

An illustration of a vibrant city scene. In the foreground, three people (a woman in a red shirt and blue pants, and two men in green and white shirts) are standing and talking near a large, abstract sculpture. The ground is paved with reddish-brown bricks. In the middle ground, a modern railway station with a dark, sloped roof is visible. The words "ENTRAAL STATION" are written on its facade. People are walking on the sidewalk in front of the station. To the right, a tall, modern glass skyscraper rises into the sky. The background is filled with green trees, blue sky, and several birds flying. The overall style is a colorful, stylized illustration.

Towards Flexible Use of railway station areas that promotes Station-City Integration

The spatial relevance, design, and assessment

Enshan Chen

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and assessment

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Preface

This thesis is the culmination of a professional and academic path dedicated to understanding and designing complex projects. Its focus and methodology are direct responses to a gap I encountered throughout this journey.

My early career after my bachelor's degree involved working on large-scale commercial complexes, including shopping malls, retail streets, and high-rise towers. This was followed by a master's research in urban design under Professor Yu Zhuang's team, where I worked on railway station areas. Stations stood out as a pinnacle of complexity, involving flow dynamics, mixed-use functions, and diverse stakeholders. I was dealing with the urban form of station areas. Yet, a clear research question rooted in the real world remained elusive.

It was this specific gap that shaped the central mission of my PhD. A significant part of this research—approximately a quarter of the program—was dedicated to defining the precise problem: the co-existence of overcrowding and underutilization, driven by temporal fluctuations in station use. This thesis is structured to address this core issue.

The work presented here is organized around a transdisciplinary response that bridges spatial design, transport engineering, and computer science. It moves from providing a fundamental understanding of the problem to developing a robust assessment framework, and finally to formulating actionable design guidance.

This integrative investigation not only provides a solution to the identified problem but also logically points to the broader potential of digital twins for managing complex built environments—a direction I will explore in my forthcoming postdoctoral research.

Enshan Chen
Delft, November 2025

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I would like to thank my co-promoter, Manuela Triggianese, for reminding me of the building-level and interior dimensions of this research. Her strategic advice to initially focus on a single case study was crucial in narrowing the scope and identifying the research question, which saved my work and contributed to successfully passing the Go/No Go process.

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I also appreciate the graduate school courses that helped expand my understanding of research, particularly the course Research Design, which boosted my understanding of research typology and challenged me to think more than a typical designer does.

I extend my thanks to my colleagues and friends, whose diverse ideas, knowledge, and methods have inspired me. The many things I learned from them include: temporal scales, the relationship between pattern recognition and data sample size, assemblage thinking, learning recommendations on computer vision, movement simulation and traveler modeling, abductive reasoning, and the importance of asking ‘why’ questions in research. These have been instrumental to this research and to developing my expertise.

I would like to thank those who have provided me with care over the years, who maintain integrity in complex environments, and who practice other fine qualities. They contribute to my accumulation of positive memories, enriching my life as a lived experience. I am deeply grateful to my parents for their unconditional love.

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Contents

- List of Tables 17
- List of Figures 23
- Summary 24
- Samenvatting 27
- Executive summary 31

1 **Introduction** 34

- 1.1 **Research background: station-city integration and user experience** 34
- 1.2 **Problem statement: overcrowding and underutilization (O&U) in railway station areas** 36
 - 1.2.1 The consequence of O&U 37
 - 1.2.2 O&U associated with events and disruptions that cause fluctuations 38
 - 1.2.3 O&U associated with non-spatial and spatial factors 38
 - 1.2.4 The potential of flexible use in mitigating O&U in stations 40
 - 1.2.5 Summarize the O&U problem 42
- 1.3 **Academic relevance** 43
 - 1.3.1 Crowding studies in crowd management 43
 - 1.3.2 The uses of public space 44
 - 1.3.2.1 User experiences in stations 45
 - 1.3.3 Academic discussions such as ‘flexible use’ addressing changes 45
 - 1.3.4 Spatial design of stations and the theme of station-city integration 48
 - 1.3.4.1 Differentiate three station-related concepts 49
 - 1.3.4.2 Station-city integration 51
 - 1.3.4.3 Dual identities of railway stations 52
 - 1.3.4.4 Design principles 53
- 1.4 **Knowledge gap: lacking integrated knowledge for spatially addressing O&U**

	in stations	53
1.4.1	Lacking knowledge integration between academic topics	54
1.4.2	Lacking knowledge for spatial design practice	55
1.5	Research objectives and research design	56
1.5.1	Research objective	56
1.5.2	Research questions	58
1.5.3	Research design	58
1.5.4	Research significance	59
1.6	Research scope and key concepts	60
1.6.1	Events	60
1.6.1.1	Events and their frequencies of happening	61
1.6.1.2	Magnitudes of user volumes	61
1.6.1.3	Events at stations or not	62
1.6.2	The temporal uses of stations	62
1.6.2.1	Activities and users	62
1.6.2.2	Spatio-temporal uses of stations	63
1.6.3	Stakeholders and interests	64
1.6.4	Intervening through spatial design and management	67
1.6.4.1	The content addressed by urban and architectural design	68
1.6.4.2	Managerial interventions	70
1.6.5	The station type and case selection	71
1.6.5.1	Selected cases	72
1.6.6	The spatial scale of railway station areas: Around a 250m range	76
1.6.7	Summarize the research scope	78
1.7	Research methodology	78
1.7.1	Multiple methods	79
1.7.1.1	Case studies	79
1.7.1.2	Literature review	80
1.7.1.3	Analytical visualization	81
1.7.1.4	Methods for developing the assessment framework	81
1.7.1.5	Methods for developing the visual assessment model	81
1.7.1.6	Methods for assessing the design principles	82

1.7.2	Theoretical model	82
1.7.3	Assessment criteria for positive solutions	83
1.8	Thesis outline	85

PART I **Contextual Foundation** 87

2 **Literature review** 88

A review of existing knowledge on flexible use from a spatial design perspective

2.1	Introduction	89
2.2	Frameworks for the literature review	91
2.2.1	Framework defining the ideal solutions' characteristics	91
2.2.2	Framework defining the knowledge types	92
2.3	Literature searching and screening	94
2.3.1	Searching strategy (Inclusion criteria)	95
2.3.1.1	Expand five clusters of keywords	95
2.3.1.2	Search with keyword combinations	96
2.3.2	Exclusion criteria	96
2.3.3	Additional references suggested by experts	97
2.4	Results and interpretations	98
2.4.1	General overview of the included articles	98
2.4.2	The literature distribution in relation to disciplines	100
2.4.3	Theoretical insights	100
2.4.3.1	Envision new types of environments, spaces, and buildings	100
2.4.3.2	The synthesis of existing types of spaces or uses	102
2.4.3.3	Theoretical insights specifically on station-related content	103
2.4.4	Design measures	105
2.4.4.1	Design measures for the flexible use of buildings or urban spaces	105
2.4.4.2	Spatial design of railway stations	108
2.4.5	User knowledge	110

2.4.5.1	Transport activities	111
2.4.5.2	Non transport activities	113
2.4.6	Relevant technologies	116
2.4.6.1	Three clusters of technologies	116
2.4.6.2	Applications of these technologies in transport or design research	118
2.4.7	Limitations of flexible use solutions	120
2.5	Knowledge gaps and future research directions	122
2.5.1	Spatial layouts supporting flexible use	123
2.5.2	Knowledge integration	124
2.5.3	Design-oriented toolsets	125

3 Spatial relevance 126

Case studies through scenario analyses

3.1	Introduction	127
3.1.1	Research questions and contributions	129
3.2	Methodology	130
3.2.1	Selected cases and case comparisons	132
3.2.2	Assumptions of flexible use in different scenarios	133
3.3	Results	135
3.3.1	National contexts' influence on overcrowding and underutilization	135
3.3.2	National-context-associated factors' influence on spatial configurations	137
3.3.3	Spatial configurations' influence on overcrowding	140
3.3.4	Spatial configurations' influence on non-transport uses	140
3.3.4.1	Spatial configurations' influence on the use of commercial areas	140
3.3.4.2	Spatial configurations' influence on leisure activities	141
3.3.4.3	Spatial configurations' influence on leisure events	142
3.3.5	Synthesize spatial configurations' influence on overcrowding and underutilization	151
3.3.6	Commonalities and differences between the Chinese and the Dutch stations	153
3.3.7	The complex interrelationships and the potential of spatial design	155
3.4	Discussions	158
3.4.1	The untapped potential of static layouts for flexible use	158

3.4.2	The nature of elements and layouts in relation to spatial scales	158
3.4.3	The role of other contextual factors	159
3.4.4	Experience transfer between different national contexts	159
3.4.5	Correlation between flexible use and station-city integration	160
3.4.6	Research contributions and limitations	160
3.5	Conclusions	161

PART II **Design Principles** 164

4 **Design principles** 165

Iteratively learned from cases and literature through analytical visualization

4.1	Introduction	166
4.2	Methodology	167
4.2.1	Objectives and scenarios to support	170
4.2.1.1	Design objectives or assessment criteria	170
4.2.1.2	Scenarios and assumptions of flexible use	170
4.2.2	The spatial, temporal, and managerial dimensions of stations	171
4.2.2.1	Spatial dimension	171
4.2.2.2	Temporal dimension	172
4.2.2.3	Managerial dimension	172
4.2.3	Data sources and data processing	173
4.2.3.1	Station cases and literature as the data sources	173
4.2.3.2	Analytical visualization for data processing	173
4.2.4	Reflect the design principles	174
4.3	Results	174
4.3.1	Ensuring event visibility	177
4.3.1.1	Make events visible by aligning main paths and open spaces	177
4.3.1.2	Leverage 'see-and-be-seen' by using stairs as stages or seats	177
4.3.2	Incorporating temporary elements and reconfiguration-supportive layouts	178

4.3.2.1	Temporary elements	178
4.3.2.2	Spare spaces preventing overcrowding	180
4.3.2.3	Path reconfiguration for safe and efficient transfers	180
4.3.2.4	Layouts that support path reconfiguration	181
4.3.2.5	Kinetic architecture and temporary use buildings	183
4.3.3	Establishing high-quality connections at different scales	184
4.3.3.1	City axes	184
4.3.3.2	District-level path networks	184
4.3.3.3	Cross-railway passages and their positioning	185
4.3.3.4	Smooth level changes through landscape design	186
4.3.4	Adopting dispersed layouts for transport capacity or urban vibrancy	187
4.3.4.1	Increase accommodating capacity by dispersed layouts of mobility nodes	187
4.3.4.2	Enliven city environment by dispersed layouts of mobility nodes	187
4.3.5	Prioritizing core spaces for humans rather than vehicles	189
4.3.5.1	Human-centered spaces	189
4.3.5.2	High spatial qualities	190
4.3.5.3	Human scale	190
4.3.6	Enabling flexible use through programming	192
4.3.6.1	Planning stations with city infrastructures	192
4.3.6.2	Dual uses of transport spaces	192
4.4	Discussion	193
4.4.1	Non-design interventions	193
4.4.2	Research contributions	194
4.4.3	Limitations and future research directions	194
4.5	Conclusion	195

5 Evaluating design principles 196

Through research-by-design and agent-based simulation

5.1	Introduction	197
5.1.1	Research objectives and conceptual framework	198
5.2	Study design	199

5.2.1	Context of the case	200
5.2.2	Design proposals	200
5.2.3	Settings of agent-based simulation for the assessment	202
5.2.3.1	The evaluation criteria or station performances	202
5.2.3.2	The digital tools for simulation	203
5.2.3.3	Temporal scenarios associated with flexible uses	203
5.2.3.4	OD matrix	203
5.2.3.5	Agent parameters	204
5.2.4	Make comparisons between design proposals	205
5.3	Results	205
5.3.1	The effects of Principle 1 (event visibility)	206
5.3.2	The effects of Principle 2 (reconfiguration-supportive layouts)	207
5.3.3	The effects of Principle 3 (quality connections)	208
5.3.4	The effects of Principle 4 (dispersed layouts)	212
5.3.5	The effects of Principle 5 (human-centered spaces)	216
5.4	Discussions	217
5.4.1	Research implications	217
5.4.2	Research contributions	218
5.4.3	Research limitations and future directions	218
5.5	Conclusions	219

PART III **Assessment Framework** 220

6 **Assessment framework** 221

Using agent-based simulation

6.1	Introduction	222
6.1.1	Assess urban design toward station-city integration and flexible use	222
6.1.2	Existing analytical methods in the urban design field	223
6.1.3	Agent-based simulation	225

6.1.4	Research gap and research questions	226
6.2	Methodology	227
6.2.1	Theoretical framework	228
6.2.2	Literature review and selection of user satisfaction indicators	228
6.2.2.1	Safety	229
6.2.2.2	(Transfer) speed	229
6.2.2.3	Ease (of wayfinding)	230
6.2.2.4	Comfort	230
6.2.2.5	(Visual) experience	230
6.2.2.6	Final selection of indicators	231
6.2.2.7	Summary	232
6.2.3	Define measurement formulas	232
6.2.3.1	Safety (regarding overcrowding during peak time and 'eyes upon streets' during non-peak time)	233
6.2.3.2	(Transfer) speed	233
6.2.3.3	Ease (of wayfinding)	233
6.2.3.4	Comfort (regarding facilities and weather-protected areas)	234
6.2.3.5	(Visual) experience	234
6.2.4	Methods and tools	235
6.3	Case study	236
6.3.1	The context of Rotterdam Central Station	237
6.3.2	Research design	237
6.3.3	Data sources	239
6.4	Application results	240
6.4.1	Mappings of user satisfaction	240
6.4.1.1	Safety (regarding overcrowding during peak time and 'eyes upon streets' during non-peak time)	240
6.4.1.2	(Transfer) speed	243
6.4.1.3	Ease (of wayfinding)	244
6.4.1.4	Comfort (regarding facilities and weather-protected areas)	245
6.4.1.5	(Visual) experience	245
6.4.1.6	Performance during events and disruptions	246

6.4.2	Relates to station-city integration and flexible use	247
6.4.3	Validation of the assessment framework	248
6.5	Discussions	249
6.5.1	Potential applications of the assessment framework	249
6.5.2	Knowledge contributions	251
6.5.3	Limitations and future research directions	251
6.6	Conclusions	252

7 Supplementary visual assessment 253

Evidence extracted from the image segmentation of street views

7.1	Introduction	254
7.1.1	From visibility to visual quality analysis	254
7.1.1.1	Visibility analysis	254
7.1.1.2	Visual quality analysis	255
7.1.2	Design-related assessment	257
7.1.2.1	Assessing existing scenarios during the pre-design or post-design stages	258
7.1.2.2	Assessing non-existing scenarios in design proposals during the design stage	259
7.1.3	Research question	260
7.2	Methodology	260
7.2.1	Extract features that are available in 3D models during the design stage	261
7.2.1.1	Proportion-based visual features	262
7.2.1.2	Count-based visual features	263
7.2.2	Model development	263
7.2.2.1	Data source and preparation	263
7.2.2.2	Algorithm selection and testing	264
7.2.2.3	Variable selection for design relevance	264
7.2.3	Incorporating the model into agent-based simulation	265
7.3	Results	265
7.3.1	A linear regression model that models the relationship between view elements and 'liveness' perception	266
7.3.2	The accuracy of modeling affected by various factors	267

7.3.2.1	Geographical diversity of data samples	269
7.3.2.2	Data noise and outliers	269
7.3.2.3	Spatial autocorrelation of data samples	270
7.3.2.4	The accuracy of image segmentation	270
7.3.2.5	The choice of algorithms	271
7.3.2.6	The choice of variable selection methods	271
7.3.2.7	The choice of variables	272
7.3.2.8	Comparing the accuracy of the models in this chapter with those in other studies	273
7.3.3	Applying the model to the case of Rotterdam Central Station	273
7.4	Discussions	275
7.4.1	Research contributions	275
7.4.2	Limitations of assessing visual quality using computational means	275
7.4.3	Future research directions	276
7.5	Conclusions	277
8	Conclusions	278

8.1	Answers to research questions	279
8.1.1	Research question 1 (PART I, Chapters 2-3)	279
8.1.2	Research question 2 (PART II, Chapters 4-5)	279
8.1.3	Research question 3 (PART III, Chapters 6-7)	280
8.1.4	Synthesis of the findings	280
8.2	Reflection on the research	282
8.2.1	Scientific contribution	282
8.2.2	Societal contribution	283
8.2.3	Research limitation	283
8.3	Recommendations	285
8.3.1	Recommendations for future research	285
8.3.1.1	Business model for valuation of flexibly used station space	286
8.3.2	Recommendations for design practice	286

	References	287
APPENDIX A	Glossary	301
APPENDIX B	The details for developing the design principles	304
	Curriculum Vitae	315
	Publications	317
	Statement on the Use of AI	320

List of Tables

1.1	Research questions in this thesis	58	2.8	New technologies applied in the studies of users and interventions	120
1.2	Cases selected considering their relevance with O&U or flexible use	72	2.9	Challenges or limitations of flexible use solutions	122
1.3	Literature review as a method employed in different chapters	80	3.1	Cases selected considering their relevance with overcrowding and underutilization	132
1.4	Assessment criteria for positive spatial interventions	84	3.2	Findings of case studies through scenario analyses	143
2.1	Additional references included based on expert recommendations	97	3.3	Daily passenger numbers and sizes of the stations	155
2.2	Theoretical insights on spaces and uses related to flexible use	102	4.1	Occupation background of the interviewees	174
2.3	Theoretical insights on station-related content	104	4.2	Design principles for flexible use of station areas with supporting heuristics	176
2.4	Design measures for flexible use	107	5.1	District-level design proposals	201
2.5	Design measures for railway stations	109	5.2	Building-level design proposals	202
2.6	User knowledge in transport and non-transport activities	114	5.3	The OD matrix simulating the transfers between stations and other places	204
2.7	Three clusters of user-based technologies	118			

5.4	Proposal comparisons	205	7.2	Different models for testing	264
6.1	Indicators selected in this chapter	232	7.3	Importance of different facilities regarding liveness	267
6.2	Importance of different facilities regarding comfort	234	7.4	Tests on different factors affecting model accuracy	267
6.3	Importance of different facilities regarding comfort	235	7.5	Model accuracy affected by variable selection methods	272
7.1	Overview of computational visual assessment methods	257	B.1	Sources of heuristics for each design principle	310

List of Figures

- 1.1 Station-city separation and integration 35
- 1.2 Overcrowding and underutilization in railway station areas 37
- 1.3 The North Plaza of Beijing West Station with features that are non-supportive of leisure events or activities 39
- 1.4 The flexible use of Rotterdam Central Station 41
- 1.5 The flexible use of the North Plaza of Shanghai Railway Station 41
- 1.6 The South Plaza of Beijing West Station with features that are non-supportive of leisure events or activities 42
- 1.7 The academic relevance of O&U in stations 43
- 1.8 'Flexible use' vs 'mixed use' 47
- 1.9 Terms in the spatial design field that deal with changes 48
- 1.10 Station buildings, station areas, and stations in railway networks 49
- 1.11 Multiple spatial scales of stations and the corresponding research focuses 49
- 1.12 Node-place model 53
- 1.13 Knowledge integrations needed 55
- 1.14 Research objectives 57
- 1.15 The main body of this research is designed into three parts with six chapters 59
- 1.16 Events and fluctuations with different magnitudes and intensities 62
- 1.17 Functional uses of stations 63
- 1.18 Spatio-temporal occupancy rate 64
- 1.19 Objectives of station flexible uses and the relevant stakeholders 66
- 1.20 Power-interest grid of stakeholders 67
- 1.21 Interventions with different frequencies on different temporal scales 67
- 1.22 Urban design of railway station areas 69

