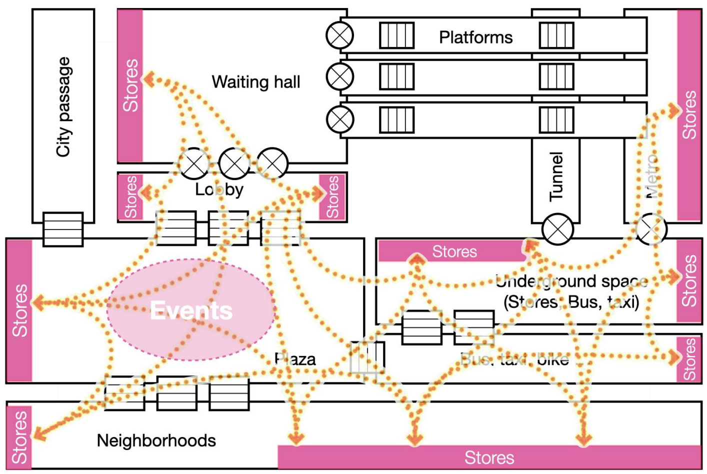

Figure 24: Reduce barriers to ease flow at the building level. (Image source: by authors)

(9) & (10) Smooth level changes by landscape design

Walking on stairs is not a smooth experience - it requires careful attention from pedestrians in case of falling down, and it is even more dangerous during overcrowding. To further advance Human-oriented spaces (7) in railway station areas, it is helpful using landscape design (figs. 25, 26) smoothing the level changes, which would also help prevent pedestrians from falling down, especially in flow-intensive areas. Landscape design can be applied at the district level or at the building level (figs. 25, 26). When applied at the building level, it can sometimes bring a fresh spatial experience (like in the Arnhem Central Station case). **However**, landscape design smoothing level change can also be expensive, and simply using escalators could be a cheaper alternative, especially when the level changes are large. It may also cause confusion in wayfinding for people who are not familiar with such level-changing spaces.

Figure 25: Smooth level changes by landscape design at the district level. (Image source: ThePaper.cn)

Figure 26: Smooth level changes by landscape design at the building level. (Image source: UNStudio.com)

(12) Programming considering the time dimension

City spaces and infrastructure can be programmed next to railway stations to promote flexible use. For example, Green parks and pedestrian-friendly streets, if located next to stations, can be temporarily restrictedly used by stations exclusively - for accommodating waiting passengers during railway peak times or for evacuation during emergent times. Similarly, large infrastructures such as sports stadiums and music venues, since they are usually not used on a daily basis, can be shared with stations for railway peak time use. In the **case** of Guangzhou, China, multiple sports stadiums were planned for backup use of railway stations if any emergency occurred during Chinese New Year times (Agency, 2016).

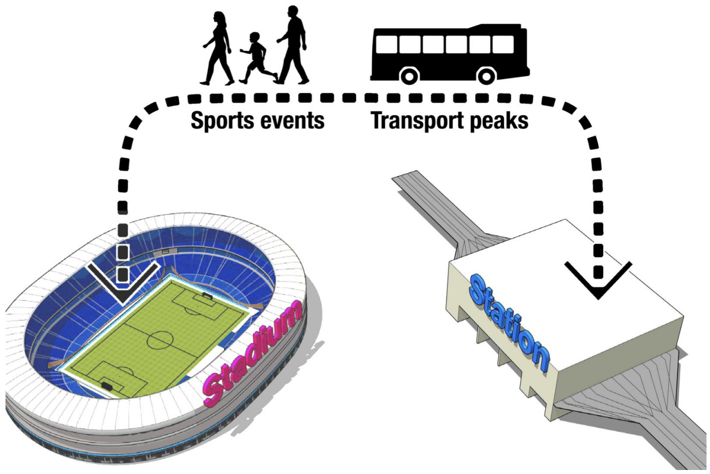

Figure 27: Programming considering the time dimension (for flexible use). (Image source: by authors)

(13) Shortcuts or optimizing paths

In some stations, the transfer between certain mobilities can be effect-consuming due to lengthy paths and procedures. For instance, at Beijing West Railway Station, if a passenger comes out of the metro and wants to go to the railway, he needs to check out from the metro, walk along the lengthy paths with level changes, and then check in at the railway with a strict security check and ticket check (fig. 28).

If there are shortcuts - direct links between the metro and the railway - in the paths (fig. 28), the passenger can save transfer distance and be relieved from double security checks. Such shortcuts exist in cases like Beijing South Railway Station. Shortcuts in paths are similar to Path regulation for adaptive redundant spaces. From a temporary perspective, the shortcuts can be dynamically used. They can be used during non-peak times for shorter transfer distances while shut down during peak times for safety (as a lengthy path has more redundant spaces to accommodate strained passengers).

Adding shortcuts, **however**, means adding extra ingress/egress paths, in which extra electronic systems are needed, increasing costs for railway companies. It also adds more complexity for the system and for the users. The well-designed Human-oriented spaces (7) along the normal paths will be missed if passengers choose the shortcuts over the normal paths.