1.23 Architectural design of railway stations 69	2.6 Keyword occurrence in the selected articles 99
1.24 Selected cases of stations 75	2.7 Publication trend in the selected articles 99
1.25 Selected cases of stations 75	2.8 The selected literature's distribution of in relation to disciplines or fields 100
1.26 Rotterdam Central Station area 77	2.9 An exemplary diagram showing 'layouts' vs 'elements' 106
1.27 Multiple ranges of station areas 78	2.10 Knowledge gaps regarding existing knowledge 123
1.28 Multiple methods used in this research 79	2.11 Knowledge integrations needed 124
1.29 Node-Place model vs Flexible Use model 83	3.1 To understand the influence of spatial configurations and national contexts 128
1.30 Values derived from the research objectives 84	3.2 Research methodology of Chapter 3 131
1.31 Embed the indicators into the theoretical Flexible Use model 85	3.3 Scenarios are observed, reviewed, or hypothetically applied to cases 131
1.32 Thesis outline 86	3.4 Case comparisons planned in this chapter 133
2.1 Spatial design is assumed by this thesis as a means to realize flexible use to reduce overcrowding and underutilization 89	3.5 The underlying logic of organizing subsections in this section 135
2.2 Framework One: primary and optional characteristics of ideal solutions 92	3.6 National contexts' influence on overcrowding and underutilization 137
2.3 Framework Two: the knowledge types 93	3.7 A conceptual basic unit of passenger flow 139
2.4 The searching and screening processes and the corresponding criteria 94	3.8 A topological mapping of the spatial configuration of Beijing West Railway Station. 139
2.5 Using keyword clusters and their combinations for searching literature 96	

3.9 Birdview of the current Rotterdam Central RS (on the district level)	145	3.23 The relationships between aspects related to the overcrowding-underutilization phenomena	157
3.10 Human-oriented spaces of the current Rotterdam Central RS	145	3.24 The nature of elements and layouts in relation to spatial scales	159
3.11 The current Rotterdam Central RS (on the building level)	146	4.1 Design principles supporting flexible use aimed at reducing overcrowding and underutilization in station areas	166
3.12 The previous Rotterdam Central RS (on the building level)	146	4.2 The methodological framework of developing design principles	168
3.13 The neighborhood connections of the previous and current Rotterdam Central RSs	146	4.3 An example of how design principles are iteratively developed	169
3.14 The previous Rotterdam Central RS (on the district level)	147	4.4 Analyze stations' spatial dimension	172
3.15 Traffic-oriented spaces of the previous Rotterdam Central RS	147	4.5 The design principles iteratively developed with accumulated heuristics	175
3.16 Birdview of Shanghai RS (on the district level)	148	4.6 Event visibility regarding path-space alignment	177
3.17 Shanghai RS (on the building level). (Source: Author)	148	4.7 Stairs for seating during events	178
3.18 Bird view of Beijing West RS (on the district level)	149	4.8 Temporary and configurable urban furniture	179
3.19 The south and north plazas of Beijing West RS	149	4.9 Reconfigurable space with installations	179
3.20 Beijing West RS (on the building level)	150	4.10 The Ferris wheel as a temporary installation	179
3.21 Beijing West RS (on the building level) with underground floors	150	4.11 Spare spaces (at the district level)	180
3.22 Spatial layouts associated with flow directions (on the building level)	154	4.12 Setting apart bottlenecks (at the building level)	180

- 4.13 Longer walking distance smoothens the peak of pedestrian numbers 180
- 4.14 Path reconfigurations 181
- 4.15 Shortcuts of paths 181
- 4.16 Layouts (of mobility nodes) affect path reconfigurations 182
- 4.17 Path regulation using non-intrusive, human-friendly elements 182
- 4.18 A changeable building—The Shed, Manhattan, New York 183
- 4.19 Changeable elements of buildings 183
- 4.20 Two city axes were planned during the redevelopment of the Utrecht Central station area 184
- 4.21 District-level axes connecting stations with neighborhoods 184
- 4.22 Reduce barriers to ease flow (at the district level) 185
- 4.23 Reduce barriers to ease flow (at the building level) 185
- 4.24 The city passages (at the building level) 186
- 4.25 Position city passages (at the district level) 186
- 4.26 Smooth level changes by landscape design (at the district level) 186
- 4.27 Smooth level changes by slopes (at the building level) 186
- 4.28 Increase transport capacity by dispersed mobility nodes (at the building level) 187
- 4.29 Enliven city environment by dispersed mobility nodes (at the district level) 188
- 4.30 Different general layouts of the station and city 188
- 4.31 The east plaza at Utrecht Stations separates the station building from the shopping mall 189
- 4.32 Human-oriented spaces vs traffic-oriented spaces 190
- 4.33 The old and the new Rotterdam Central stations. 190
- 4.34 King's Cross Station Square (7500m²). (Source: kempsarchitecturallighting.com) 191
- 4.35 'Train station in the forest'—Jiaxing station. (Source: [Gooood](http://Gooood.com), n.d.) 191
- 4.36 Programming considering the temporal dimension (for flexible use) 192
- 4.37 Seasonal practice of 'Paris Beaches' 193
- 5.1 Chapter 5 integrates multiple research topics 198
- 5.2 The initial spatial settings of the case at the district and building levels 200
- 5.3 District-level proposals 201
- 5.4 Building-level proposals 202

5.5	Proposals' performance	206	6.6	The structure of this chapter	227
5.6	Event visibility in proposal B1 and B3	206	6.7	The assessment framework in the assessment process	227
5.7	The shortcut path in proposal D1	207	6.8	Pyramid of (railway station) customer needs	228
5.9	The direction change, transfer distance, and visual quality in proposals D1 and D2	209	6.9	Various indicators of user needs	231
5.11	The crowd density (during rush hours and disruption times) and visual quality in proposals D2 and D3	212	6.10	The indicators' critical role within the assess framework	232
5.12	The crowd density, accommodation capacity during disruptions, and transfer distance in proposals B1 and B3	214	6.11	Instance segmentation and semantic segmentation	235
5.13	Visual quality and potential event sites in proposals D3 and D4	216	6.12	Methods and tools used in this chapter	236
5.14	The interrelationship between contexts, principles, and user experiences	218	6.13	The previous and the current Rotterdam Central Stations	237
6.1	Chapter 6 is at the intersection of three topics	223	6.14	The study area of Rotterdam Central	238
6.2	Space and users are interrelated in urban design	223	6.15	Compare different temporal scenarios	238
6.3	Common methods used in the urban design field	224	6.16	The stations on the district level	238
6.4	Exemplary evaluation of spatial openness using different approaches	224	6.17	The stations on the building level	239
6.5	A photo of a real-world scene vs a 3D representation model of a design	225	6.18	Mapping results	241
			6.19	Mapping results	242
			6.20	Mapping results	243
			6.21	Agents' transfer time and transfer distance	244
			6.22	Direction changes in trajectories	244

6.23 Weather-protected areas and seats	245	7.7 Research results	266
6.24 Proportions of different elements in agents' view	246	7.8 The data noise or outliers in the data	270
6.25 Flow density and agents' transfer time in the current station during normal time and event time	247	7.9 Mapping the visual quality in the current and the previous Rotterdam Central Station areas	274
6.26 Design interventions and their relevance to station-city integration and flexible use	248	7.10 Future research directions	277
6.27 The assessment framework's potential applications in practice	250	8.1 Limited parts of reality have been simulated	284
6.28 A limited part of reality is simulated	250	8.2 A spectrum of future research that incorporates technology	285
7.1 A photo of a real-world scene vs a 3D representation model of a design	259	B.1 The Utrecht Central Station area - 250m vs 500m.	305
7.2 Positioning of the study of Chapter 7 in the landscape of design-related visual analysis	259	B.2 The Rotterdam Central Station area - 250m vs 500m	305
7.3 Research methodology of Chapter 7	261	B.3 The Beijing West Railway Station area - 250m vs 500m.	306
7.4 Extracting two types of image features—the proportion of elements and the number of elements in the scenes	262	B.4 The literature selected and the relevance to the research findings	307
7.5 Comparison of semantic segmentation of images by machine and by human	263	B.5 Examine relevance and compare cases	308
7.6 Modeling a design scene regarding the proportion and the number of elements	265	B.6 The table of internal evaluation of design principles	309
		B.7 The design principles related to the event typology	314

Summary

Railway station areas with periodic events causing fluctuations in the number of passengers often experience overcrowding during peak time and underutilization during non-peak time. Overcrowding is a safety concern—potentially causing stampede, and underutilization is a waste of space resources. Exemplary stations include Beijing West Station and Amsterdam Bijlmer ArenA Station. In this thesis's vision, stations can be designed for flexible use to ease overcrowding and underutilization: during peak times, stations use spaces of the neighborhoods to increase accommodating capacity; during non-peak times, stations provide their empty spaces to be used by non-passengers for leisure activities and events. In this way, the station and city share each other's spaces, achieving station-city integration. According to this thesis's pilot observations on cases, overcrowding, underutilization, and flexible use all have spatial relevance. The overcrowding and underutilization issue exists, the vision of flexible use is intriguing, and they have spatial relevance; However, they have not been jointly investigated in existing research, as revealed by the literature reviews in [Chapter 1 \(section 1.3\)](#) and [Chapter 2](#).

This thesis **aims** to provide designers and other stakeholders with the tools and insights to better understand, assess, and design railway station areas in a way that they can support flexible use (aimed at reducing overcrowding and underutilization) and promote station-city integration. This thesis addressed three **research questions**: What is the **spatial relevance** of the overcrowding and underutilization in the station area? What are the **design principles** for station areas that support flexible use? How can design proposals be **assessed** as supportive of flexible use?

To answer these questions, three parts of research were conducted. In [Part I, Chapter 3](#) conducts an investigation of the spatial relevance of overcrowding and underutilization. In [Part II, Chapter 4](#) establishes a set of design principles guiding design practices, and [Chapter 5](#) assesses the design principles (implemented in design proposals). In [Part III, Chapter 6](#) develops an assessment framework facilitating design evaluation, and [Chapter 7](#) serves as a component of the assessment framework.

These chapters were conducted using multiple **methods** ([subsection 1.7.1](#)), including case studies, literature reviews, research-by-design, and software development. Case studies were conducted to examine the spatial relevance and to develop design principles. Cases were selected for their relevance to overcrowding, underutilization, or

flexible use, and for their importance as major stations within their respective national contexts. These cases include Beijing West Railway Station (RS), Shanghai RS, Rotterdam Central RS (both the current and the former cases), Utrecht RS (both the current and the former cases), and Station Xtreme (a virtual station). A literature review was conducted to identify the indicators for the assessment framework, followed by software development to operationalize its application. Research-by-design was used to generate novel solutions when developing the design principles; it is also used to generate design proposals for assessing the design principles.

Multiple **results** were achieved in different chapters. First, the spatial relevance investigation chapter ([Chapter 3](#)) resulted in a relationship mapping of factors associated with overcrowding, underutilization, or flexible use. National-context-related factors, such as security checks, ticket assignments, and traveling patterns, affect the fluctuation in the number of passengers due to periodic events, influencing the size of spare spaces. Despite these factors being critical, spatial aspects, including spatial layouts, elements, and qualities, also affect overcrowding, underutilization, or flexible use. For example, spatial connections between stations and their adjacent urban areas, bottlenecks and barriers in pedestrian paths, spare space for circulation, spaces as event venues, and human-scale spaces that facilitate spontaneous leisure activities, all affect the activities of transport travelers during peak times and the activities of non-transport users during non-peak times. This confirms the high potential of spatial design, in which these aspects are arranged.

Second, the design principle chapter ([Chapter 4](#)) resulted in the development of a set of design principles, including: (1) ensuring event visibility by aligning paths and spaces, (2) incorporating temporary elements and reconfiguration-supportive layouts, (3) establishing high-quality connections at different scales, (4) adopting dispersed layouts for transport capacity or urban vibrancy, and (5) prioritizing core spaces for humans rather than vehicles, (6) enabling flexible use through program planning. These principles were first reviewed by field experts during interviews and then evaluated using research-by-design and simulations.

Third, the design principle assessment chapter ([Chapter 5](#)), where four proposals of the virtual station—Station Xtreme—containing design principles are assessed, results in a series of assessments. These assessments show that the principles in general are effective, while each principle has its strengths and limitations.

Fourth, the assessment framework chapter ([Chapter 6](#)) resulted in an assessment framework using agent-based simulation, which contains a theoretical model (which consists of five user needs: safety, speed, ease, comfort, and experience, with differences in peak and non-peak times), indicators, and digital tools. Rotterdam Central Station is used as a case to demonstrate how the framework works. The results show that the framework is capable of assessing design alternatives by identifying changes in user satisfaction in different scenarios at different times. In this way, the station's performance in supporting flexible use is evaluated. This assessment framework is applicable at the district level (at a scale of around 250m) with substantial details to inform design decision-making, and it is useful during the design stage when only limited data is available.

Lastly, a linear regression model, as a component of the assessment framework, is developed specifically for assessing the visual quality of 'liveness' ([Chapter 7](#)). Developing this model involves data extraction using image segmentation, testing models, and testing variable selection methods. The results reveal that factors such as the number of pedestrians and the proportions of trees, buildings, and water positively influence perceptions of street 'liveness.' The developed linear regression model is practical for assessing the visual quality of new scenes in design practice. However, developing this model shows significant limitations of computational means in assessing visual quality. Computational means, like this model, face challenges of generalization (going beyond a single environment type), reliable accuracy, and incorporating other critical visual features.

This thesis **contributes** to the design research and practice of station areas that suffer from overcrowding and underutilization, advancing spatial understanding and solutions that support flexible use and promote station-city integration. Regarding multiple types of target audiences—including designers, researchers, and stakeholders ([subsection 1.5.3](#))—this thesis offers insights and solutions that respond to both theoretical and practical needs. First, it clarifies the mechanisms of factors affecting the overcrowding-underutilization phenomena, raising awareness of the issue and highlighting the spatial relevance. Second, this thesis provides the design and research communities with an assessment framework, which contains digital tools enhancing designers' toolboxes. This framework also contains a linear regression model. Developing this model involves extracting data from datasets, which enhances the scientific evidence for visual quality assessment using computational means. Third, this thesis enriches the design knowledge base with its developed design principles that offer actionable guidance for real-world design practice.

This thesis builds its **novelty** in emphasizing the temporal dimension—a dimension that is central to the O&U issue and flexible use, and is largely missing in existing station research. This thesis also expands the meaning of station-city integration—it establishes a new form of integration where stations and cities support temporal function changes and sharing resources, beyond mere static and physical collocation.

Samenvatting

Stationsgebieden die te maken hebben met periodieke evenementen die schommelingen in passagiersaantallen veroorzaken, ervaren vaak overmatige drukte tijdens piekuren en onderbenutting buiten de piekuren. Overmatige drukte vormt een veiligheidsrisico—met het potentieel om tot gedrang of paniek te leiden—, terwijl onderbenutting een verspilling van ruimtelijke middelen is. Voorbeelden zijn stations zoals Peking-West Railway Station en Station Amsterdam Bijlmer ArenA. In de visie van dit proefschrift kunnen stations worden ontworpen voor flexibel gebruik om overmatigedrukte en onderbenutting te verminderen: tijdens piekuren maken stations gebruik van ruimtes in de omliggende buurten om de opvangcapaciteit te vergroten; buiten piekuren stellen stations hun lege ruimtes beschikbaar voor niet-passagiers voor recreatieve activiteiten en evenementen. Op deze manier delen het station en de stad elkaars ruimtes, waarmee station-stadsintegratie wordt bereikt. Volgens de observaties in de casussen in dit proefschrift hebben overmatige drukte, onderbenutting en flexibel gebruik allemaal een ruimtelijke relevantie. De problematiek rondom overmatige drukte en onderbenutting is erkend, de visie van flexibel gebruik is veelbelovend én beide hebben een duidelijke ruimtelijke relevantie; ze zijn echter nog niet in samenhang onderzocht, zoals blijkt uit het literatuuronderzoek in [Hoofdstuk 1 \(Sectie 1.3\)](#) en [Hoofdstuk 2](#).

Dit proefschrift **beoogt** ontwerpers en andere belanghebbenden te voorzien van middelen en inzichten om stationsgebieden beter te begrijpen, te beoordelen en te ontwerpen, zodat deze flexibel gebruik kunnen ondersteunen (gericht op het verminderen van overmatige drukte en onderbenutting) en station-stadsintegratie kunnen bevorderen. Dit proefschrift behandelt drie **onderzoeksvragen**: (1) Wat is de **ruimtelijke relevantie** van overmatige drukte en onderbenutting in stationsgebieden? (2) Wat zijn de **ontwerpprincipes** die flexibel gebruik ondersteunen voor stationsgebieden? (3) Hoe kunnen ontwerpoplossingen worden **getest** op hun ondersteuning voor flexibel gebruik?

Om deze vragen te beantwoorden is het onderzoek in drie delen uitgevoerd. In [Deel I, Hoofdstuk 3](#) wordt de ruimtelijke relevantie van overmatige drukte en onderbenutting onderzocht. In [Deel II, Hoofdstuk 4](#) wordt een reeks ontwerpbeginselen vastgesteld die de ontwerppraktijk sturen, en in [Hoofdstuk 5](#) worden deze ontwerpbeginselen (zoals toegepast in ontwerpvoorstellen) beoordeeld. In [Deel III](#) wordt in [Hoofdstuk 6](#) een beoordelingskader ontwikkeld dat de evaluatie van ontwerpen vergemakkelijkt, en

dient [Hoofdstuk 7](#) als een ondersteunend onderdeel van dit beoordelingskader.

Deze hoofdstukken zijn uitgevoerd met behulp van verschillende **methoden** ([subsectie 1.7.1](#)), waaronder casestudies, literatuuronderzoek, ontwerpend onderzoek (research-by-design) en softwareontwikkeling. Casestudies zijn uitgevoerd om de ruimtelijke relevantie te onderzoeken en ontwerpbeginselen te ontwikkelen. Casussen zijn geselecteerd op basis van hun relevantie voor overmatige drukte, onderbenutting of flexibel gebruik, en het belang als hoofdstations binnen de respectievelijke nationale context. Deze casussen omvatten Peking-West Railway Station, Shanghai Railway Station, Rotterdam Centraal (zowel de huidige als de voormalige situatie), Utrecht Centraal (zowel de huidige als de voormalige situatie) en Station Xtreme (een virtueel station). Er is een literatuuronderzoek uitgevoerd om de indicatoren voor het beoordelingskader te identificeren, gevolgd door softwareontwikkeling om de toepassing ervan te operationaliseren. Ontwerpend onderzoek is ingezet om vernieuwende oplossingen te genereren voor het ontwikkelen van de ontwerpprincipes; Ontwerpend onderzoek is ook gebruikt om ontwerpvoorstellen te genereren voor het testen van deze ontwerpprincipes.