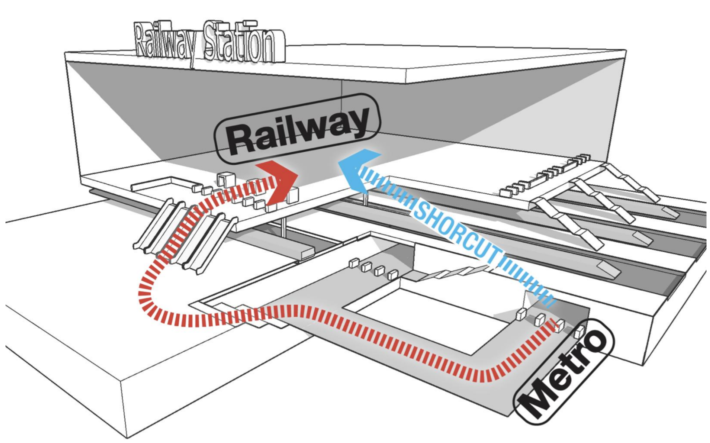

Figure 28: Shortcuts or optimizing paths. (Image source: by authors)

(14) & (15) Flexible buildings or building components

If a station has huge fluctuations of use, to support Flexible use (1), it can be designed as a flexible building or a building with some flexible components (figs. 29, 30). Besides 'flexible buildings' (Geraedts, 2008), various types of buildings titled with concepts enable a certain degree of flexibility. These concepts include 'changeable,' 'movable,' or 'temporary buildings,' 'multi-functional' (in temporal dimension), 'reconfigurable,' 'kinetic' (Parametric Architecture, 2024), and so on. These buildings have the flexibility either by changing their use (functions) or their existence (assemblage) during different times.

Architects have long proposed flexible buildings or even flexible cities (Parametric Architecture, 2024); however, real-world-built examples are rare due to the high cost and maintenance. For station cases, there are some stations that are only temporarily used during event times, such as Rotterdam Stadion Station, and temporary station buildings during the construction of the main new station buildings, such as in the Rotterdam Central Station case. In Shanghai South Railway Station and Beijing West Stations, redundant checking machines located in the gate areas, as flexible building components, are flexibly used during peak times.

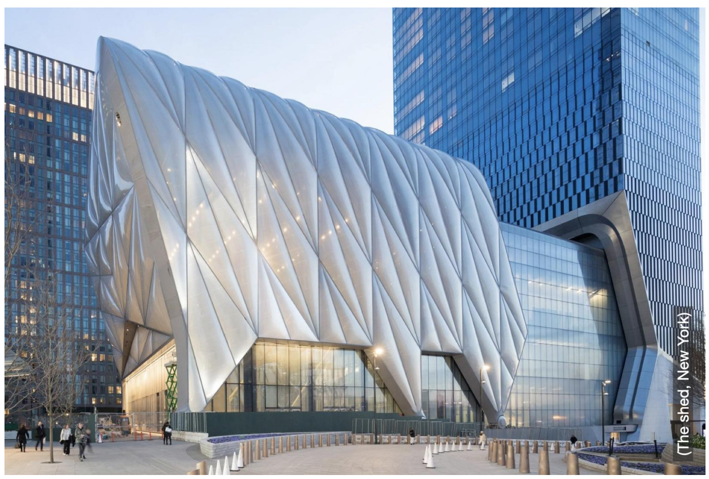

Figure 29: A changeable building - the Shed. (Image source: Architecturaldigest.com)

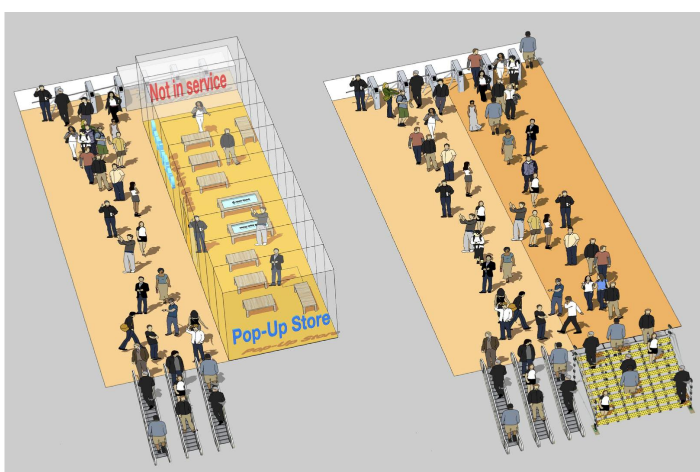

Figure 30: Changeable building components. (Image source: by authors)

(16) Add installations and facilities

If a station's spaces are huge and boring□ then installations and facilities (fig. 31) can be added to create human-oriented spaces (7). Installations and facilities can stimulate events, reduce the size of huge empty spaces to make them more human-scale, and make the scenes visually diversified (i.e., complexity). Installations can be interactive (e.g., ferry wheels) or just visually interesting (e.g., big inflatable art installations (Ivers, 2018)). Installations and facilities can also be Reconfigurable elements (17).

However, if the installations and facilities are not attractive by themselves, then they can deteriorate the space quality. For instance, in the Antwerpen Central Station case, when the ferry wheel is installed, the corresponding facilities, such as ticket-selling points, can make the square messy. On the street level, pedestrians' views are much blocked by these facilities, and the beautiful facade of the station is less visible to pedestrians.

Figure 31: Add installations and facilities. (Image source: Flickr.com)

(17) & (26) Reconfigurable elements or spaces

Reconfigurable elements or spaces can be used to vibrate the environment if station spaces are empty during non-peak times. Reconfigurable elements can be reconfigured into different layouts for different use scenarios. This reconfiguration can implemented either by event organizers or by users through spontaneous activities (e.g., people who use urban furniture will move the furniture by themselves). Reconfigurable elements can be urban furniture (fig. 32), potted plants, art installations, stalls, and so on (Ivers, 2018). Reconfigurable spaces, which may filled with reconfigurable elements, can be used as venues for different events/activities (fig. 33).

Figure 32: Reconfigurable elements. (Image source: (Ivers, 2018))

Figure 33: Reconfigurable spaces. (Image source: Shutterstock.com)

(18) & (19) Redundant spaces be (11) Adaptive with path regulation

If the station has surges of passengers during peak times; and if mobility sites or bottlenecks are too close, then the strained passengers will quickly add up to overcrowding. In this **context**, it is necessary to add redundant spaces or, equivalently, set apart bottlenecks (Hoogendoorn and Daamen, 2004) (figs. 34, 35).

Redundant spaces reduce overcrowding in two ways: Firstly, redundant spaces are extra spaces that accommodate strained pedestrians. Secondly, redundant spaces make pedestrians walk longer, and since different people walk at different speeds, the surges/peaks of pedestrians at the origins will be smoothed when the pedestrians arrive at their destinations (fig. 36). Despite redundant spaces being necessary for safety concerns (i.e., to prevent overcrowding) during peak times, the long distances added by the redundant spaces can be unacceptable for passengers during non-peak times. In this situation, temporary Shortcuts or optimizing paths (P13), should be adopted, or make the spaces as Adaptive redundant spaces with path regulation (11) (fig. 37).

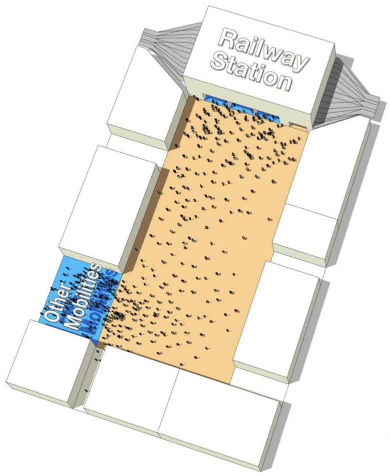

Figure 34: Redundant spaces at the district level. (Image source: by authors)

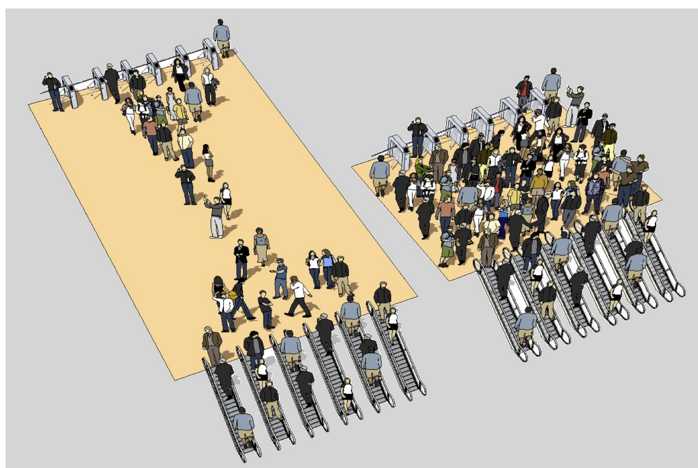

Figure 35: Setting apart bottlenecks at the building level. (Image source: by authors. Inspired by the research conclusion in (Hoogendoorn and Daamen, 2004))

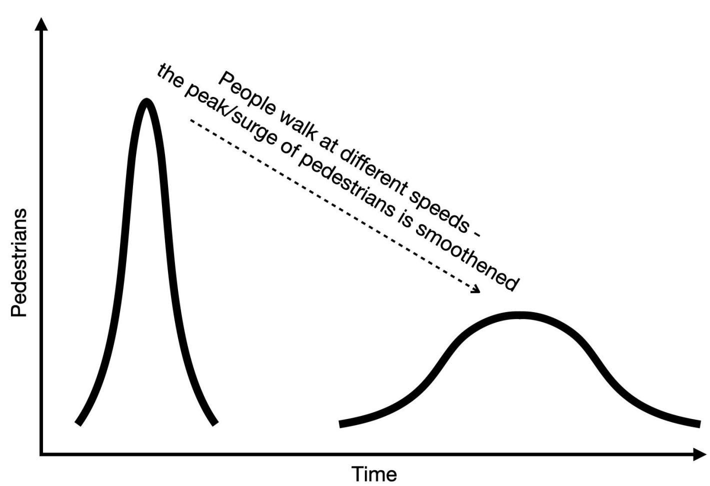

Figure 36: The peak of pedestrians is smoothed since people walk at different speeds. (Image source: by authors)