Verschillende **resultaten** zijn behaald in de afzonderlijke hoofdstukken. Ten eerste resulteerde het hoofdstuk over het onderzoek naar ruimtelijke relevantie ([Hoofdstuk 3](#)) in het in kaart brengen van de relaties tussen factoren die samenhangen met overmatige drukte, onderbenutting of flexibel gebruik. Factoren gerelateerd aan de nationale context, zoals veiligheidscontroles, toewijzing van treinkaartjes en reizigerspatronen, beïnvloeden de schommelingen in passagiersaantallen tijdens periodieke evenementen, wat de omvang van restruimtes beïnvloedt. Hoewel deze factoren cruciaal zijn, spelen ook ruimtelijke aspecten—zoals ruimtelijke indeling, bouwkundige elementen en ruimtelijke kwaliteiten—een rol bij overmatige drukte, onderbenutting of flexibel gebruik. Bijvoorbeeld: ruimtelijke verbindingen tussen stations en hun aangrenzende stedelijke gebieden, knelpunten en barrières in voetgangersroutes, restruimte voor doorstroming, ruimtes die dienen als evenementenlocatie, en ruimtes op menselijke schaal die spontane recreatieve activiteiten faciliteren, beïnvloeden allemaal de activiteiten van reizigers tijdens piekuren en van niet-reizigers buiten piekuren. Dit bevestigt het hoge potentieel van ruimtelijk ontwerp waarin deze aspecten vorm worden gegeven.

Ten tweede resulteerde het hoofdstuk over ontwerpbeginselen ([Hoofdstuk 4](#)) in de ontwikkeling van een reeks ontwerpprincipes, waaronder: (1) het waarborgen van de zichtbaarheid van evenementen door het uitlijnen van routes en ruimtes, (2) het integreren van tijdelijke elementen en indelingen die herconfiguratie ondersteunen, (3) het realiseren van hoogwaardige verbindingen op verschillende schaalniveaus, (4) het toepassen van gedecentraliseerde indelingen voor vervoerscapaciteit of stedelijke levendigheid, (5) het prioriteren van ruimte voor mensen in plaats van voertuigen, en (6) het maatschappelijk en ruimtelijk faciliteren van flexibel gebruik door middel van programma-planning. Deze beginselen zijn eerst beoordeeld door experts uit het werkveld tijdens interviews en vervolgens geëvalueerd met behulp van ontwerpend onderzoek en simulaties.

Ten derde resulteerde de evaluatie van de ontwerpprincipes ([Hoofdstuk 5](#))—waarin

vier voorstellen voor een virtueel station (Station Xtreme) zijn beoordeeld—in een reeks concrete bevindingen. Deze tonen aan dat de principes in het algemeen effectief zijn, hoewel elk principe specifieke sterkten en beperkingen kent.

Ten vierde resulteerde het hoofdstuk over het beoordelingskader ([Hoofdstuk 6](#)) in een beoordelingskader op basis van agent-based simulatie. Dit kader bevat een theoretisch model (bestaande uit vijf gebruikersbehoeften: veiligheid, snelheid, gemak, comfort en beleving, met verschillen tussen piek- en daluren), indicatoren en digitale middelen. Station Rotterdam Centraal is gebruikt als casus om de werking het model te demonstreren. De resultaten tonen aan dat het kader in staat is om ontwerpalternatieven te beoordelen door veranderingen in gebruikerstevredenheid in verschillende scenario's en op verschillende tijdstippen te identificeren. Op deze manier wordt de prestatie van het station in het ondersteunen van flexibel gebruik geëvalueerd. Dit beoordelingskader is toepasbaar op wijkniveau (op een schaal van ongeveer 250 meter) met voldoende detail om ontwerpbeslissingen te onderbouwen, en is waardevol tijdens de ontwerpfase wanneer slechts beperkte data beschikbaar zijn.

Tot slot is een lineair regressiemodel ontwikkeld als onderdeel van het beoordelingskader, specifiek gericht op het beoordelen van de visuele kwaliteit van 'levendigheid' ([Hoofdstuk 7](#)). De ontwikkeling van dit model omvatte het extraheren van data met behulp van beeldsegmentatie, het testen van modellen en het testen van methoden voor variabelenselectie. De resultaten laten zien dat factoren zoals het aantal voetgangers en de proporties van bomen, gebouwen en water de perceptie van de levendigheid van straten positief beïnvloeden. Het ontwikkelde lineaire regressiemodel is praktisch toepasbaar voor het beoordelen van de visuele kwaliteit van nieuwe situaties in de ontwerppraktijk. Het ontwikkelen van dit model bracht echter ook aanzienlijke beperkingen aan het licht van computationele methoden bij het beoordelen van visuele kwaliteit. Computationele methoden, zoals dit model, kampen met uitdagingen op het gebied van generaliseerbaarheid (toepasbaarheid buiten één specifiek type omgeving), betrouwbare nauwkeurigheid en het opnemen van andere cruciale visuele kenmerken.

Dit proefschrift **draagt bij** aan het ontwerponderzoek en de ontwerppraktijk van stationsgebieden die kampen met overmatige drukte en onderbenutting, door het ruimtelijk inzicht te vergroten en oplossingen te bieden die flexibel gebruik ondersteunen en station-stadsintegratie bevorderen. Voor verschillende doelgroepen—waaronder ontwerpers, onderzoekers en belanghebbenden ([subsectie 1.5.3](#))—biedt dit proefschrift inzichten en oplossingen die beantwoorden aan zowel theoretische als praktische behoeften. Ten eerste verheldert het de mechanismen achter de factoren die het fenomeen van overmatige drukte versus onderbenutting beïnvloeden, wat het bewustzijn van de problematiek vergroot en de ruimtelijke relevantie onderstreept. Ten tweede voorziet dit proefschrift de ontwerp- en onderzoeksgemeenschap van een beoordelingskader met digitale instrumenten die de gereedschapskist van ontwerpers verrijken. Dit kader omvat tevens een lineair-regressiemodel. De ontwikkeling hiervan omvatte het extraheren van data uit datasets, wat het wetenschappelijke bewijs versterkt voor het digitaal beoordelen van visuele kwaliteit. Ten derde verrijkt dit proefschrift de aanwezige ontwerp kennis met de ontwikkelde ontwerpprincipes die toepasbare richtlijnen bieden voor de actuele

ontwerppraktijk.

De **vernieuwing** in dit proefschrift schuilt in de nadruk op de temporele dimensie—een dimensie die essentieel is voor de problematiek van overmatige drukte en onderbenutting en flexibel gebruik, maar die in bestaand stationsonderzoek grotendeels ontbreekt. Dit proefschrift verruimt bovendien de betekenis van station-stadsintegratie: het introduceert een nieuwe vorm van integratie waarin stations en steden temporele functiewijzigingen en het delen van middelen ondersteunen, verder reikend dan louter statische en fysieke samenvoeging.

Executive summary

The challenge: overcrowding and underutilization

Railway stations that experience fluctuating passenger demands frequently suffer from two opposing phenomena: severe overcrowding during peak times and significant underutilization during non-peak periods. Overcrowding presents serious safety risks and degrades the passenger experience, while underutilization results in a massive waste of valuable spatial, financial, and maintenance resources.

A “station sizing paradox” currently plagues infrastructure development: designing larger stations to safely accommodate peak flows inevitably exacerbates the presence of empty, underutilized voids during off-peak times, and conversely, shrinking station sizes to reduce voids leads to dangerous peak-time crowding. This issue is often locked in by rigid national standards that dictate spatial dimensions based exclusively on maximum peak capacities.

The vision: flexible use and station-city integration

To resolve this paradox, the thesis proposes “flexible use” as a spatial and managerial strategy. Flexible use envisions a dynamic sharing of space between the railway station and the surrounding city.

- **Peak/disruption times:** Stations utilize adjacent neighborhood spaces and plazas as temporary buffers to increase their accommodating capacity.
- **Non-peak times:** Stations open their underutilized empty spaces to non-passengers for civic events, commercial engagement, and leisure activities.

This temporal and functional integration creates a new, deeper form of “station-city integration” that goes beyond simply placing a station in a dense urban environment for a physical collation.

Strategic insights

- **Stakeholder value creation:** Implementing flexible use aligns the interests of various stakeholders. Mitigating underutilization protects the financial interests of real estate investors and commercial operators, while providing flexible venues for events boosts local economic vitality and social cohesion for local governments.
- **The impact of national contexts and operations:** Overcrowding is not simply a product of passenger volume; it is heavily dictated by internal operational factors. Strict security checks, rigid ticket-to-seat assignments, and inexperienced travelers with bulky luggage severely reduce transfer efficiency, creating artificial bottlenecks that force stations to require larger spare spaces.
- **Flow organization trade-offs:** The fundamental layout of pedestrian flow impacts space utilization. Unidirectional flow layouts (common in Chinese stations) separate ingress and egress, which allows for higher maximum volumes but disperses passengers and increases the risk of underutilization. Bidirectional shared paths (common in Dutch stations) concentrate flow but can intensify crowding during passenger surges.
- **Spatial relevance and design potential:** A station’s operational performance is intrinsically tied to its physical layout. For example, spatial bottlenecks and constrained pathways exacerbate peak-hour overcrowding, while obscured sightlines and rigid boundaries limit commercial foot traffic and adaptability during off-peak hours. By intentionally altering the underlying spatial configuration, spatial design demonstrates significant potential to ease O&U and promote flexible uses.

Actionable design principles

The research identifies specific design principles to ensure station areas can successfully accommodate flexible use:

- **Establish high-quality connections:** Create seamless spatial links across different scales between the station and its adjacent urban districts. If a station is isolated by heavy traffic barriers, it cannot borrow city space during peak disruptions, nor can it invite citizens in for leisure during off-peak hours.
- **Adopt dispersed layouts:** Dispersing mobility nodes across the building or district level increases overall transport capacity and helps distribute transportation capacity and urban vibrancy more evenly across the station area.

- **Prioritize human-centered spaces:** Keep vehicles and heavy transport infrastructure away from the immediate core spaces. This creates a pedestrian-friendly environment and frees up coherent central plazas that can be utilized for both passenger flow management and leisure events.
- **Ensure event visibility:** Align paths and spatial sightlines so that temporary events or commercial areas are easily visible and accessible to the public, overcoming the psychological barrier of entering a transit-first environment.
- **Support reconfiguration:** Incorporate temporary elements, movable furniture, and flexible spatial layouts that can easily adapt to shifting daily or seasonal demands.

Assessment framework

To aid design practice, the thesis provides a comprehensive assessment framework to evaluate spatial proposals before physical construction begins. This multi-layered framework features:

- **Multi-layered user needs model:** Evaluates proposals against a pyramid of user needs—safety, speed, ease, comfort, and experience. The framework dynamically tests specific spatial indicators for each need: **safety** (measured by flow density and overcrowding during peak times, versus the level of visual surveillance, or “eyes on the street,” during non-peak times), **speed** (measured by transfer time and transfer distance), **ease** (measured by direction changes in trajectories), **comfort** (measured by access to weather-protected areas and seating), and **experience** (measured by the proportions of different visual elements in the user’s view).
- **Agent-based simulation:** Functions as an evaluative engine by modeling individual pedestrians and their dynamic interactions with the physical environment. This provides a rigorous method for spatial design assessment, enabling the testing of proposed spatial configurations against user satisfaction metrics across spatial-temporal scenarios.
- **Visual quality modeling:** Incorporates a linear regression model, developed through image segmentation of street views, to computationally assess the visual experience and “liveness” of the built environment.
- **Early-stage decision support:** Provides actionable, data-driven insights to inform design decision-making during initial conceptual stages when only limited operational data is available.

1 Introduction

This Introduction chapter provides a background to the research, states the problem of overcrowding and underutilization (O&U) in railway station areas, reviews relevant literature, identifies the knowledge gap, sets a research objective of advancing spatial understanding and solutions for flexible use to address O&U in stations, designs the research, defines the research scope and key concepts, describes the research methodology, and outlines the thesis structure. This chapter, introducing the thesis, is also complemented by the following detailed [Chapter 2](#), revealing the knowledge gap through a systematic literature review.

1.1 Research background: station-city integration and user experience

Rail travel is the most energy-efficient form of motorized passenger transportation ([Newman and Kenworthy, 1999](#); [European Environment Agency, 2021](#)), and station user experience is essential to promoting rail travel. During typical train journeys, passengers spend time on trains and in stations. To make rail travel attractive among competing transport means ([Kasraian et al., 2015](#)), it is essential to leverage the trains' speed to reduce passengers' travel time ([Chen and Wei, 2013](#)), and improve user satisfaction at railway stations to make stations' environments pleasant for passengers during waiting ([Van Hagen, 2011](#)).

One potential means to promote rail travel and improve user satisfaction is station-city integration. As a concept, 'station-city integration' has no definitive definition; rather, it is a concept with growing meanings in the ongoing discourse (E.g., see [Zemp 2011](#); [Da Conceição 2015](#); [Dai 2015](#); [Triggianese et al. 2019](#); [Cheng et al. 2021](#); [Wang 2022](#); [Du 2023](#)) ([Figure 1.1](#)). In general, it is an ideal scenario in which stations and cities are appropriately integrated to address negative issues and achieve positive benefits. It has multiple proposed benefits of broad **societal relevance**, including reducing

automobile dependency to curbing urban sprawl (Calthorpe and Poticha, 1993), promoting a willingness to travel by public transportation (Cervero and Kockelman, 1997), fostering an appreciation of properties around stations (Cervero, 1994), bringing development profits for developers (Shikata et al., 2013), enabling megacities to function (Shikata et al., 2013), catalyzing urban regeneration (Novy and Peters, 2012), improving the living and working environment around station areas (Dai et al., 2019), and improving user satisfaction (Triggianese et al., 2019, p. 131).

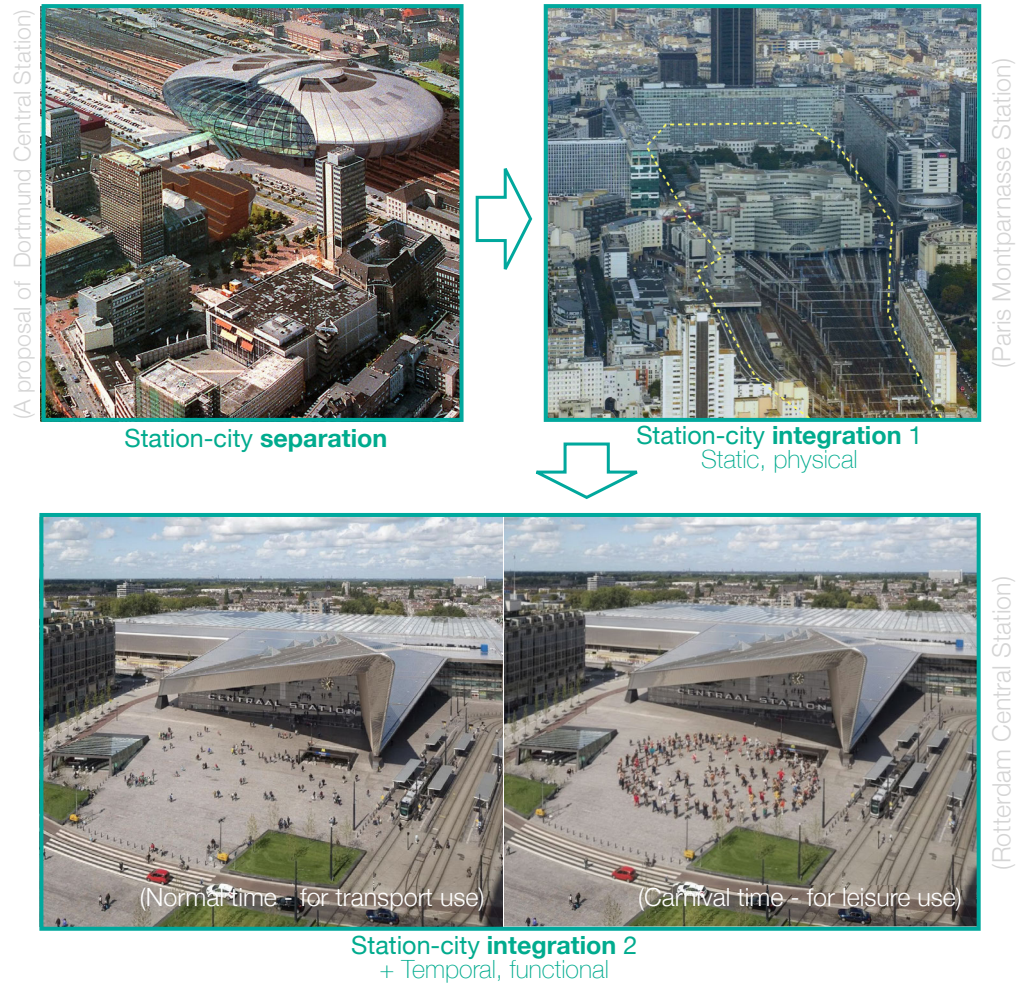


FIG. 1.1 Station-city separation and integration. (Sources: Up-left: ruhrnachrichten.de; Up-right: bonjour-ratp.fr, the yellow line marks the station and track area; Down-left: rotterdamcentrum.nl; Down-right: annotated by the author based on the situation during the Summer Carnival time)

However, in certain railway stations with drastic usage fluctuations, a recurring phenomenon of overcrowding and underutilization (O&U) negatively affects user

experience (Figure 1.2), limiting the potential benefits of station-city integration. In addressing the O&U issue, this thesis provides designers and other stakeholders with insights and solutions. It focuses on the temporal dimension—a dimension central to the O&U issue and flexible use, and is largely missing in existing station research. This thesis expands the meaning of station-city integration—it establishes a new form of integration in which stations and cities support temporal changes in function and share resources; hence, both stations' and cities' maximum capacity is increased, and underutilization is reduced, lowering investment and intensifying the use of resources. This differs from most existing research, which focuses on static collocation of stations and cities, where only the physical building density is increased (Figure 1.1).

The following two sections describe the O&U issue from two distinct perspectives. section 1.2 first details the empirical, real-world manifestations, consequences, and design-related causes of overcrowding and underutilization. Building on this physical and spatial foundation, section 1.3 then situates these challenges within broader academic discussions, establishing the theoretical relevance of the research.

1.2 Problem statement: overcrowding and underutilization (O&U) in railway station areas

This section frames the challenge of overcrowding and underutilization (O&U) primarily through an empirical, spatial lens, describing the phenomenon, consequences, causes, and potential solutions in certain railway station areas. Given the author's living experience in China and study experience in the Netherlands, the cases studied in this research are mostly chosen from these two countries. Beijing West Railway Station is a clear example illustrating the O&U phenomena. Online commentary on this station reflects seemingly contradictory complaints—some people criticize it as being overcrowded (Jialing and Yue, 2021), while others criticize it as being underutilized (Yu, 2018). This contradiction is not due to misinformation; it reflects variations in station use across different times. The station is occasionally overcrowded during peak times and underused during off-peak periods. This fluctuation in use between peak and off-peak times highlights the temporal dynamics that undermine a consistent, positive user experience.

Beyond Beijing West Railway Station, many other stations periodically experience overcrowding and underutilization (Mccarthy, 2018; Chinadaily, 2014; Aseniya, 2019; Holt, 2025). For instance, in China and South Korea, major stations in megacities face overcrowding during the Spring Festival due to mass migrations (Mccarthy, 2018;

Chinadaily, 2014). Similarly, in Europe, all stations in Amsterdam are challenged by overcrowding during King's Day (Times, 2015); stations like Amsterdam Bijlmer ArenA and Manchester Victoria are challenged during sports games and concerts (Aseniya, 2019; Holt, 2025). Conversely, these stations usually remain underutilized during off-peak periods (Figure 1.2).



FIG. 1.2 Overcrowding (the left image) and underutilization (the right image) in railway station areas. (Source: Left—163.com; Right—Sohu.com)

1.2.1 The consequence of O&U

Overcrowding is a safety concern. In extreme cases, station overcrowding causes death (Chinadaily, 2008). Dangerous overcrowding in stations appears on the news from time to time (ITV News, 2015; At5, 2014; Hartvannederland, 2022; At5, 2019; Chenchen and Simin, 2021; Bilibili, 2021; Juanming, 2024). In cases like Amsterdam Bijlmer ArenA station (Joosten, 2022), railway companies have to shut down stations to prevent anticipated overcrowding, which causes inconvenience to users and revenue loss to railway companies. Overcrowding in stations is as concerning as overcrowding in other public spaces or buildings.