During peak times, paths can be regulated by fences or lines to ensure pedestrians move in an orderly queue, which prevents pedestrians from concentrating randomly or even resulting in stampedes. Instead of fences or lines, which are quite intrusive elements, more user-friendly, even interactive spatial elements can be used, such as urban furniture, water bodies, fountains, potted plants, art installations, and stalls (fig. 38) (These are also Reconfigurable elements (17)). To further satisfy the waiting passengers in the regulated zigzag paths, it is beneficial to create a pleasant environment of staying, compensating for the longer waiting time. Notably, path regulation has its **limitations** as it has managerial costs and can easily raise complaints from passengers or nearby citizens; therefore, it should be used sparingly with strong necessity.

During non-peak times, the path-regulating elements can be removed to let passengers move with the shortest transfer distance, and the redundant spaces can be used by city users for leisure activities/events.

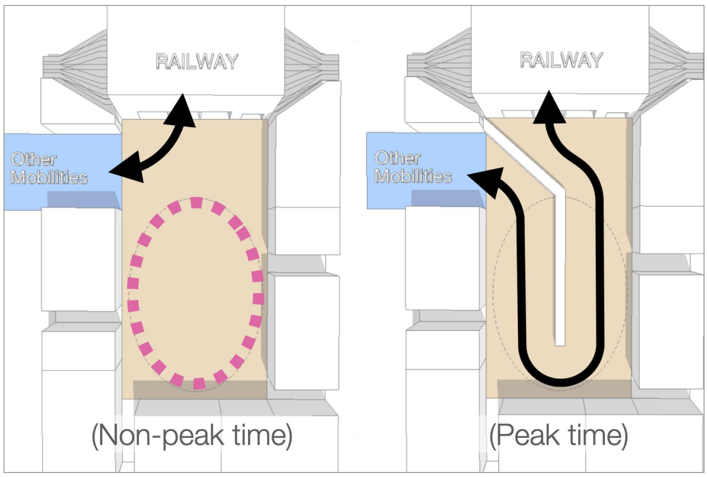

Figure 37: Adaptive redundant spaces with path regulation: left - non-peak time; right - peak time. (Image source: by authors)

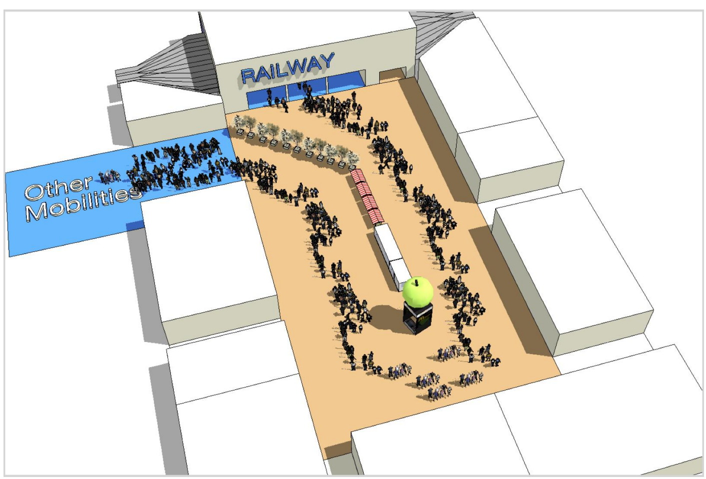

Figure 38: Path regulation using reconfigurable elements. (Image source: by authors)

(20) & (21) City passages and their positioning

If railway tracks cut city areas apart, then it is necessary to enable passengers and city users to move across the tracks easily for easy transfer and for vibrating the environment. In this context, well-designed/planned city passages and their positioning are needed. At the district level, city passages across railway tracks should be positioned according to the stations' usage as well as the city neighborhoods' conditions (fig. 39). The passages should avoid bringing interference between transport passengers and city leisure users. At the building level, city passages can be designed with fine details, with enough lighting, and not too dark to make people feel unsafe (fig. 40).

The more passages, the more choices for pedestrians to pass through; **however**, it takes financial cost to build passages, and for large railway stations at the building level, it is often quite difficult to vertically arrange the passages with many other fundamental elements (including railway platforms, the ground, and stations' internal passages).