On the other hand, underutilization also causes negative consequences. First, it causes a boring user experience. At night, large underutilized spaces with insufficient light can even make people feel unsafe. Beyond causing a negative user experience, underutilization is a waste of resources. Stations are typically complex buildings that require substantial financial investment. The large land occupied by stations is usually valuable, especially when they are located in high-density cities. Given these negative consequences of O&U, it is necessary, or at least helpful, to reduce overcrowding and underutilization. Aimed at understanding O&U further and seeking potential solutions, this research examined relevant academic discussions described in the following section.

1.2.2 O&U associated with events and disruptions that cause fluctuations

Stations' overcrowding and underutilization (O&U) are often associated with events and disruptions that cause fluctuations in pedestrian number and the stations' capacity, respectively. Large events—such as holidays, festivals, sports games, or concerts—lead to increased passenger flow to nearby stations, often resulting in overcrowding ([Netease, 2018](#)). This type of overcrowding can be mitigated through crowd management, including measures such as managing passenger flows in real time or temporarily closing station gates to avoid overcrowding in front of stairs and platforms ([Aseniya, 2019](#)).

Disruptions in railway systems—such as mechanical equipment failure, railway line failure, or railway staff strikes ([Rijndetereinen, n.d.](#))—lead to reduced station capacity, often leaving passengers stranded and causing crowding. To reduce disruptions, engineering optimization is commonly taken to make railway systems more resilient ([Bešinović, 2020](#)).

To accommodate passengers during events or disruptions, stations are often designed with extra-large spaces, such as the huge plazas and station halls in many stations ([Dai et al., 2019](#)), and the wide boulevard at Amsterdam Bijlmer ArenA Station. These spaces can be underutilized during non-peak times.

1.2.3 O&U associated with non-spatial and spatial factors

Besides events and disruptions, overcrowding and underutilization (O&U) are also **associated with other non-spatial factors**, including security checks ([Dai et al., 2019](#)), ticket assignments, and increased or decreased demand for rail travel ([Peters and Tolkoff, 2016](#); [Kasraian et al., 2015](#)). First, crowding is more likely to occur at stations with strict security checks, where passengers often need to queue or be stranded in front of the checkpoints. Second, when a ticket is assigned strictly to a specific train and a seat, as all train services in China and the Eurostar train services in Europe, the passenger needs to arrive at the station much earlier to avoid missing the train. Therefore, stations have more waiting passengers, leading to a more crowded environment. Third, the increased or decreased demand for rail travel over the years—for example, the annual number of passengers of Beijing West stations keeps increasing—affects station crowding.

These non-spatial institutional, operational factors are also deeply intertwined with broader societal perspectives on crowding. From a cultural and psychological standpoint, crowding is not merely a metric of physical density, but a perceived stressor that impacts passenger well-being, safety perceptions, and emotional comfort. Conversely, severe underutilization can strip these vital transport stations of their

perceived civic vitality and public security. Perceptions of crowd density vary across cultures. Research has reported that the station platform's normal crowd density in Beijing, China, is twice as high as the maximum crowd density value defined in a Swiss standard (Heuvel, 2022, p 50), demonstrating a significant density tolerance difference.

In this research's pilot case study of Beijing West Railway Station (RS), on-site observations indicate that overcrowding and underutilization (O&U) are **associated with spatial aspects**; In other words, O&U exhibits **spatial relevance**. In Beijing West RS, the north ground main plaza and the massive sunken plaza are configured separately, with only weak links between them (Figure 1.3). The available empty space in the sunken plaza does not alleviate the pedestrian crowding on the main. This spatial configuration affects passenger flow dynamics, determining the distribution of stranded versus passing passengers and, consequently, the occurrence of crowding. The spatial relevance is in the particular interests of this design-oriented research.



FIG. 1.3 The North Plaza of Beijing West Station with features that are non-supportive of leisure events or activities. (Source: meipian.cn; annotated author)

Beijing West RS, often perceived as **over-sized**, is not a single example of its kind. In both the Chinese and Dutch contexts, many contemporary station redevelopments have been approached as politicized urban megaprojects. These developments are driven by administrative ambitions, high-speed rail integration, and urban competitiveness branding, which frequently result in over-scaled and over-sized infrastructure (Flyvbjerg et al., 2010; Peters and Novy, 2012). The 'voids' and underutilized spaces in these station areas are not natural spatial phenomena. Rather, they represent the path-dependent consequences of a specific historical era of transport planning.

From a technical perspective, this physical over-sizing is also institutionalized and codified by rigid **national standards** for station layout. Statutory codes dictate peak-hour square-meter-per-passenger allocations, which traditionally mandate static spatial dimensions tailored exclusively to maximum peak capacities ([Ministry of Construction of the People's Republic of China, 2011](#); [European Commission, 2014](#)). Once cast in concrete, these oversized structures create a physical lock-in (path dependency). Because these massive spatial footprints cannot easily be shrunk, they pose long-term socio-economic and structural challenges to their efficient use. (For design solutions addressing over-sized spaces, see [subsection 4.3.5](#) 'human scale' paragraph.)

Additionally, this thesis identifies a **paradox of station sizing** in station design, arising when only one of the two—overcrowding or underutilization—is considered. To alleviate overcrowding during peak times, stations can be designed larger with more available spaces, but this results in greater underutilization during off-peak times. Conversely, to reduce underutilization, stations can be designed smaller with less space, but this exacerbates overcrowding during peak times. This is a paradox of simply changing the stations' size, with only overcrowding or underutilization considered. It highlights a core challenge in the spatial design of these fluctuation-related stations: addressing both peak and non-peak space uses across fluctuating temporal situations.

1.2.4 The potential of flexible use in mitigating O&U in stations

The above [subsection 1.2.3](#) described oversizing and the paradox of station sizing, and introduced a challenge in spatial design—balancing space efficiency and user capacity across fluctuating temporal demands. Consequently, effective solutions should deal with overcrowding and underutilization together. Considering overcrowding and underutilization are two related phenomena in the changing situations of stations, this thesis hypothesizes flexible use as a solution; this is because the word flexible linguistically means 'able to change or be changed easily according to the situation' ([Dictionary, n.d.](#)).

Another heuristic for flexible use as a solution is those rare real-world cases where stations are flexibly used. For example, in the Rotterdam Central Station case, during the Rotterdam Summer Carnival time (non-peak time of transport), the station front plaza is used for event-goers dancing; During the station's opening ceremony, the nearby neighborhoods' spaces were occupied by the station to accommodate participants. If transport disruptions happen, the same neighborhoods' spaces can be occupied by the station to accommodate detained passengers ([Figure 1.4](#)).

In another example, at Shanghai Railway Station, large South and North plazas are designed to accommodate transportation needs during peak travel periods, such as the Spring Festival. The North Plaza remains mostly empty on non-peak days. Elderly

people gather and dance on this plaza in the evenings, utilizing the space more effectively during non-peak times (Figure 1.5).

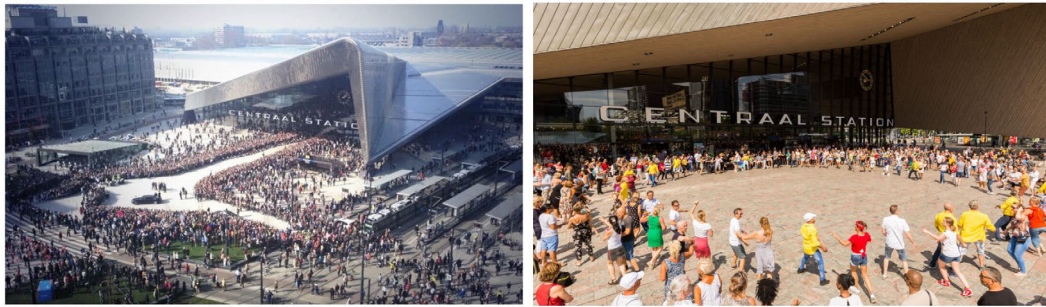


FIG. 1.4 The flexible use of Rotterdam Central Station for the opening ceremony (the left image) and dancing (the right image). (Source: Left—West8.com; Right—Tropicaliente.nl)



FIG. 1.5 The flexible use of the North Plaza of Shanghai Railway Station for transportation (the left image) and dancing (the right image). (Source: Left—Douyin.com; Right—photoed by the author)

Flexible use typically involves **managerial interventions**. While small leisure activities normally happen in public spaces spontaneously when the environment is pleasant (Gehl, 1987), larger events typically require managerial efforts to organize and maintain. Taking stations as an example, during peak times, the pedestrian flow is monitored through sensors and cameras (Heuvel, 2022; Aseniya, 2019), and on-site station staff may regulate the pedestrian flow to prevent overcrowding by taking measures such as setting crowd control belts. During non-peak times, using the station spaces for events such as dancing or having markets on plazas requires the hosts to organize and maintain order (Van Nieuwenhuize, 2023).

This research also sees that the flexible use of stations requires suitable **spatial configurations** to support activities and events. For example, the South Plaza of Beijing West Station, with many staircases making the space fragmented, is non-supportive of

large events during non-peak times. Its sunken plaza, with no easy access to pedestrians, is non-supportive of leisure activities during non-peak times (Figure 1.6).



FIG. 1.6 The South Plaza of Beijing West Station with features that are non-supportive of leisure events or activities. (Source: Wikipedia; annotated author.)

Despite examples like Rotterdam Central Station and Shanghai Station, the flexible use of stations remains rare. The potential of flexible use in mitigating overcrowding and underutilization (O&U) is seldom realized in real-world practice.

1.2.5 Summarize the O&U problem

In summary, overcrowding and underutilization (O&U) occur in railway stations that have fluctuations, causing negative consequences to user experience and socio-economic values. O&U in these stations are associated with multiple factors, including events and disruptions, security checks, ticket assignments, travel demand changes over the years, and spatial configurations. This research sees a station sizing paradox and demonstrates that proper solutions should jointly address overcrowding and underutilization. Flexible use is a potential solution to jointly mitigate overcrowding and underutilization, resolving the paradox of station sizing. However, this potential has rarely been realized, as real-world examples of flexibly used stations remain scarce.

1.3 Academic relevance

While the preceding section outlines the issue of O&U and potential flexible use through a localized spatial lens and emphasizes its tangible, real-world impacts, this section situates the issue in a broader, multi-disciplinary academic discourse, introducing relevant academic literature. Given that no existing studies specifically address this issue—i.e., reducing overcrowding and underutilization (O&U) in stations through urban and architectural design, taking flexible use as a potential solution. Adjacent topics in multiple fields are examined (see [Figure 1.7](#)), including crowd management, the use of public spaces, flexible use, and urban and architectural design of railway stations. Overcrowding is a central topic for **crowd management** in the civil engineering field. Spatial underutilization relates closely to research on **public spaces** in the urban design field. The concept of **flexible use** is examined across the spatial planning and design disciplines. **Urban and architectural design**—or briefly call them ‘spatial design’—of stations has been studied in the spatial design field, where **station-city integration** is an important theme.

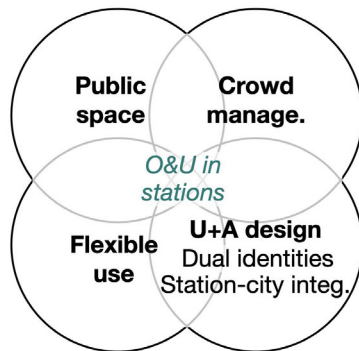


FIG. 1.7 The academic relevance of O&U in stations. (Source: Author)

1.3.1 Crowding studies in crowd management

Crowding is an important topic in the transportation engineering field ([Peacock et al., 2011](#)). Crowd movement has been studied regarding the pedestrians' collective and individual features, such as pedestrians' preferred walking speed ([Fruin, 1971](#)), direction preferences, psychology ([Campos Ferreira et al., 2022](#)), and cultural backgrounds. Extreme crowding leads to stampedes, of which much remains unknown ([Almeida and Schreeb, 2019](#)) due to the low frequency of happening and lack of recorded data.

In crowd management studies, the **physical environments** examined are typically limited to small-scale building elements such as corridors, corners, crossings, exits (Duives et al., 2013), gates (Andresen et al., 2016). Specifically for railway stations, Heuvel (2022) focused on passenger behavior on station platforms. Other studies have investigated the placement of gates and escalators within stations (Hoogendoorn and Daamen, 2004).

Technologies have been developed to monitor, simulate, validate, predict, and intervene in pedestrian flows in railway stations, helping reduce overcrowding. Monitoring can be done through Bluetooth, WIFI, GPS, sensors, phone signals, cameras, and ticket checking information (Heuvel, 2022). Crowd simulation can be facilitated by various software programs (Dubroca-Voisin et al., 2019). If the pedestrian flow is properly simulated, predictions and necessary interventions on the flow can be made. In real-world cases like Amsterdam Bijlmer ArenA station, where crowding recurs due to the nearby stadium's sports events, these technologies are actively employed (Aseniya, 2019).

These crowding studies, conducted within the engineering field, do exhibit certain limitations. First, they typically focus only on basic needs such as safety, while ignoring perceptual or experiential user needs (Van Der Hoeven and Juchnevic, 2016). Moreover, the micro-level environments or elements examined by these studies are typically too small to be considered as urban or architectural interventions.

1.3.2 The uses of public space

The use of public spaces to promote vitality—as opposed to underutilization—is a key research focus in the field of urban design (Gehl, 1987; Whyte, 2001; Mehta, 2007). Foundational studies in this field emphasize the role of human activity in shaping and activating public spaces. For example, Jacobs (1961) examined the dynamics of community life and urban neighborhoods, arguing that mixed uses, short blocks, building diversity, and density foster urban vitality. Gehl (1987) categorized different activities in public space—including necessary activities, optional activities, and social activities. He argued that spatial design directly shapes the prevalence of optional and social activities through factors such as human-scale design, edge effects, sensory richness, and visibility and permeability.

Beyond behavioral observations on activities, environmental psychology has emerged as a critical lens for understanding how individuals perceive and interact with public spaces (Gifford, 2001). This field explores the cognitive and emotional responses to spatial features, such as safety, comfort, and aesthetic appeal, which jointly influence how people use and experience urban environments.

Recent research has expanded on these foundational ideas by examining specific aspects of specific public spaces that contribute to their vibrancy. For example, Whyte

(2001) explored the micro-level social dynamics of plazas and small urban spaces, identifying key factors that contribute to their liveliness, including seating arrangements, sunlight exposure, and proximity to street activity. Ewing and Handy (2009) measured features of street elements as related to people's perceptions of street walkability. Long and Ye (2019) reviewed studies that utilize new technologies to analyze human-scale urban form in relation to space performance.

While much of the literature examines public spaces in general—such as streets, plazas, and parks—a few studies focus specifically on station areas. Studies by Dai (2015); Du (2023); Trip (2008) have explored place-making strategies in high-speed rail stations, emphasizing the importance of design quality in fostering a sense of place and enhancing user experience. However, these studies, often rooted in transport planning, tend to lack the spatial granularity needed to inform detailed architectural and urban design interventions (Klaasen, 2001).

1.3.2.1 User experiences in stations

In the context of railway stations—a specific type of public space, Van Hagen investigated user experience through a series of studies (Van Hagen, 2009, 2011; Hagen and Heiligers, 2015; Van Hagen and Bron, 2014). One of his key contributions is the development of a user experience pyramid, which consists of five hierarchical levels of user needs—safety and reliability, speed, ease, comfort, and experience (Van Hagen, 2011). Beyond these needs, he also emphasizes the value of creating emotionally engaging and memorable moments during railway journeys (Van Hagen and Bron, 2014).

1.3.3 Academic discussions such as ‘flexible use’ addressing changes

Stations' situations shifting between overcrowding and underutilization provide a changing context for potential solutions; In this context, in addition to flexible use (subsection 1.2.4), a series of terms, which share an underlying essence of dealing with changes or being able to change, are relevant potential solutions. These terms include flexibility of buildings, kinetic architecture, flexible spaces, temporary use, urban open spaces, event spaces, resilience, and mixed use. They frequently co-occur in the same literature due to their similarity in meanings [e.g., see the papers by Roggema (2014) and Geraedts (2008)]. Still, across the broader multidisciplinary literature, these terms have different emphases on different systems—systems ranging from as small as building facade components to district elements, landscapes, or even cities, and are used in different disciplines—including architectural design, urban design, landscape architecture, spatial planning, and management, as explained below.

In the architectural design discipline, the concept of **flexibility of buildings** has been explored through various frameworks and design strategies. For example, [Alkhansari \(2018\)](#) summarized tactics of flexibility in architecture, including 'open plan', 'pre-fabricated modules', 'similar spaces', 'extendable unit', 'attachment and detachment of adjacent units', 'common space between adjacent units', 'portable walls', and 'retractable furniture in a multifunctional space'. [\(Geraedts, 2008\)](#) proposed a framework with indicators for assessing flexibility for architecture. [Ou \(n.d.\)](#) proposed design typologies of flexible buildings. [\(Katsikakis, 2017\)](#) advocates flexibility of office working spaces. [Cellucci and Di Sivo \(2015\)](#) defined criteria and strategies for flexibility, specifically on housing.

Kinetic architecture is another concept describing buildings that support changes. Kinetic architecture is a kind of building with kinetic components—components that are driven by mechanical engines. It has been studied in relation to building facades, movable structures, and buildings designed to be dismantled and reassembled [\(Engadget, 2019; Johnson et al., 2019; Megahed, 2017; Miguel, 2024; Smith, 2023\)](#). Kinetic buildings, however, are expensive to build and maintain. Only rare examples of kinetic buildings have been built so far. Beyond buildings, a study by [Dąbrowska-Żóhtak et al. \(2021\)](#) transforms the kinetic idea to urban design of urban spaces. This study introduces mechatronized city elements, including liftable bollards modifying streets' access, rotatable benches and boards reconfiguring urban plazas' layouts, and foldable umbrellas or moveable roofs adjusting the weather protection.

In the urban planning discipline, a series of terms with the meaning of flexibility has been developed, which typically focuses on non-physical content such as planning process, user activities, social movements, and real estate management. For example, [Carr and Dionisio \(2017\)](#) proposed seven guidelines for creating **flexible spaces** to overcome problems in contemporary spatial planning. These guidelines include fixed non-renewable tenancies, shared tenancies, reconfigurable spaces, minimalist regulatory frameworks, the requirement of new uses, designing for unscheduled uses, free or minimal cost tenancies, and potential off-site expansions.

[\(Madanipour, 2018\)](#) analyzed **temporary use** of space through a detailed single case study, examining the processes where multiple actors collaborated to make use of a temporarily empty building, showing the opportunity as well as limitations in such practice. [Dovey \(2012\)](#) advocates **assemblage** thinking, treating urban systems as complex adaptive systems. His research examines how temporary informal settlements provide growth, productivity, and creativity.

In the landscape architecture discipline, [Thompson \(2002\)](#) proposed new **urban open space** towards the 21st century, with 'loose-fit' landscapes, allowing opportunities for the socially marginalized, shifting within dynamic urban networks. [Ivers \(2018\)](#) proposed the idea of **staging urban landscape** through activation and curation. His research documented dozens of flexible public spaces—including urban plazas, parks, and waterfronts—through vivid imagery.

In the urban design discipline, [Smith et al. \(2021\)](#) developed a typology of **event**

spaces that associate city events with the public spaces. This typology has nine types of event spaces categorized according to the level of public accessibility and the mobility of event audiences. [Ardeshiri et al. \(2016\)](#), for explaining **flexibility in urban spaces**, illustrated relevant spatial elements and qualities that are supportive of flexible use, including positive outdoor spaces, spaces with multi-modal behavioral patterns, multi-use buildings, active frontages, and fine amenities.

Across numerous disciplines, the concept of resilience has been explored. The concept of resilience was first introduced in ecology to reduce risks in systems that, due to being overly optimized for efficiency, lacked the capacity to absorb sudden changes ([Holling, 1973](#)). Over time, this concept has evolved, spread across numerous fields ([Hosseini et al., 2016](#)). Recent research has also incorporated the resilience concept into spatial planning and design fields ([Büyüközkan et al., 2022](#)). For example, [Mehmood \(2016\)](#) proposed urban resilience in spatial planning. [Shafiei Dastjerdi et al. \(2021\)](#) synthesized findings in literature and built a conceptual framework for assessing **resilient place**.

In the spatial planning and design disciplines, **mixed use** is widely promoted. From this thesis's perspective, the distinction between mixed-use and flexible use is whether the temporal dimension and changing situations are inevitably involved. When different uses occur at different times in response to changing conditions, the space should be more accurately described as a flexible use space ([Figure 1.8](#), left). In contrast, when multiple uses coexist simultaneously within a fixed context, the space is better classified as a mixed-use space ([Figure 1.8](#), right). A few concepts share similar meanings with mixed use, including multiple uses, all-in-one, and multi-function. 'Mixed use' and 'multiple uses' are terms describing land use in the urban planning field. 'Multi-function' ([Blueid, n.d.](#)) and 'all-in-one' are used to describe buildings and architectural programs. In the context of stations, mixed-use development—combining transport functions with non-transport functions such as offices, dwellings, and facilities—is sometimes proposed for generating commercial revenue and enhancing user experience ([Peters, 2009](#); [Bruinsma, 2009](#)).

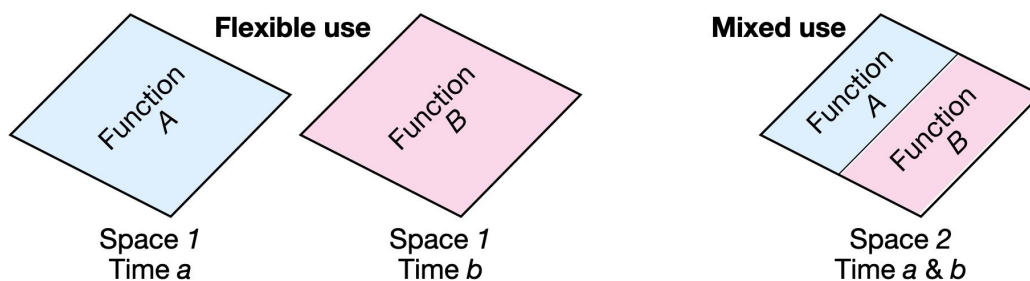


FIG. 1.8 'Flexible use' vs 'mixed use'. (Source: Author)

Most mixed-use research omits or only implicitly addresses the temporal dimension and its temporal dynamics—for instance, the research by [Rabianski and Clements \(2007\)](#). A small number of studies have explicitly incorporated the temporal dimension, thereby aligning mixed use more closely with the concept of flexible use—as seen in

the work of Hoppenbrouwer and Louw (2005); De Wilde (2006). This thesis treats flexible use as a distinct concept and intentionally avoids using the term mixed use to highlight the context of changing conditions over time.

Considering the systems and fields the above concepts focus on, flexible use is the most accurate term for describing railway station areas. The content, however, remains underexplored at the intersection of urban and architectural design (Figure 1.8).

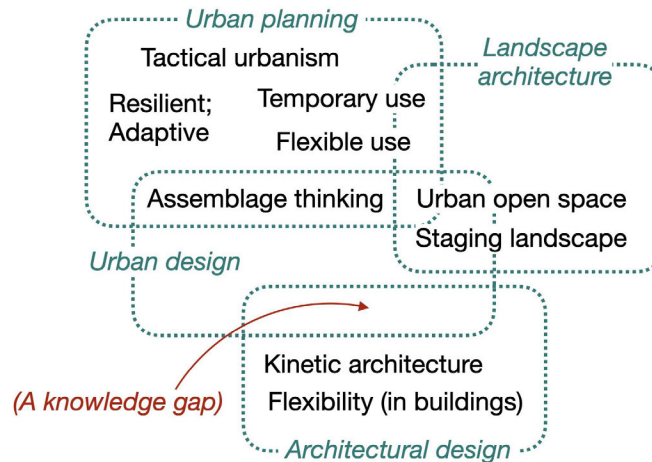


FIG. 1.9 Terms in the spatial design field that deal with changes

1.3.4 Spatial design of stations and the theme of station-city integration

This subsection introduces research about stations in the spatial design and planning fields. First, it introduces research on station buildings, station areas, and stations in railway networks, in the disciplines of architectural design, urban design, and spatial planning, respectively. It then points out predominant research themes, including transit-oriented development and station-city integration. In these themes, central topics include stations' dual identities, assessments of stations, and the multiplicity of actors involved in station development. Lastly, with a particular interest in practice, this research also reviews existing design principles of stations.

1.3.4.1 Differentiate three station-related concepts

This research differentiates three station-related concepts—station buildings, station areas, and stations in railway networks—regarding the disciplines of architectural design, urban design, and spatial planning, respectively (Figure 1.10). These three types of concepts are interrelated—any station building is situated within railway and urban transport networks, with local effects on station areas and global effects on railway networks, and vice versa. Despite the interrelationship, each type of entity has its own design concerns and priorities. Each of the disciplines approaching these entities has its typical differentiated objectives, scopes, and methods, with unique strengths and limitations (Figure 1.11).

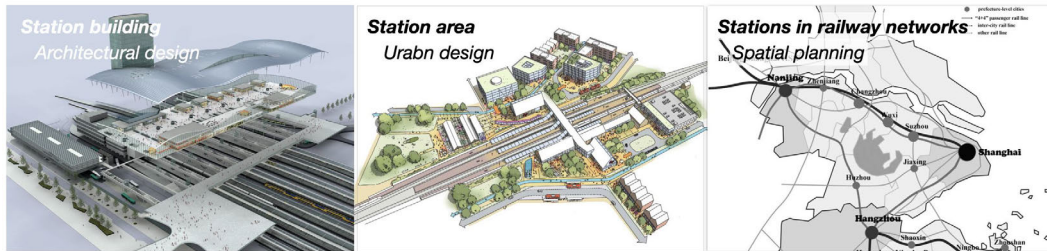


FIG. 1.10 Station buildings, station areas, and stations in railway networks.
(Source: Left—Bentheimcrouwel.com, Middle—Networkrail 2023, Right—Tang et al. 2011)

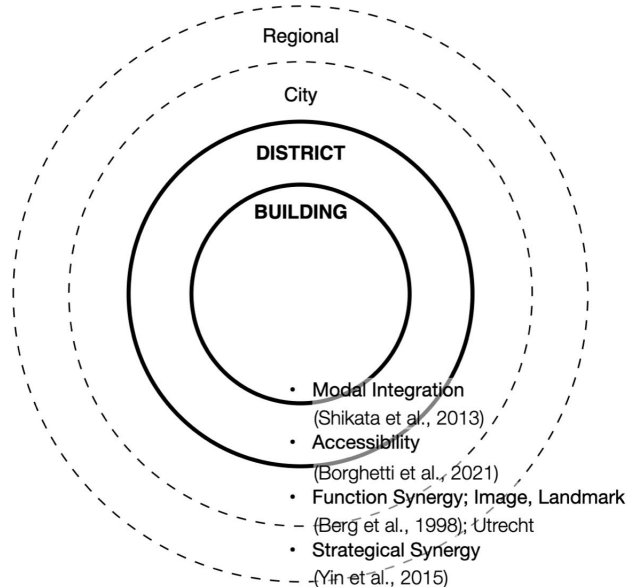


FIG. 1.11 Multiple spatial scales of stations and the corresponding research focuses. (Source: Author)

Architectural design studies of **railway station buildings** date back a long time. For example, in 1956, [Meeks \(1956\)](#) examined the architectural evolution of railway stations from the nineteenth century to the twentieth century. [Richards and Mackenzie \(1986\)](#) analyzed stations regarding geographical contexts, demographic aspects (e.g., class, race, and sex), and social aspects (e.g., economy, work, war, and culture). Large stations once were engineering masterpieces as the long-span roofs were technically novel ([Meeks, 1956](#)). Stations also have symbolic and cultural values as the gates of cities, glorifying cities' status and architectural style was a central consideration in architectural design ([Meeks, 1956](#)). [Ross \(2000\)](#) studied the planning, design, and management of railway stations, treating railway stations as architectural landmarks.

Beyond symbolic and cultural aspects, architectural studies have also investigated functional and experiential aspects of station buildings. For example, [Edwards \(1997\)](#) examined stations' layouts and typologies. [Van Der Spek \(2003\)](#) examined mobility nodes' layouts and station buildings' compositions for better modal integration of stations. [De Wilde \(2006\)](#) analyzed the multiple use of station buildings, regarding spatial quality, building structures, engineering, safety, and financial investment. [Cavallo \(2008\)](#) explored the role that architecture can mediate the integration or separation between railroads and cities. [Da Conceição \(2015\)](#) explored how architecture can contribute to the improvement of the spatial performance of European stations. [Shikata et al. \(2013\)](#) examined the historical phases of Japanese station-city integration practice, explaining the features of stations developed in each phase with representative cases. These Japanese station cases are mostly located in typical Japanese high-design urban contexts, mixed with city buildings or infrastructures such as shopping malls or underground commercial streets.

A large body of studies on stations in **railway networks** at city and regional levels emerged from the 1990s in the fields of spatial planning and human geography ([Bruinsma et al., 2008](#)). Stations within railway networks bring economic opportunities to cities and leverage the cities' industries or businesses ([Van Den Berg and Pol, 1998](#); [Bertolini and Spit, 1998](#)). Scholars have been studying stations' or railway networks' effects on cities, based on data from station areas ([Bruinsma, 2009](#); [Debrezion et al., 2007](#)). [Yin et al. \(2015\)](#) synthesized research findings on high-speed railway's effects on urban development, aiming to provide implications for Chinese railway practice.

Urban design research focusing on **station areas** emerged relatively late. For example, Deike Peters conducted a series of case studies on the urban design of stations ([Peters and Tolkoff, 2016](#); [Peters, 2009](#); [Peters and Novy, 2012](#); [Novy and Peters, 2012](#); [Loukaitou-Sideris et al., 2017](#)). These case studies are detailed, documented building-level interventions that influence district-level configurations—for example, optimizing tram stop layouts to reduce traffic space, tunneling roads to improve pedestrian walkability, and creating pedestrian passages through buildings to enhance cross-rail connectivity. [Triggianese \(2023\)](#) highlighted design as a decision-making tool that offers a platform for robust discourse on critical issues. [Van Acker and Triggianese \(2021\)](#) explored the urban design challenges in designing stations for small and medium-sized European cities, pointing out that the station in this context is no longer shaped as a monolithic, architectural cathedral, but interweaves as a system of public infrastructure and facilities.

Research has also explored applying **place-making**—an urban planning and design approach—to station area development. Place-making is about creating places that are not just functional, but also beautiful and meaningful to the people who live, work, and play there ([Project For Public Spaces, 2018](#)). Regarding station areas, Du synthesized a definition of place quality in high-speed rail station areas, including a spatial dimension associated with aesthetic qualities of urban spaces, a socio-cultural dimension associated with experienced ‘sense of place,’ and an economic dimension associated with the agglomeration of economic activities ([Du et al., 2021](#); [Du, 2023](#)).

[Trip \(2008\)](#) investigated to what extent urban quality has been considered in the station development process in the cases of Amsterdam South Station and Rotterdam Central Station. [Jehle et al. \(2022\)](#) studied pedestrians’ perceptual accessibility in relation to six qualities, including directness, simplicity, traffic safety, security, comfort, and built environment.

Design and planning research, including the placemaking approach, has explored the possibility of surrounding stations with vital urban environments, or even transforming station areas into urban centers ([Kusumo, 2007](#)), which are prone to high-density development. However, when stations are located in certain low-density contexts, like rural areas, high-density development is not always an ideal option. Alternatively, one option is surrounding stations with green parks, remaining a low-density environment; for example, the newly built Jiaxing Station in China, themed a ‘train station in the forest’ ([Gooood, n.d.](#)), illustrates such an option.

Across different spatial scalar levels, the following topics have been frequently addressed: station-city integration, transit-oriented development, stations’ dual identities and multiple generic functions, stations’ assessment, and multi-actor decision-making processes. Station-city integration has commonly been set as a research context, as well as Transit-Oriented Development (TOD). Station’s dual identities have been commonly set as the theoretical framework as well as the assessment framework in research. Similar to the dual identities idea, multiple generic functions of stations have been investigated and identified. In the development of stations, especially of station areas, multiple actors are commonly involved. The following paragraphs elaborate more on these topics.

1.3.4.2 Station-city integration

Station-city integration is an ideal scenario where stations and cities are appropriately integrated to resolve negative issues and to achieve positive benefits, as described at the beginning of this thesis ([section 1.1](#)). Station-city integration has been discussed or practiced in various continental or national contexts, such as Europe ([Peters and Novy, 2012](#)), Japan ([Shikata et al., 2013](#)), and China ([Cheng et al., 2021](#)).

In this thesis, station-city integration is a vision featured with an explicit temporal

dimension. It is a type of integration of stations and cities that is achieved by enabling temporal function changes and sharing their resources. In this way, both stations' and cities' maximum capacity is increased, and underutilization is reduced, lowering investment and intensifying the use of resources. This is different than static collocation of stations and cities, where only the physical building density is increased.

Another widely addressed topic is **Transit-Oriented Development (TOD)**. It is a type of urban development that maximizes the amount of residential, business, and leisure space within walking distance of public transport, promoting a symbiotic relationship between dense, compact urban form and public transport use (Calthorpe and Poticha, 1993; National Academies of Sciences, Engineering, and Medicine, 2004). It has been established as a research context in some studies focusing on railway stations (Shikata et al., 2013; Singh et al., 2017), but more commonly, it is applied to metro stations (Calthorpe and Poticha, 1993; National Academies of Sciences, Engineering, and Medicine, 2004; Ibraeva et al., 2020; Knowles et al., 2020).

1.3.4.3 Dual identities of railway stations

A few studies have consolidated the theoretical foundations of station-city integration—studies proposing the dual identities of stations or identifying the multiple generic functions of stations. According to Bertolini and Spit (1998), stations function both as nodes within the railway network and as places embedded in cities (Figure 1.12), and ideal stations should balance these two identities. Numerous station studies have adopted this idea of dual identities, and use the node-place assessment framework to evaluate station performance or railway development (Peek et al., 2006; Ortuno-Padilla et al., 2017; Kim et al., 2018). Some studies also expanded the dual identities into multiple functions or components. For example, the 'butterfly mode' addresses stations as places, nodes, humans, and mobilities (Ministerie Van Algemene Zaken, 2020, p. 31). Through focus groups, expert interviews, and workshops, Zemp et al. (2011) identifies five generic functions of stations, including "linking catchment area and transport network, supporting transfer between modes of transport, facilitating commercial use of real estate, providing public space, and contributing to the identity of the surrounding area."

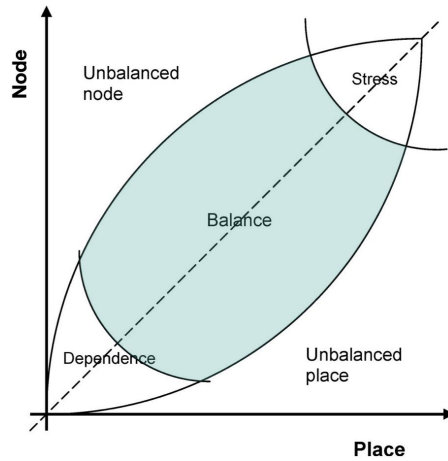


FIG. 1.12 The Node-place model by Bertolini. (Source: Bertolini 1999)

1.3.4.4 Design principles

Regarding the design practice of stations, a few manuals of design principles have been developed. For example, the company Network Rail in the UK has developed design principles for stations (Anthony and Frank, 2021) and station areas (Networkrail, 2023). The company ‘Spoorbeeld’ (the Dutch word for ‘Railway Image’) in the Netherlands has developed design principles for different aspects of stations, including urban design of station areas (Spoorbeeld, n.d.). These kinds of guidance are established with diverse objectives to improve station qualities. Regarding the specific problem of overcrowding and underutilization, specific design principles addressing the problem are still lacking.

1.4 Knowledge gap: lacking integrated knowledge for spatially addressing O&U in stations

This section outlines a multifaceted knowledge gap. As described in the problem statement (section 1.2), there is overcrowding and underutilization (O&U) in some railway stations (i.e., stations that have fluctuations associated with events or disruptions). Ideally, this research expects existing knowledge that provides a deep

and comprehensive understanding of the issue of O&U in stations, and provides solutions to it. However, the literature review (section 1.3) shows that although many studies are partially relevant, none specifically address the issue of O&U in stations, resulting in a fragmented body of knowledge. This highlights a need to develop integrated knowledge (subsection 1.4.1). Considering the format of knowledge, there is a lack of descriptive knowledge explaining spatial relevance, as well as know-how knowledge for assessing and designing station areas (subsection 1.4.2).

1.4.1 Lacking knowledge integration between academic topics

Given the problem statement and literature review, the following three gaps in knowledge integration have been identified (See also subsection 2.5.2). First, there is **a lack of integration of knowledge about overcrowding and underutilization**. Overcrowding and underutilization happen in stations at different times. Solely resolving any of them without considering the other may lead to a paradox of station sizing, where reducing overcrowding leads to more underutilization, and vice versa (subsection 1.2.3). Therefore, overcrowding and underutilization should be considered together, which favors the flexible use of stations (subsection 1.2.4 and subsection 1.3.3) and requires taking the temporal dimension into account (subsection 1.3.3). While in existing literature, studies about crowd management address overcrowding (subsection 1.3.1), studies about the use of public spaces address underutilization (subsection 1.3.2), and the integration is yet to be achieved (Figure 1.13, ①). In studies about the dual identities of stations (subsection 1.3.4) and mixed use of stations (subsection 1.3.3), the temporal dimension is usually not explicitly stated.

Second, there is **a lack of knowledge integration between flexible use and spatial design of station areas**. For easing overcrowding and underutilization (O&U), spatial design is a potential means of intervention, as O&U are associated with spatial factors (subsection 1.2.3) and stations can be intervened by spatial design (subsection 1.3.4). For easing O&U, flexible use is a potential solution, because it linguistically means 'able to change easily according to the situation' (Dictionary, n.d.), enabling it as a solution to change for addressing overcrowding and underutilization (subsection 1.3.3); flexible use happens in rare real-world cases like Shanghai Station (subsection 1.2.4). Considering the potential of spatial design and flexible use, it is meaningful to integrate them (i.e., spatial design station areas that support flexible use) (Figure 1.13, ②). However, integrated knowledge is lacking. Existing literature on flexible use lacks spatial details at the district level (subsection 1.3.3).

Third, there is **a lack of knowledge integration between flexible use (for addressing O&U) and station-city integration** (Figure 1.13, ③). Station-city integration is a growing concept that conveys positive values (subsection 1.3.4). Promoting flexible use can be a new positive value to enrich the meaning of station-city integration. Also, benefiting from the proper integration, stations can have a larger capacity for peak

time uses, or have spaces optimally used during non-peak times, promoting more flexible use. However, hardly any studies on station-city integration address flexible use (which should not be conflated with mixed use, see [subsection 1.3.3](#)), nor any studies on flexible use of stations taking integration into account.