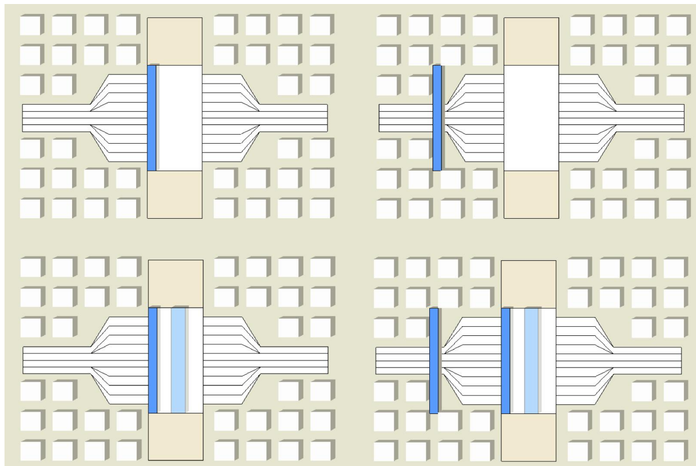

Figure 39: Position city passages (at the district level). (Image source: by authors)

Figure 40: The city passages (at the building level). (Image source: Amsterdam-viptours.com)

(24) Stairs as stages or seats

Typically, in station areas, grand stairs should be avoided as much as possible because they hinder the flow of pedestrians and may even result in people falling down. To address small level changes, instead of using stairs, it is better to Smooth level changes by landscape design (9) & (10). To address large level changes, instead of using stairs, it is better to use escalators. Given the same width, escalators have a larger capacity than stairs, and escalators, if not running, can still be used as stairs (Fruin, 1971).

However, in some situations, large stairs still exist in station areas, such as those designed as backups of escalators for evacuations. Or stairs just happen to exist in the station areas - like the grand stairs of the Cologne Cathedral in front of the Cologne Central Station.

If grand stairs exist, and if leisure events are expected as a measure to reduce emptiness, then the grand stairs can be designed as potential performance stages or audience seats, which takes advantage of the level change to leverage the see-and-be-seen relationship between audiences and performers (see also Principle Make events visible by aligning main paths and open spaces (6)).

Figure 41: Stairs as stages or seats. (Image source: Architectenweb.nl)

(25) City axes

City axes help to emphasize the connections, concentrate the flow of leisure users, and energize the environment. City axes also make the spatial structure of certain areas recognizable to decision-makers, thereby also promoting collaborations for different stakeholders to align the important spaces and facilities, for creating memorable experiences for users when they move in the environment. City axes have been successfully implemented in some (re)development projects of station areas, for **example**, the Utrecht Central Station area (fig. 42), the Rotterdam Central Station area, and the Delft Station area.

Figure 42: Two city axes were planned during the redevelopment of the Utrecht Central Station area. (Image source: Structuurplan, Stationsgebied Utrecht, December 2006)

4 Discussion

In this chapter, we first discuss several byproducts during the research process, including multiple perspectives for viewing the design principles (Section 4.1), non-design interventions (Section 4.2), and a station typology (Section 4.3). Then we outline the research contributions (Section 4.4) and limitations (Section 4.5).

4.1 Perspectives to view the design principles

During the research process, parallel with the new principles being developed, various perspectives emerged. These multiple perspectives can be seen as theoretical lenses through which to view the design principles (DPs) or typologies of the DPs. The multiple perspectives provide diverse ways for designers to relate to the individual principles. The perspectives also guide designers in finding new principles that follow the same way of thinking. In the following sections, we present these perspectives by viewing design principles as patterns within a network (Section 4.1.1) and as principles about different station components (Section 4.1.2), and viewing design principles from other perspectives (Section 4.1.3).

4.1.1 View design Principles as patterns within a network

We first arrange the resulting design principles in a **network** from the district level to the building level (fig. 43). This perspective is inspired by Alexander's pattern language (Alexander, 1979, p. 314), whose structure is a network usually organized in a hierarchical **scalar** order. The cross-scale connections between principles are important because each principle relies on the smaller principles it contains, and sometimes also the larger principles in which it is contained. For example, to Connect with neighborhoods (8), station areas need proper Positioning of city passages (21) at the district level, and well-designed City passages (20) at the building level; and sometimes even City axes (25) on a sub-city level.