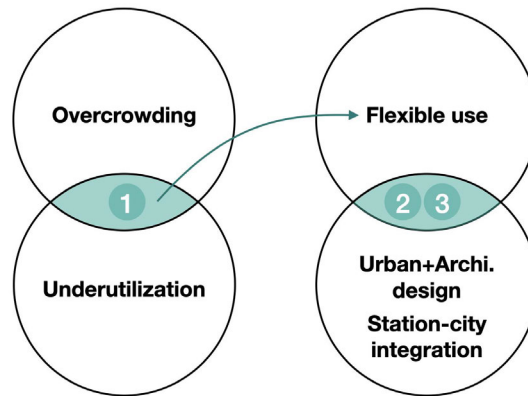


FIG. 1.13 Knowledge integrations needed. (Source: Author)

1.4.2 Lacking knowledge for spatial design practice

Considering the design practice on railway stations, three types of knowledge are currently lacking. First, there is insufficient **understanding of the spatial relevance** of overcrowding and underutilization (O&U) in railway stations. Overcrowding, underutilization, and flexible use are influenced by a complex interplay of spatial and non-spatial factors (see [section 1.2](#)), as observed in pilot case studies. However, existing literature has not systematically documented or analyzed these relationships. A more detailed understanding of the causal interrelationships among these factors—along with a clearer articulation of their spatial relevance—is needed to provide a solid foundation for effective design practice.

Second, for design practice, rigorous assessment frameworks are essential for evaluating and improving design quality ([Carmona et al., 2003](#)). Overcrowding and underutilization in stations are temporal phenomena and should be addressed regarding both peak and non-peak conditions. However, as revealed in the preceding literature review ([subsection 1.3.4](#)), existing assessment frameworks largely overlook the temporal dimension (see [subsection 1.3.4](#), dual identities of stations and assessment; and [subsection 1.3.3](#), mixed use). **Assessment frameworks that incorporate the temporal dimension** are currently lacking.

Third, in design practice, clear design principles—such as design principles—is essential for translating complex spatial challenges into actionable interventions

(Carmona et al., 2003). While a few design principles documents on railway stations exist (Anthony and Frank, 2021; Networkrail, 2023), none specifically address the flexible use aimed at reducing overcrowding and underutilization (O&U) in stations. **design principles for the flexible use of stations** aimed at reducing O&U are lacking.

1.5 Research objectives and research design

This section sets the research objectives and research design. In designing the research, it asks research questions (subsection 1.5.2), plans different parts and chapters to work on (subsection 1.5.3), and aims for corresponding research significance (subsection 1.5.4).

1.5.1 Research objective

Aiming to fill the aforementioned knowledge gap in the integration of knowledge and its application in practice, this research sets its objectives as follows:

Advance **flexible use** (aimed at reducing overcrowding and underutilization in railway station areas) through **urban and architectural design**, promoting **station-city integration**. In doing so, the research will provide spatial **understanding**, as well as **solutions** in the form of an assessment framework and design principles), for actors who are involved with the station design and development, with user experience as a key consideration (Figure 1.14).

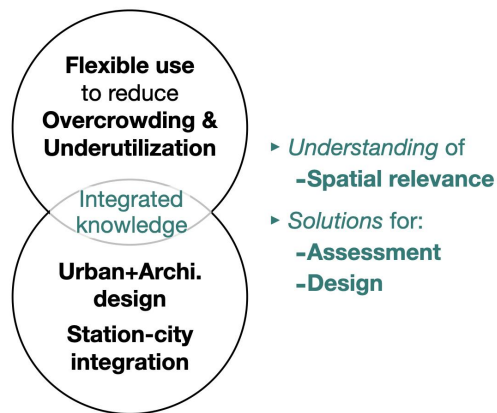


FIG. 1.14 Research objectives. (Source: Author)

This research aims for knowledge integration between topics, including flexible use, overcrowding and underutilization, urban and architectural design, and station-city integration. It hypothesizes **flexible use** as a solution aimed at reducing overcrowding and underutilization (O&U), expecting stations to share spaces and resources with cities at different times. In this way, stations become integrated with cities both physically and functionally, forming a deeper level of station-city integration. Flexible use, aimed at reducing O&U, becomes a new positive value in the discourse of **station-city integration**.

This research situates itself within the field of spatial design, motivated by two considerations. First, overcrowding and underutilization have spatial relevance, and spatial design demonstrates potential to mitigate them ([subsection 1.2.3](#)). Second, the author has an educational background in the spatial design field and has the objective to contribute to this field. More precisely, this research positions itself at the intersection of '**urban and architectural design**'. Urban design of station areas at the district level, and architectural design of station buildings at the building level, are redoften related. For instance, a district axis proposed in an urban design scheme will only function if there are passages across the buildings on that axis. Therefore, it is necessary to study urban and architectural design jointly in this research.

The research aims to develop **three forms of knowledge** corresponding to the knowledge needed in practice ([subsection 1.4.2](#)): (1) a description of spatial relevance—to help designers and stakeholders understand how spatial aspects, among other aspects, affect overcrowding and underutilization (O&U), flexible use, and station-city integration; (2) an assessment framework that incorporates the temporal dimension—to facilitate designers, researchers, and stakeholders in design evaluations; (3) a set of design principles—to inform designers to make practical design schemes for stations that support flexible use and station-city integration. These three forms of knowledge sit at the intersection of the aforementioned academic topics—each relates to O&U, flexible use, and spatial design ([subsection 1.4.1](#)), forming a better integration between these academic topics.

1.5.2 Research questions

To achieve the research objectives, this research addresses three main research questions, each containing multiple specific sub-questions, as listed in [Table 1.1](#).

TABLE 1.1 Research questions in this thesis

Main research questions	Sub-questions
1. What is the spatial relevance of the overcrowding and underutilization in the station area?	► How do national contexts affect the overcrowding-underutilization phenomena in railway stations? ► How do spatial configurations affect the overcrowding-underutilization phenomena in railway stations, and hence, what is spatial design's potential? (Chapter 3)
2. What are the design principles for station areas that support flexible use?	► What are the design principles for railway station areas that support flexible use? ► How can design principles of complex projects, like railway stations, be developed in a systematic way that enables synthesizing, probing, and validating knowledge? (Chapter 4) ► How effective are the design principles of flexible use of stations, as demonstrated through research-by-design and agent-based simulations (ABS)? ► What will these design principles be like when applied to new cases? (Chapter 5)
3. How can design proposals be assessed as supportive of flexible use?	► To what extent can agent-based simulation help assess user satisfaction to facilitate the spatial design of station areas (that are integrated with cities and support flexible use)? (Chapter 6) ► How to computationally assess the visual quality of the built environment for design use? ► What are the limitations of ABS in assessing complex projects like railway stations? (Chapter 7)

1.5.3 Research design

The main body of this research is divided into three parts with six chapters. To investigate the three main questions, this research sets three primary chapters: [Chapter 3](#) (Describing spatial relevance), [Chapter 4](#) (Developing design principles), and [Chapter 6](#) (Developing assessment framework), respectively. [Chapter 2](#) (Literature Review) examines existing solutions that are relevant for the flexible use of stations, revealing the gaps to be filled by this thesis. During the research process, a component of the assessment framework—the visual assessment model—grew significantly in scope and importance. This led to its distinction as a separate supplementary [Chapter 7](#). As the research progressed, the possibility emerged to apply the assessment framework to evaluate design proposals generated based on the design principles. In response to this insight, an additional [Chapter 5](#) was introduced to explicitly structure this application and evaluation process ([Figure 1.15](#)).

To provide a coherent thematic progression, the thesis is presented in three parts. PART I (Chapters 2 and 3) provides the contextual foundation required for the subsequent research. PART II (Chapters 4 and 5) focuses on the development of design principles for the flexible use of railway stations. Finally, PART III (Chapters 6 and 7) presents the assessment framework ([Figure 1.15](#)).

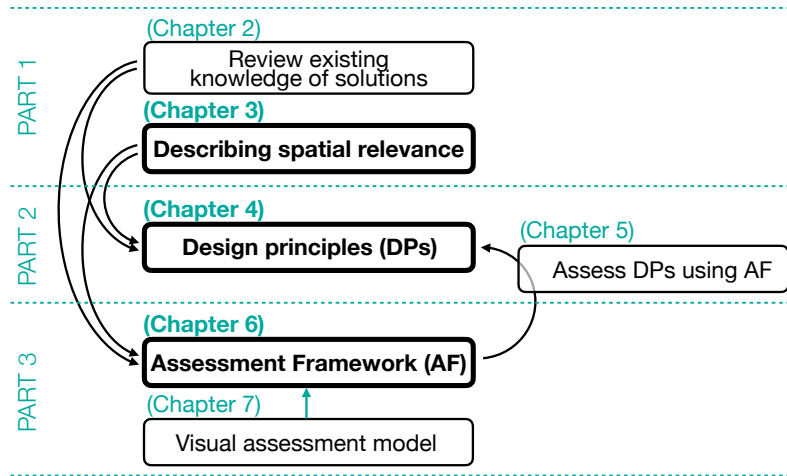


FIG. 1.15 The main body of this research is designed into three parts with six chapters. (Source: Author)

The **target audience** of this research's outcomes, in a broad sense, is actors who are relevant or interested in the design and development of station areas. More specifically, the description of spatial relevance is for stakeholders and designers; the design principles are for designers; the assessment framework is for actors who want to do an assessment of stations, such as researchers, designers, consultancy companies, developers, or government departments.

1.5.4 Research significance

With research packages planned and the target audience set, this research anticipates societal and academic significance. With a focus on railway stations that experience recurring overcrowding and underutilization (O&U), this research has **societal significance** by informing the design of stations that are supportive of flexible use aimed at reducing O&U, and are more efficient, resilient, affordable, and sustainable. The research produces a description of the spatial relevance, an assessment framework, and a set of design principles, which help understand the role that spatial design can play, guide the design practice, and facilitate design assessment, respectively.

Overcrowding and underutilization (O&U) have a general relevance beyond railway stations, as it is common across other types of infrastructures and public spaces, such as airports, stadiums, music venues, sports centers, hospitals, and libraries. The O&U-mitigating approaches, developed in this research, for railway stations, can inform similar approaches for other infrastructures.

This research has **academic significance** by addressing the underexplored potential of flexible use as a spatial design strategy aimed at reducing overcrowding and underutilization. It enriches the knowledge base of relevant fields, fosters cross-disciplinary knowledge integration, and extends the boundaries of existing research. The research outcomes—a description of the spatial relevance, an assessment framework, and a set of design principles—collectively broaden methodological approaches and conceptual foundations in urban and architectural design of stations.

1.6 Research scope and key concepts

With the aforementioned research objective defined and research questions presented, it is still overly broad to conduct research considering the complexity of stations' O&U and flexible uses. This section further clarifies key concepts to narrow down the research scope. The following subsections define what events ([subsection 1.6.1](#)) are considered as affecting stations, the diverse temporal uses of stations ([subsection 1.6.2](#)), relevant stakeholders and their corresponding interests ([subsection 1.6.3](#)), to what extent spatial and management interventions are considered ([subsection 1.6.4](#)), the station type and case selection ([subsection 1.6.5](#)), and the spatial scale of station areas ([subsection 1.6.5](#)).

Notably, temporality is a crucial aspect in this thesis, as it relates to event frequencies and durations, frequencies of intervention on stations, and the efficiency of space use. To describe temporality, a few extra technical concepts, such as the magnitude of user volume, intensity of fluctuations, and spatial-temporal occupancy ratio, are used in the following subsections.

1.6.1 Events

The events affecting stations, as considered in this thesis, have the following characteristics: they happen with frequencies between multi-weekly and yearly; they cause peaks of user volumes with different magnitudes or intensities; and physically, they do not necessarily happen at stations.

1.6.1.1 Events and their frequencies of happening

Events can happen with different **frequencies**, or correspondingly, can be observed at different **temporal scales**. Railway station areas are affected by a spectrum of events across different temporal scales, ranging from rare pandemics, Olympic games, yearly festivals (Mccarthy, 2018), multi-weekly railway disruptions (Rijdscheldere, n.d.), weekly markets, and daily commuting.

This research focuses on events and disruptions that occur with a frequency between multi-weekly and yearly, such as sports events, festivals, and railway disruptions. These events are particularly relevant to railway stations for several reasons: they produce significant pedestrian fluctuations that can potentially be mitigated through spatial design; they exhibit recurring patterns that can be analyzed; and they remain underexplored in spatial design research.

In contrast, high-frequency events, such as daily and weekly commuting, are more characteristic of metro station dynamics and are extensively studied in the context of Transit-Oriented Development (TOD) (Ibraeva et al., 2020). Meanwhile, low-frequency events, such as the Olympic Games, are too rare to allow for meaningful pattern recognition (Alexander, 1977; Sanchez and Essex, 2018).

1.6.1.2 Magnitudes of user volumes

These abovementioned different kinds of events bring different **magnitudes** of peak user volumes to stations. When evaluating these volume peaks in relation to their duration, these fluctuations display distinct **intensities** (i.e., the concentration of volume over time). For instance, daily commuting during workdays generates predictable morning and evening peak volumes during rush hours. Weekend passenger flows are typically smoother, lacking significant surges. A major festival (e.g., the Rotterdam Summer Carnival) can sustain a large volume of users throughout the entire day. A football match may force a massive surge of passengers through a nearby station (e.g., Amsterdam Bijlmer ArenA) within a highly compressed window of just 20 minutes (Figure 1.16).

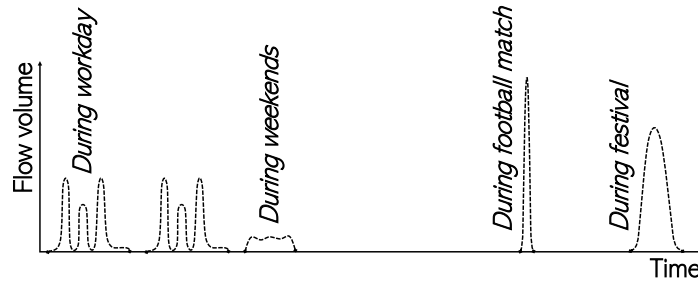


FIG. 1.16 Events and fluctuations with different magnitudes and intensities.
(Source: Author)

1.6.1.3 Events at stations or not

Notably, the events that affect station dynamics do not necessarily have to occur within the physical station buildings (e.g., an exhibition inside a concourse). They can also take place in the immediate vicinity outside the station (e.g., a market assembly on the station plaza), at a short distance away (e.g., a sports match in a stadium located 200 meters from the Amsterdam Bijlmer ArenA station), or even at a city-wide scale (e.g., the Chinese Spring Festival migration affecting major railway stations).

1.6.2 The temporal uses of stations

1.6.2.1 Activities and users

Regarding the uses of stations, in the context of station-city integration, this thesis assumes that both **transport** and **non-transport** activities happen within stations. Transport activities include passengers waiting for their trains, transferring between different modes of transport, or enjoying **commercial services** like catering and retail stores. Different types of passengers have their different traveling purposes, with diverse needs and psychological preferences (Van Hagen, 2009).

Non-transport activities include non-passengers or local citizens using station spaces as public spaces for civic or leisure activities, such as gathering on the plaza or hanging out in station retail stores. Both passengers and non-passengers can potentially use station commercial services, if these services are not in gated areas that require train tickets. Station-related properties may be used as work spaces, adding to the complexity of uses (De Wilde, 2006).

Notably, some of these activities involve users staying in certain spaces for relatively long periods (e.g., waiting, gathering), while others involve users passing by certain

spaces in short periods (transferring between modes, hanging out). To measure the space usage regarding these activities, the temporal dimension must be considered.

Stations are not only spaces for human activity, but they are also complex infrastructural assets that require regular operational support. A series of indispensable **supportive activities** must be conducted regularly to keep services operational, safe, and satisfactory. These operational tasks encompass routine cleanliness and sanitation practices within high-traffic concourses, ongoing maintenance and repair of technological and mechanical devices (such as automated ticket gates and escalators, and building equipment), strict security tasks, and safety inspection tours. Many of these supportive activities, like repairing, preferably take place during off-peak or nighttime hours when user density is low, so that the interference of supportive activities on main activities can be minimized.

In the context of flexible use of stations, this thesis also assumes stations to be possibly being used as venues for events, like people dancing on squares, or exhibitions in station concourses. Organizing these events often involves the pre-event setup, event running, and post-event dismantling (Allen et al., 2022, pp. 79-82). In summary, this thesis assumes several types of activities happen in stations—transport activities, commercial activities, and events—with related supportive activities (Figure 1.17).

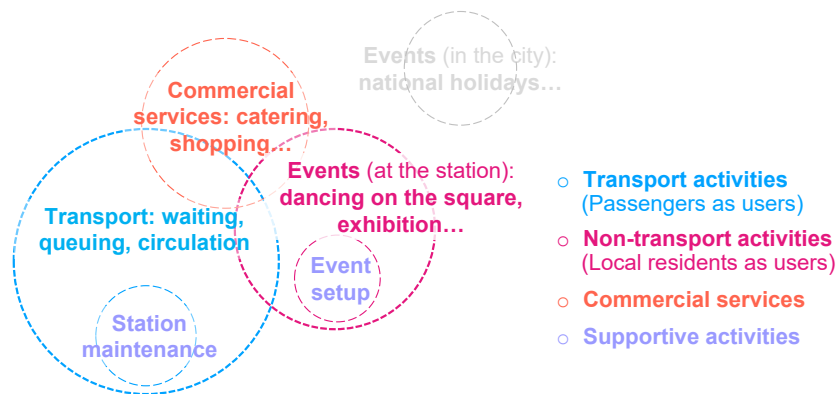


FIG. 1.17 Functional uses of stations. (Source: Author)

1.6.2.2 Spatio-temporal uses of stations

The use of space typically involves the spatial and temporal dimensions (De Wilde 2006; Fruin 1971; Timmermans et al.). In transport planning, human geography, and urban planning fields, the 'space-time concept' is used as an important term, describing the available space and time as unified resources provided by transport infrastructures, cities, or regions Timmermans et al.; Benz (1986). Technically,

describing how space is used by activities, involves the measurement of occupancy regarding space and time; e.g., [Li et al. \(2024\)](#) defined the concept ‘spatio-temporal occupancy rate’ to measure the rate of time in which the space is occupied by traffic flow; [Benz \(1986\)](#) evaluates the capacity or the use of transport spaces by measuring of space and time required versus available for passenger queuing and circulation. Given that a certain area of space or a specific period of time can be partially occupied, this thesis defines two concepts to differentiate the uses of space and time: **spatial occupancy rate**, defined as the proportion of area occupied by events; and **temporal occupancy rate**, which refers to the proportion of time during which the space is occupied by events ([Figure 1.18](#)). To evaluate space utilization across both dimensions simultaneously, the integrated **spatio-temporal occupancy rate** can be computed by multiplying the spatial occupancy rate by the temporal occupancy rate.