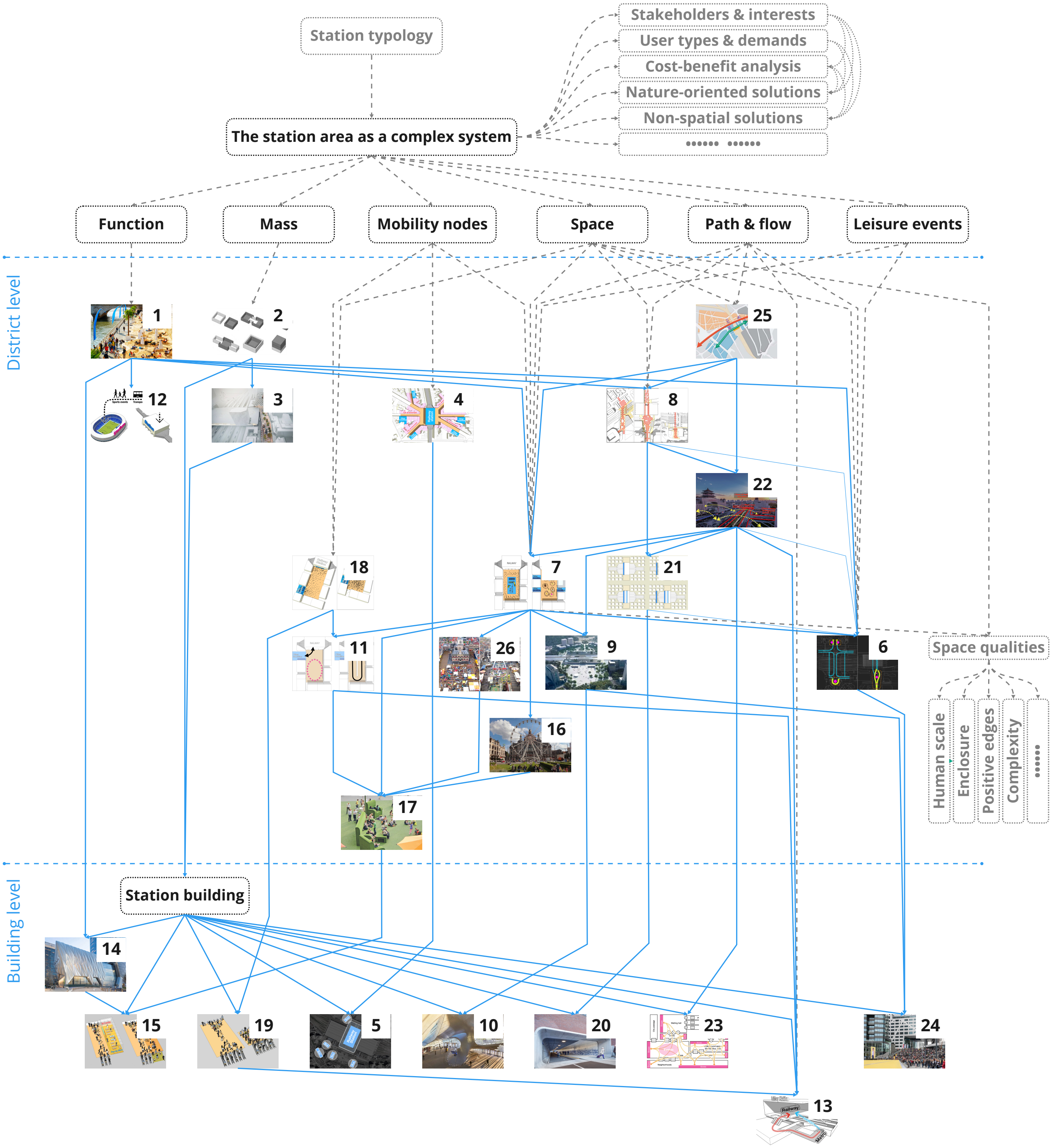

Figure 43: The design principles (patterns) within a network. (Image source: by authors)

4.1.2 View design principles as principles for different station components

The design principles can be categorized according to the component types of station areas which they deal with. On top of the aforementioned network, we already categorized the principles as related to **function, mass, space, flow & path, mobility nodes**, and **leisure events** (fig. 43), most of which are common perspectives used in urban, architectural, and railway station design. As part of the built environment, station areas can be seen as function versus form, as the mass versus the void (space) (Rossi et al., 1982; Trancik, 1986), as constellations of mobility nodes (including railway platforms, bus stops, tram stops, bike parking, car parking, and so on) (van der Spek, 2003); Space users in station areas move along various paths generating pedestrian flow; Additionally, to be demand-responsive, station areas should also support leisure events during non-peak times when they are not used for transportation.

4.1.3 Other perspectives to view the design principles

The design principles can be viewed from more perspectives (fig. 44): From the problem-solving perspective – addressing **overcrowding versus emptiness** – some principles primarily address the former, some primarily address the latter, and some address both. From a **spatial versus managerial** perspective, some principles are purely about spatial interventions, while others also require managerial interventions; In this sense, principles can also be seen as **fixed and semi-flexible**.

The principles can also be seen as related to **different event types** (see Supplementary Materials, fig. 52). For instance, if there are **large** events (e.g., mass gatherings and concerts), then design principles Adaptive redundant spaces with path regulation (11) and Human-oriented spaces (7) should be adopted to reserve large open spaces that are event-supportive; While if the stations are designed in a scattered layout (to Vibrate city environment by scattered mobility nodes (5)), then possibly only **small** events can be held in station areas.

The design principles can be viewed as rules of **elements and layouts** (Liu, 2020); However, elements and layouts are actually similar unless a certain scale is chosen to analyze them. In the aforementioned network (fig. 43), the layout on a smaller level can be the element on a higher level (e.g., City passages (20) can be parts of City axes (25)). In fact, just like a layout, an element 'is itself entirely a pattern of relationships' (Alexander, 1979, p. 89); it also defines relationships between different entities as the layout does. Besides the above perspectives, more perspectives can still be developed as long as they help designers relate easily to certain design principles.

	Objectives		*Spatial design relevance*				*Spatial or managerial*		*Sources of heuristics*			*Research by design*			*Event typology relevance*	*Station typolgy relevance*	
	Reduce overcrowding	Reduce emptiness	Building	Square, outdoor elements	Layout	Function	Spatial	+Managerial	Literature review	Case study	Research by design	Effects of a design	Effects of changing a design	Change contexts, scales, etc.	Event typology relavance	Major stations	Smaller stations
1. Flexible use	●	●	●	●	●	●	●	●	●	○	○	○	○	○	●	●	●
2. Suitable general layouts of the station and city	●	●	○	○	●	○	●	○	●	○	○	○	○	○	●	●	●
3. Set apart non-transport function	●	○	○	○	●	●	●	○	○	●	○	○	○	○	○	●	○
4. Vibrate city environment by scattered mobility nodes	○	●	○	○	●	○	●	○	○	●	●	○	○	●	●	●	○
5. Increase accommodating capacity by scattered mobility nodes	●	○	○	○	●	○	●	○	○	●	○	○	○	○	○	●	○
6. Make events visible by aligning main paths and open spaces	○	●	○	●	●	○	●	○	○	○	●	●	○	○	●	●	○
7. Human-oriented spaces	○	●	○	●	●	○	●	○	○	●	○	○	○	○	●	●	●
8. Connect with neighborhoods	●	●	○	○	●	○	●	○	○	●	○	○	○	○	○	●	●
9. Smooth level changes by landscape design (District level)	●	●	○	●	○	○	●	○	○	●	●	○	○	○	○	●	○
10. Smooth level changes by landscape design (Building level)	●	●	●	○	○	○	●	○	○	●	○	○	○	○	○	●	○
11. Adaptive redundant spaces with path regulation	●	●	○	●	●	○	●	●	○	●	●	○	●	●	●	●	○
12. Programming considering the time dimension	●	●	○	○	○	●	●	○	●	○	●	○	○	●	●	●	○
13. Shortcuts or optimizing paths	○	●	●	○	●	○	●	○	○	○	●	○	●	○	○	●	○
14. Flexible buildings	●	●	●	○	○	○	●	●	●	●	○	○	○	○	●	●	●
15. Flexible building components	●	●	●	○	○	○	●	●	○	○	●	○	○	○	○	●	●
16. Add installations and facilities	○	●	○	●	○	○	●	●	○	●	○	○	○	○	●	●	●
17. Reconfigurable elements	●	●	○	●	○	○	●	●	●	○	○	○	○	○	●	●	●
18. Redundant spaces	●	○	○	●	●	○	●	○	○	○	●	○	○	○	○	●	○
19. Setting apart bottlenecks	●	○	●	○	●	○	●	○	●	○	○	○	○	○	○	●	○
20. City passages	●	●	●	●	○	○	●	○	○	●	○	○	○	○	○	●	●
21. Position city passages	●	●	○	●	●	○	●	○	○	○	●	○	○	○	●	●	●
22. Reduce barriers to ease flow (District level)	○	●	○	●	○	○	●	○	○	●	●	○	●	○	●	●	●
23. Reduce barriers to ease flow (Building level)	○	●	○	●	○	○	●	○	○	●	●	○	○	○	●	●	●
24. Stairs as stages or seats	○	●	○	●	○	○	●	○	○	●	○	○	○	○	●	●	○
25. City axes	○	●	○	○	●	○	●	○	○	●	○	○	○	○	●	●	○
26. Reconfigurable spaces	●	●	○	●	○	○	●	●	●	●	○	○	○	○	●	●	●

Figure 44: The design principles viewed from different perspectives. (Image source: by authors)

In summary, with the above multiple perspectives, designers can view the design principles and relate them using various logic; and researchers/designers can develop new principles following the same ways of thinking.

4.2 Non-design interventions

Many purely managerial (non-design) interventions are discovered during the research process. Some of these interventions can be more effective than spatial interventions, some can be more costly, and some can be fantasies at the current time. Providing as a takeaway knowledge, We report the following managerial interventions:

To avoid overcrowding/stampedes, there are various managerial interventions, including 1) Rescheduling holidays for the public - different groups of people having the same holidays at different times; 2) Using city terminals - like those for the airport - to modify the logistics of long-distance travelers' packages and relieve the security checks at the station buildings; 3) manage regional-level transportation (e.g., there is a coordination of scheduling trains between several railway stations in Amsterdam city when there are sports events near Bijlmer Arena station, preventing people from coming to the stations when the station capacity is surpassed); 4) shutdown stations; 5) when organizing city-level events, use multiple scattered event spots - so that there will not be an over-concentration of massive people at one spot during special times such as when it is raining; 6) manage user expectations - notifying passengers that during peak time there will be longer transfer time than usual; 7) in certain railway stations, passengers are restricted from entering the station buildings (so the overcrowding can be prevented) until a specific time before their train's departure. For instance, during our site visits in December 2022 at Beijing West Railway Station, passengers were not permitted to enter the station more than 6 hours prior to their scheduled departure time; at Shanghai Railway Station, this time limit was 2 hours.