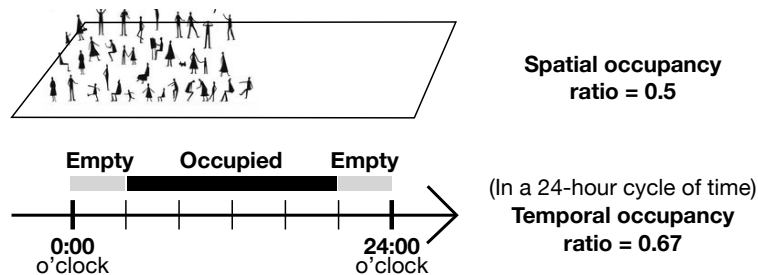


FIG. 1.18 Spatio-temporal occupancy rate. (Source: Author)

The spatio-temporal occupancy rate provides an aggregate descriptor of how physical space and temporal durations are consumed relative to total available space-time resources. However, achieving efficient and satisfactory station uses across the aforementioned diverse activity types requires looking beyond a singular focus on maximizing occupancy; it requires the consideration of multiple systemic factors and a variety of optimization strategies. For example, supportive operations are ideally scheduled during off-peak hours to minimize interference with primary passenger and civic activities. Station operators often aim to minimize queuing, waiting, and circulation times for passengers; yet, once waiting time is minimized to a certain operational threshold, the strategy must pivot toward improving the qualitative waiting experience rather than continuously optimizing waiting time ([Van Hagen, 2009](#)). Commercial stakeholders, such as retail and catering operators, may seek the opposite effect, aiming to prolong the staying time of customers within their spaces to maximize economic patronage.

1.6.3 Stakeholders and interests

From a spatial political economy perspective, urban transport infrastructures are not merely technical assets for functional mobility, but contested arenas where the production of space is continuously negotiated among diverse socio-economic forces

(Lefebvre, 1991; Harvey, 2006). Railway station areas epitomize this dynamic; they represent critical spatial nodes where the imperatives of capital accumulation, real estate commodification, and public civic life converge. The physical and programmatic configurations of these areas reflect the shifting power structures and resource allocations among various institutional, commercial, and civic stakeholders.

This socio-spatial production typically involves multiple actors. Station areas usually have site boundaries beyond the railway companies' own lands, involving other entities' lands and properties. The rail and property development often involves investment from different entities, including railway companies, real estate developers, and local and national governments (Chen and Zhuang, 2022; Triggianese, 2014). The public, as taxpayers, is also often involved (Novy and Peters, 2012). Different interest groups, such as NGOs or unions for heritage preservation, for environmental preservation, for citizens' livability, or for retail, may participate as well (Van Den Berg and Pol, 1998; Chen and Zhuang, 2022; Novy and Peters, 2012; Wang, 2022; Dai, 2015). Different actors' interests potentially align or conflict with others (Zemp et al., 2011; Novy and Peters, 2012).

Among these relevant actors, designers play an important role in mediating diverse interests by exploring tangible design proposals. Additionally, when users are absent from the decision-making process, designers have the power to incorporate users' needs (Chen and Zhuang, 2022; Triggianese, 2014, 2023) into design proposals. This research, although not diving deeply into the decision-making process, treats multiple actors as the target audience of the research outcomes (subsection 1.5.3).

To structurally map the diverse stakeholders and their interests, Figure 1.19 depicts the links between specific stakeholder interests and the objectives of flexible station utilization. Specifically, the objective to reduce overcrowding is a direct need of immediate station users—both passengers navigating transit and non-passengers utilizing the facility—as well as station operators tasked with maintaining safety and efficient pedestrian circulation. Concurrently, the imperative to reduce underutilization aligns with the financial and structural motives of station real estate investors and owners, who seek optimized asset efficiency, alongside station operators and commercial operators who benefit from sustained, balanced foot traffic. Finally, creating flexible or temporary uses providing station spaces as venues for events and civic activities introduces shared opportunities for users (passengers and non-passengers), commercial operators seeking market exposure, and local communities and local governments aiming to enhance social cohesion, neighborhood livability, and local economic vitality.

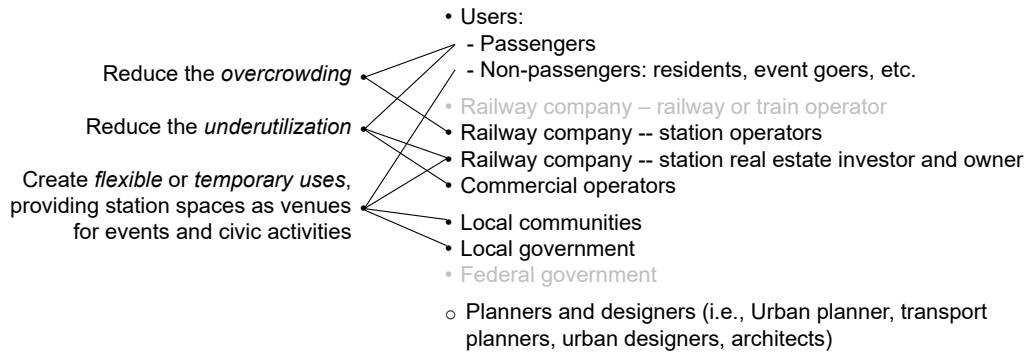


FIG. 1.19 Objectives of flexible station uses and the relevant stakeholders.
(Source: Author)

Building upon this relational mapping, and following an established power-interest grid framework [Bryson \(2004\)](#); [Ackermann and Eden \(2011\)](#), [Figure 1.20](#) illustrates an analytical evaluation of stakeholder interests and power. In this analytical matrix, station real estate investors and owners, alongside station operators and commercial operators, occupy positions of exceptionally high interest and high formal power, as they wield direct financial control and operational decision-making authority over the physical infrastructure. Conversely, the direct beneficiaries of stations—passengers, non-passengers, local communities, and local governments—demonstrate high interest but possess relatively limited direct structural power to dictate spatial configurations.

Within this power mapping, designers and planners (encompassing urban planners, transport planners, urban designers, and architects) occupy a distinct, highly nuanced position on the grid, characterized by a high level of interest and an intermediate, open circle designation of power. Planners and designers, although they are typically commissioned by their clients—station investors and owners—do not make direct decisions on the projects, they still exert huge power as they plan and design the project at an initial stage and intervene at a fundamental level, translating abstract stakeholder demands into concrete spatial proposals.

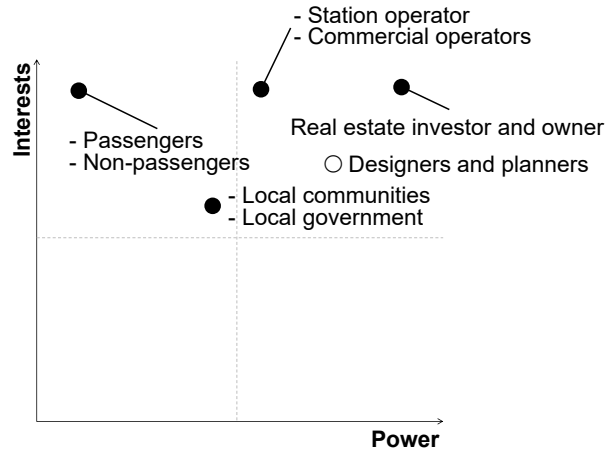


FIG. 1.20 Power-interest grid of stakeholders.
(Source: Author)

1.6.4 Intervening through *spatial design and management*

Spatial design (i.e., urban design and architectural design) is one discipline that provides interventions to stations, alongside spatial planning and management disciplines, among others. One key difference between these disciplines is their typical interventions' frequency and temporal scale. Spatial design interventions typically occur infrequently, with a frequency of once every several years, corresponding to a long-term temporal scale. Spatial planning interventions are even less frequent, typically occurring once every several decades, reflecting an even broader temporal scale. Management interventions are more frequent, occurring on shorter temporal scales, e.g., ranging from hourly to daily or seasonal. Notably, spatial design can provide a physical, spatial basis for management interventions; conversely, management interventions require spatial design to provide a suitable physical, spatial basis.

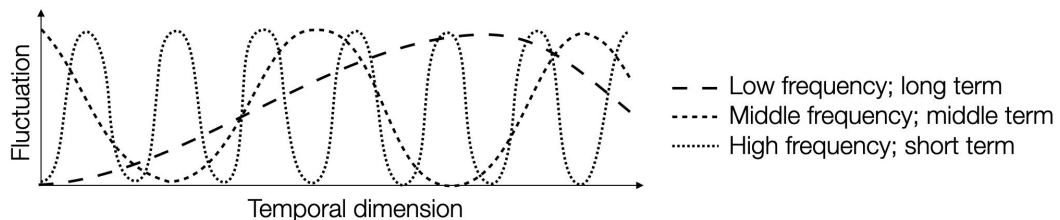


FIG. 1.21 Interventions with different frequencies on different temporal scales.
(Source: Author; inspired by Figure 130, on p. 38 of [De Jong and Van Der Voordt 2002](#))

1.6.4.1 The content addressed by urban and architectural design

Both urban and architectural design encompass a wide range of practices. Typically, urban design deals with aspects at the district level, and architectural design deals with aspects at the building level. This subsection outlines the specific aspects that are relevant to this research at these two levels in these two disciplines.

In this thesis, two types of aspects are treated as **core content**: (1) **pedestrian flow**, (2) **user experience**, and (3) **spaces** that people can pass through or linger in, whose qualities directly affect pedestrian flow and user experience. In contrast to core content, other aspects are treated as **secondary content**, which affects pedestrian flow, user experience, and space performance.

At **both the district and building levels**, the following core content are considered: pedestrian flow dynamics (considering temporal variations), potential event venues, user experience (e.g., safety, speed, ease, comfort, experience, according to [Van Hagen 2011](#)), pedestrian paths (which could across multiple physical elements like footbridges, tunnels, passages, or plazas) ([Edwards 1997](#), pp. 50-83; [Ross 2000](#), pp. 103-213; [Bach et al. 2009](#), pp. 206-220). The following secondary content are considered: layouts of mobility nodes (e.g., railway stations' affiliated metro stations, bus stops, tram stops, taxi drop-off and pick-up areas, car parking sites, bike parking sites), event-related managerial interventions ([subsection 1.2.4](#))—which are part of the contexts for spatial design interventions.

At the **district level**, the following core contents are also considered: urban spaces (e.g., plaza). The following secondary content is considered: urban buildings, and district structures. [Figure 1.22](#) illustrates a general picture of station areas that are dealt with by urban design. At the **building level**, the following core contents are also considered: paid areas, and indoor commercial areas. The following secondary contents are also considered: ticket gates. [Figure 1.23](#) illustrates a general picture of station buildings that are dealt with by architectural design. Building elements integrated into the district-level structures, such as pedestrian passages across the buildings, are considered with priority.

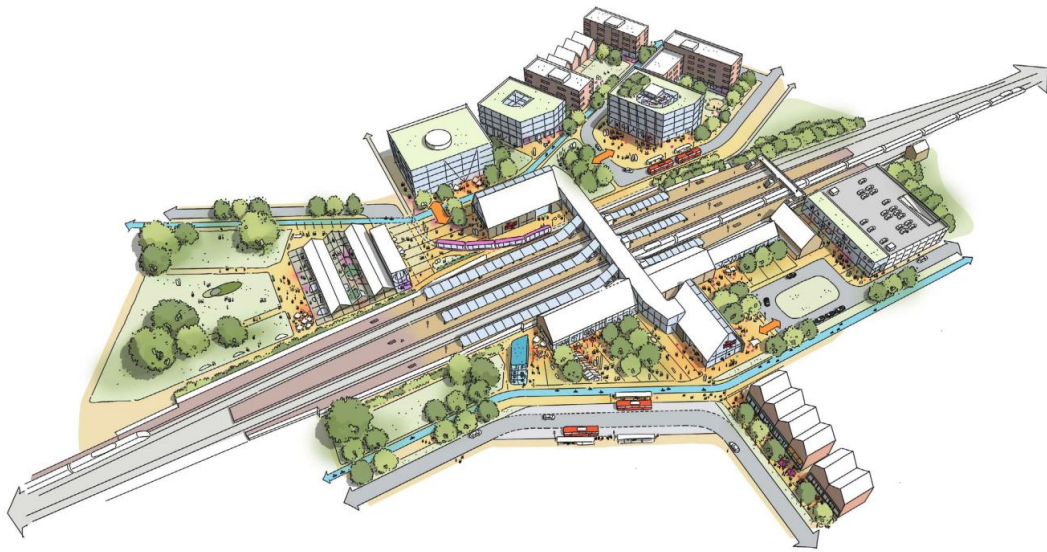


FIG. 1.22 Urban design of railway station areas.
(Source: [Networkrail 2023](#), p. 54)

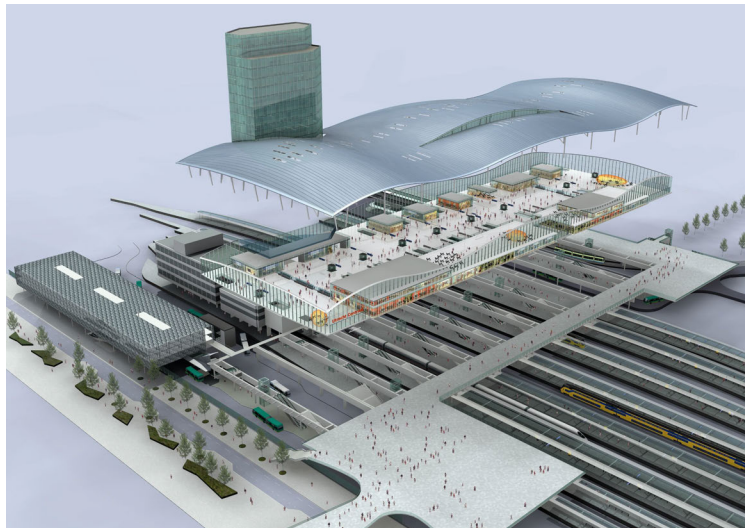


FIG. 1.23 Architectural design of railway station buildings.
(Source: [Benthamcrouwel.com](#))

Notably, in this thesis, urban design and architectural design are differentiated. Some literature and cases advocate blending the practices of urban design and architectural design, where urban design adopts design strategies that are typically only used at the building level, or architectural design adopts design strategies that are typically only used at the district level. For example, a book highly cited by papers on station-city integration in China—Holistic design on urban architecture [Han \(1999\)](#), promotes the following trends: the social integration and megastructuralization of buildings, and the verticalization and interiorization of urban design. Transferring building-level design strategies to district-level is common and effective in high-density contexts like Hong Kong, Japan, and South Korea, with station cases like Kowloon Station ([Xue et al., 2012](#)), Shibuya Station, and Yongsan Station.

However, such strategies show limitations when they are used outside of high-density contexts. For example, an high-density urban and architectural proposal for Rotterdam Central Station area developed in 2000 by William Alsop, with its appealing station buildings like champagne glasses, blending urban spaces and buildings ([Wederopbouwrotterdam, n.d.](#)), was ultimately rejected due to concerns that the area's low intensity of use would render it underutilized and unsafe and the it would cost too much to build ([Elise, 2017](#)). Additionally, applying building-level strategies to districts sometimes leads to oversized city elements that lack the human scale. This is illustrated by a proposal for Sloterdijk Station, where a 1-kilometer-long roof was proposed to cover the station area ([Triggianese et al., 2019](#), p. 190). Given these limitations and the non-reliance on a high-density context (see [subsection 1.6.5](#)), this research maintains a clear distinction between urban and architectural design whenever feasible.

1.6.4.2 Managerial interventions

In response to events and disruptions, and to promote flexible use during non-peak time, managerial interventions at stations can be taken, and spatial design solutions should support these managerial interventions. This research considers two types of interventions: (1) organizing events in station areas during non-peak times and (2) regulating access to stations' elements, such as pedestrian paths. According to [Carr et al. \(1992\)](#), there are multiple types of rights in public space, including access, claim, change, ownership, and disposition, and so on. These rights can be regulated through managerial interventions, and regulating access is a common practice in stations and during events.

1.6.5 The station type and case selection

Railway stations are among the most rapidly and widely constructed building types in modern history (Richards and Mackenzie, 1986, pp. 52, 385), making the definition of station typologies both necessary and challenging (Peters and Novy, 2012).

Nevertheless, regarding topic relevance, practicality for site visits, and research impacts, this research defines an ideal type of station with the following set of station features, which also serve as the **criteria for case selection**:

- 1 Exhibit overcrowding and/or underutilization phenomena
- 2 Have addressed overcrowding and/or underutilization through spatial design.
- 3 Show the phenomenon of flexible use, or have the capacity to support it.
- 4 Surrounded by city environments (such as city districts or green spaces).
- 5 Located in the Netherlands or China.
- 6 Serve as major stations in their respective cities or countries.

As described in the research objective (subsection 1.5.1), this research addresses flexible use to mitigate overcrowding and underutilization in stations, promoting station-city integration. It seeks spatial understanding of the problem as well as develops spatial solutions. Therefore, the ideal station cases should involve challenges such as overcrowding and underutilization, or present solutions like flexible use. They should also locate in city environments where the relationship between the station and the city—whether separated or integrated—plays a significant role. Criteria 1–4 reflect these considerations.

The ideal station cases are confined to China and the Netherlands, owing to the author's physical proximity, which facilitates on-site visits to gain experiential understanding. The author, being Chinese and studying in the Netherlands, is thus positioned to engage directly with these contexts. However, the theoretical and empirical insights derived from these Chinese and Dutch cases are not inherently restricted to these two nations, as case study research is often designed to generate theoretical insights that transcend the specific contexts under examination (Flyvbjerg, 2006; Yin, 2002). The ideal station cases are set as major stations in their respective cities or countries, making the findings likely to attract significant attention and impact.

While this research primarily focuses on the selected station cases, it will also reference—though not examine in depth—other building types and public spaces (e.g., stadiums, shopping malls, airports, and metro stations) where relevant to the analysis.

Notably, high density is not a criterion in this research, though it is central to some station studies in the transit-oriented development discourse (Knowles et al., 2020). In contexts like North America, high-density surroundings are often a prerequisite for transit-oriented development, ensuring sufficient ridership (Calthorpe and Poticha, 1993). In contrast, in China, station users typically arrive from across the entire city, not just adjacent neighborhoods, making high density less critical. Furthermore, this research highlights the flexible potential of station areas—such as their use as

low-density leisure green spaces during off-peak hours, exemplified by Jiaxing Station (Gooood, n.d.). This reinforces why high density is not a decisive criterion here.

1.6.5.1 Selected cases

Based on the above criteria, this research selects seven cases: six real-world stations—Beijing West Railway Station (RS), Shanghai RS, the former and current Rotterdam Central RS, and the former and current Utrecht RS—as well as one virtual case, Station Xtreme, which is proposed and designed as part of this research (Table 1.2; Figure 1.24 and Figure 1.25). For both Rotterdam and Utrecht stations, their former and current scenarios are analyzed as different cases due to their spatial differences. The total number of cases is limited due to the project's time constraints (Small, 2009). These cases serve different chapters' research purposes (see subsection 1.7.1, case studies).

TABLE 1.2 Cases selected considering their relevance with O&U or flexible use

Cases	Overcrowding	Underutilization	Flexible use	City environment surrounded
Beijing West Railway Station (RS)	Overcrowding happens occasionally	Large underutilized commercial spaces	–	• Dense city areas are surrounded • Heavy traffic between the station and the surrounding city districts; Weak links through footbridges and tunnels
Shanghai RS	[Compared to Beijing West RS] No obvious overcrowding	–	• Vibrant surrounding commercial environment; • The North Plaza is flexibly used for transportation during peak days and for dancing during non-peak days	• Dense commercial city areas are surrounded • Walkable to the surrounding areas
The current Rotterdam Central RS	–	–	• Vibrant commercial environment; • Leisure events on the station plaza occasionally	• City areas surrounded • Easily walkable to the surrounding areas
The former Rotterdam Central RS	–	–	[Compared to the current station] Not possible to have leisure events on the plaza	• City areas surrounded • Heavy traffic between the station and the surrounding city districts

Continued on next page

The current Utrecht Central RS	[Compared to the former station] Overcrowding resolved	–	• Vibrant commercial environment; • Leisure events on the plaza	• Dense city environment surrounded • Easily walkable to the surrounding areas
The former Utrecht Central RS	Crowded (Loukaitou-Sideris et al., 2017)	–	–	• City areas surrounded • The shopping mall mixed with the station building causes confusion in wayfinding
Station 'Xtreme'	A nearby stadium creates a peak flow of rail travelers, causing potential overcrowding	–	–	• City areas surrounded • Heavy traffic between the station and the stadium

Note: Except for the virtual Station 'Xtreme', all others are in China or the Netherlands, and are major stations in the respective cities or countries.