4.3 Station typology implied by the cases

Considering that station is the type of building with the most variety (Richards and MacKenzie, 1986, p. 52)), a typology is usually of concern in studies of stations (e.g., see (Peters and Novy, 2012)), and meanwhile, a universal typology is hardly achievable. In this research, for case selection, we take two factors that are most relevant for overcrowding and emptiness - first, degrees of fluctuation and second, performance addressing fluctuation (see Section Cases). The selected cases themselves have more intrinsic features, which imply a certain station typology, and by considering these features, we can better tell how generalizable the research outcomes are. Some intrinsic features of the selected cases include: Firstly, the continental or national contexts - China and the Netherlands; Secondly, the varying size of stations and cities - the selected cases cover small to large cities and stations (fig. 45). Stations' size affects their roles in the cities (Van Acker and Triggianese, 2021), and cities' size affects mobility patterns. Size affects the complexity of stations and the cost of spatial-managerial interventions; Thirdly, security checks - there are strict security checks in Chinese stations while no such in Dutch cases; Fourthly, different flow patterns - in Chinese stations, the flow of egress and ingress is separated in different paths (like airports), while in Dutch stations, it happens in the same paths; Lastly, there are different ways public spaces are used - more diverse leisure activities/events happen in Dutch cases than in Chinese cases.

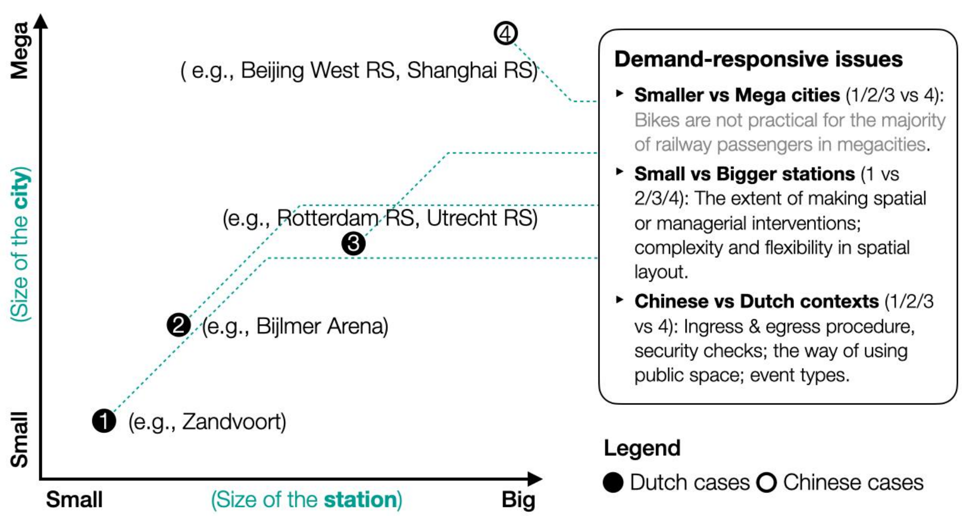

Figure 45: Station typology implied by the cases. (Image source: by authors)

4.4 Research contributions

This paper has two contributions to the design knowledge body: First, **contently**, it provides more than two dozen design principles that facilitate designers to address overcrowding and emptiness issues of station areas. This paper also provides multiple associated perspectives, which can be used to view the principles in different ways, and be used as theoretical lenses to help designers investigate new principles. The research outcome also enriches the content of relevant academic discussions, such as urban open space, responsive landscape, with a 'loose-fit' feature (Thompson, 2002); and traffic space is public space (Bendiks and Degros, 2020).

Second, **methodologically**, this paper provides a seven-step methodological framework, which can be generalized to develop other types of design principles. This methodological framework has its only values as compared to similar frameworks/workflows in literature. For example, compared to Christopher Alexander's way of developing his pattern language - through over eight years of project practice (Alexander, 1977), evaluate principles by feelings - our framework is more practical for much shorter time frames thanks to multiple data sources being used, and produce more objective outcomes thanks to expert reflections. Compared to the way van der Hoeven and Juchnevic (2016) developed their design principles, our framework is a new alternative.

4.5 Limitations and future research directions

This paper exhibits several limitations and future research directions. Firstly, there can be hidden limitations of some design principles that we do not yet know. Secondly, with the same selected cases, there are more pairs of comparisons between them, yet not examined by us due to the project's time frame (We documented to what extent we have examined in Supplementary Materials, fig. 50). Thirdly, more cases of different continental and national contexts can be researched in the future.

During our interviews with field experts, they pointed out more limitations - the design principles in this paper are mostly about the spatial form of districts or buildings, while other things are less investigated: programming, user types, spatial qualities, nature-based solutions, and cost-benefit analysis of solutions. Acknowledging this, we set the future research directions as such.

5 Conclusion

In the introduction, we proposed two research questions: 1) What are the design principles for demand-responsive railway station areas? and 2) What is a practical way to develop design principles? The first question is answered by the resulting design principles. These design principles are interconnected, covering a wide range of components of the station areas, and can be viewed from various perspectives. The second question is answered by the seven-step methodology framework for developing design principles. Design principles can be effectively identified through research by design based on multiple data sources.

Supplementary Materials

1. The detailed descriptions (of the literature, cases, research by design, evaluations, the range of station areas, design principles' relevance with events, and so on).

2. The interactive website for displaying the design principles from different perspectives (http://c1309928130.pythonanywhere.com/)

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