Beijing West Railway Station (RS) is one of the four major stations in Beijing (as of 2025), China. It is shown on social media as being crowded occasionally (Jialing and Yue, 2021; Bilibili, 2021), where passengers get delayed for dozens of minutes to hours. Meanwhile, it has huge underground spaces that are underutilized, as reported by news (Yu, 2018) and observed by the author's on-site visit in 2022. The station is surrounded by dense city areas, with footbridges and tunnels linking them, crossing wide traffic roads.

Shanghai Railway Station is one of the three major stations in Shanghai (as of 2024), China. Compared to Beijing West RS, Shanghai RS is hardly seen on social media as congested or underutilized. It has a vibrant surrounding commercial environment. Its North Plaza is used by elderly people dancing during non-peak days. The station is surrounded by dense commercial city areas. It is walkable between the station and the surrounding areas.

The current Rotterdam Central Station is the largest station in Rotterdam, the Netherlands. It was redeveloped between 2007 and 2014, and it is one of six stations redeveloped through the Dutch 'new key projects' (Majoor and Schuiling, 2008). It has a pleasant plaza where leisure events happen from time to time, such as people dancing during the Rotterdam Summer Carnival, the railway company organizing promotion events, or live streamers dancing and creating social media content. The current station has also won many design prizes as it positively transformed the area (MVSA, 2022). The station is surrounded by city areas. It is easily walkable between the station and the surrounding areas.

In contrast with the current station, the former Rotterdam Central Station did not support leisure activities on the plaza because all transport facilities occupied it. The former station's surrounding environment was unsatisfactory due to heavy traffic (Loukaitou-Sideris et al., 2017). The station was surrounded by city areas. There was a ground-level main road with heavy car traffic between the station and the surrounding city districts.

The current Utrecht Central Station is the largest station in Utrecht, the Netherlands.

It was redeveloped between 2011 and 2016, and part of its surrounding areas are still undergoing redevelopment. It is also one of six stations redeveloped through the Dutch 'new key projects' (Majoor and Schuiling, 2008). The west plaza of the new station occasionally hosts leisure events such as exhibitions (Muis, 2018). The station is surrounded by city areas. It is easily walkable between the station and the surrounding areas. With a plaza in between, the adjacent shopping mall on the east brings lively images and experiences to rail passengers.

In contrast with the current station, the former Utrecht Central Station was complained about by passengers as being crowded. The station was surrounded by city areas. The shopping mall on the east was built in a mixed style with the station building, causing confusion in wayfinding.

The virtual Station Xtreme is a synthesized case study designed to evaluate the proposed design principles with high generalizability, free from the strict constraints of a single real-world location. While real-world stations like Amsterdam Bijlmer ArenA experience the extreme stadium-driven passenger fluctuations relevant to this study, their relatively successful urban integration lacks the severe infrastructural barriers needed to rigorously test station-city integration. Therefore, Station Xtreme deliberately adopts the heavily fractured spatial layout of Amsterdam Sloterdijk—separated from its surroundings by traffic roads, viaducts, and open-air parking lots—while incorporating the volatile crowd fluctuations of Bijlmer ArenA. This composite setting creates a spatially relevant and demanding case that challenges the spatial design to simultaneously resolve overcrowding, underutilization, and station-city separation.

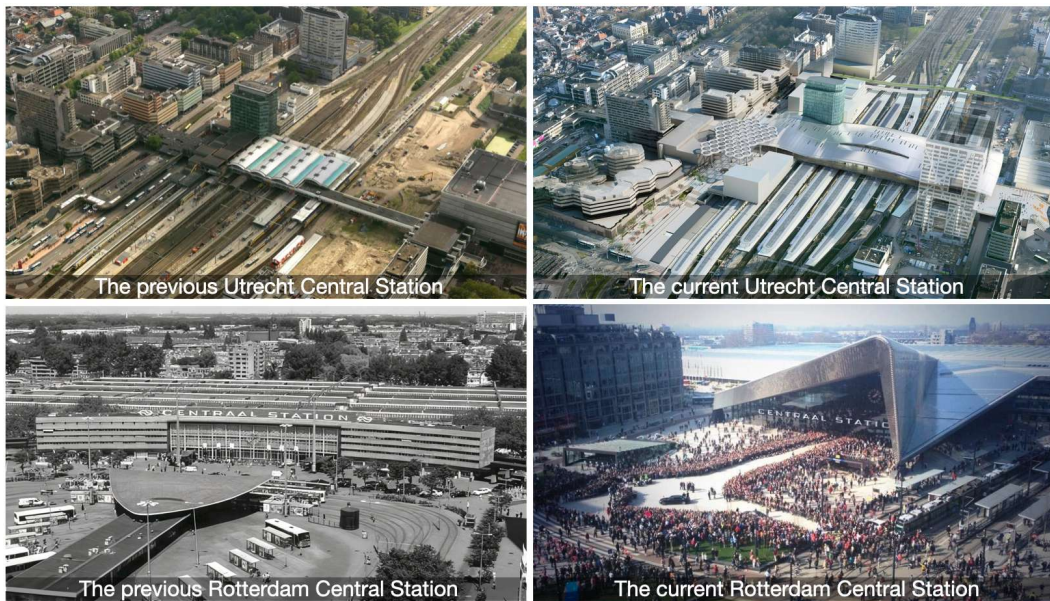


FIG. 1.24 Selected cases of stations. (Sources: Up-left—[youtube.com](https://www.youtube.com); Up-right—[gooood.cn](https://www.gooood.cn); Down-left—fotos.serc.nl; Down-right—[west8.com](https://www.west8.com))

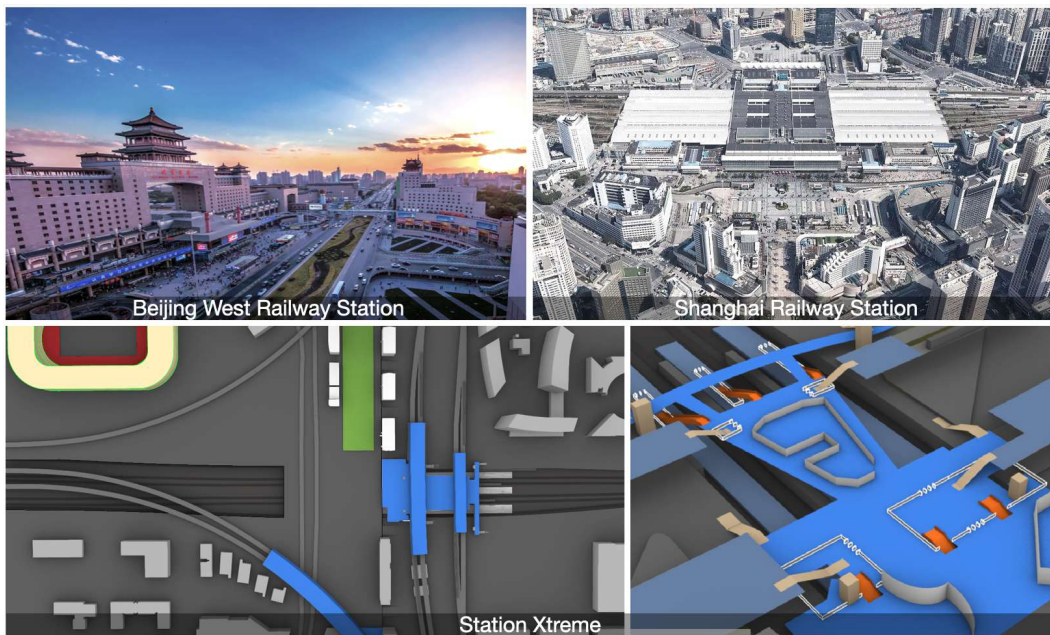


FIG. 1.25 Selected cases of stations. (Source: Up-left—[meipian.cn](https://www.meipian.cn); Up-right—[skyscrapercity.com](https://www.skyscrapercity.com); Down-left and down-right—by the author)

1.6.6 The spatial scale of railway station areas: Around a 250m range

This research focuses on the urban and architectural design of station areas and station buildings (subsection 1.5.1). Station buildings are normally clearly identifiable, while station areas typically have vague ranges. Thus, it is essential to define the range of station areas for this research.

In defining the range of station areas, existing approaches rely on various factors, including walkable radius, functional-historical elements, topography, and a development perimeter (Bertolini and Spit, 1998; Zhang et al., 2019). Walkable radius is possibly the most widely adopted one because it is simple and can be applied across different cases. With a slight variance in different literature, this radius value typically lies between 500-700m distance or a 5- to 10-minute walk (Calthorpe and Poticha, 1993; Bertolini, 2008).

However, based on the following considerations, this thesis adopts a radius of around 250-300m maximum as the station area, about half of the typical walkable radius value (Figure 1.26, see more diagrams in the thesis appendix). First, this thesis studies user satisfaction in railway stations, and perception instead of walking ability is prioritized. Scholars like Peek and Van Hagen (2002) recommended a 300m radius for the so-called 'station environment'; Bach et al. (2009, pp. 211-212) mentioned 300m as an important scale for urban design of stations, regarding pre-transport to stations and accessibility of station buildings. During field visits, the author also found that the stations are usually perceivable around a maximum 250m range (Figure 1.26). Second, because station areas are public spaces, insights from other types of public spaces are comparable for understanding user behavior and design implications. Studies of green parks suggest a maximum of 300m walking distance (Konijnendijk, 2023) from residents' homes to green spaces. Third, this smaller range serves this thesis's explorative nature to investigate spatial configurations that lie in urban design and architecture domains, and it relates more to user perception ability (Enshan et al., 2025b).

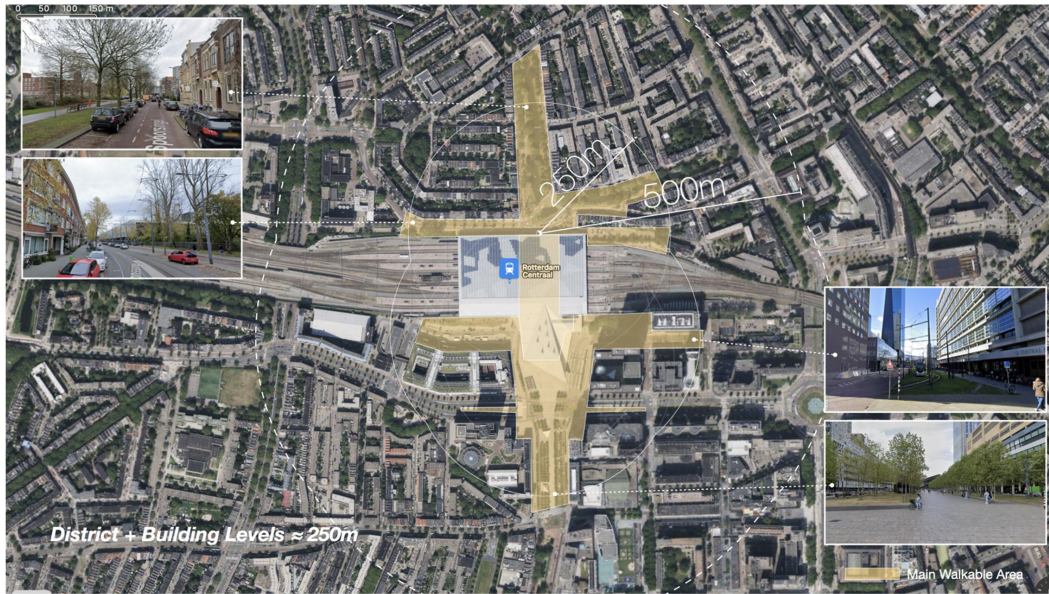


FIG. 1.26 Rotterdam Central Station area. (Source: Google Maps; annotated by the author)

This smaller range (around 250m), compared to the larger range (around 500m), is barely investigated in existing assessment literature, for at least two reasons. First, it is difficult to find a positive relationship between the station's proximity and economic performance when the location is too close to the station buildings, due to railway noise and pollutants. This makes planners favor the larger range for a positive relationship. Second, given the formula for the area of a circle ($\text{Area} = \pi r^2$), an increase in radius (e.g., by 250 m) in a peripheral area, compared to the same radius increase in a core area, results in a substantially larger area size, which highlights the importance of the catchment area. Nevertheless, this thesis sees 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 (Figure 1.27).

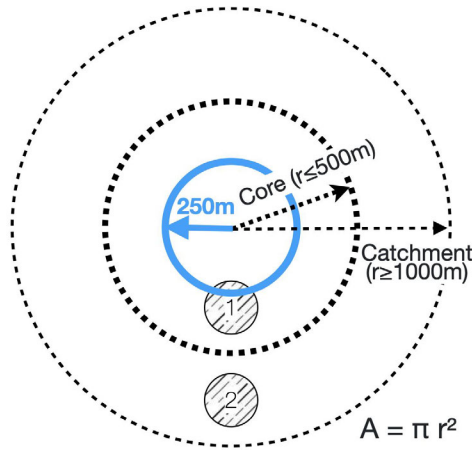


FIG. 1.27 Multiple ranges of station areas. (Source: Author)

1.6.7 Summarize the research scope

To summarize, this research has the following scope:

- It addresses fluctuations—associated with events or disruptions—that occur at a temporal scale ranging from multi-weekly to yearly.
- The focus is on major Chinese or Dutch railway stations experiencing overcrowding and/or underutilization, particularly those embedded within city environments with relevance to station-city integration.
- The spatial scope of the station area is defined as approximately a 250-meter radius.
- Within this area, the research investigates urban and architectural design aspects, including 3D spaces, layouts of transportation nodes, pedestrian flows, and user experience.

1.7 Research methodology

With chapters ([subsection 1.5.3](#)) planned and research scope ([section 1.6](#)) refined in the above sections, this section introduces the research methodology. Overall, this research uses multiple methods ([subsection 1.7.1](#)) in these chapters. This chapter also describes components that are fundamental to the multiple methods. These components include a theoretical model ([subsection 1.7.2](#)) and criteria for positive

solutions (subsection 1.7.3). For more specific descriptions of each method, please refer to the corresponding chapters.

1.7.1 Multiple methods

Multiple methods are used during this research (Figure 1.28). Case studies, literature review, and analytical visualization are the main methods. Additional methods are used for developing the assessment framework, developing the visual assessment model, and validating the design principles.

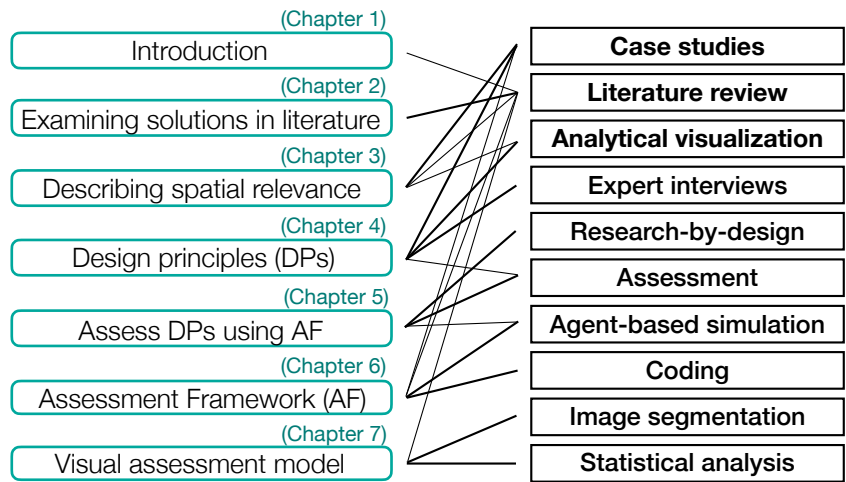


FIG. 1.28 Multiple methods used in this research. (Source: Author)

1.7.1.1 Case studies

In this research, case studies (Yin, 2002; Tasci et al., 2020) are used to investigate the spatial relevance of overcrowding and underutilization in station areas (Chapter 3), identify design principles (Chapter 4), test the application of design principles (Chapter 5), and test the application of assessment framework (Chapter 6). Case selection criteria and cases' basic information are explained in subsection 1.6.5.

Seven cases, described in subsection 1.6.5, are selectively used in different chapters. For understanding the spatial relevance, Chapter 3 examines problematic cases that experience overcrowding and underutilization. These cases include Beijing West Railway Station (RS), the former Rotterdam Central RS, and the former Utrecht Central

RS. For developing design principles, [Chapter 4](#) studies cases that resolved overcrowding or underutilization, or support flexible use. These cases include Shanghai RS, the current Rotterdam Central RS, and the current Utrecht Central RS. These cases are also compared with the problematic cases to make the positive spatial solutions more evident. For testing the application of the assessment framework, [Chapter 6](#) uses the former and current Rotterdam Central RS. For assessing design principles through the assessment framework, [Chapter 5](#) makes proposals for a virtual station—Station Xtreme.

1.7.1.2 Literature review

Five literature reviews are conducted in this research ([Table 1.3](#)): the first one in [Chapter 1, section 1.3](#) broadly examines the relevant existing academic knowledge at a high level to inquire about the problems, assessment, and solutions; the second in the whole [Chapter 2](#) specifically examines the existing solutions; the third in [Chapter 3, section 3.1](#) specifically examines existing explanations of the problems; the fourth in [Chapter 6, section 6.1](#) specifically examining existing assessment methods, and the associated user satisfaction indicators; and the fifth in [Chapter 7, section 7.1](#) specifically examines existing visual assessment methods that are based on computer vision. [Chapter 4](#) addresses the knowledge gap identified in [Chapter 2](#), so no addition literature review is conducted. [Chapter 5](#) primarily applies the outcomes of [Chapter 6](#) and [Chapter 4](#), without conducting additional literature review.

TABLE 1.3 Literature review as a method employed in different chapters			
Thesis chapters	Sections	Aims of employing literature review (LR)	Scopes of the LR
Ch1. Thesis introduction	Section 1.3	Examine academic knowledge on the problems, assessments, and solutions	Spatial design and planning, transport planning, management
Ch2. Literature review	–	Examine existing solutions	Spatial design and planning, transport planning, management, human geography, computer science
Ch3. Spatial relevance	Section 3.1	Examine existing explanations of the problems	Spatial design
Ch4. Assessment framework	Section 4.1	Examine existing assessment methods, and associated indicators	Spatial design and planning, transport planning, and computer science
Ch5. Visual assessment model	Section 5.1	Examine existing visual assessment methods that are based on computer vision	Computer science, spatial design and planning

Note: The research disciplines or fields listed in the ‘Scopes of the LR’ column were identified iteratively—some were predetermined before the literature review, while others emerged as relevant during the sampling process.

1.7.1.3 Analytical visualization

In this research, analytical visualization is used in two ways: First, it is used to analyze how hypothetical scenarios will impact stations in [Chapter 3](#). Second, analytical visualization is used to visualize design principles learned from cases and literature, and examine their variations ([Chapter 4](#)). When a design principle is identified in existing cases or literature of a specific scale in specific contexts, analytical visualization is used to transfer and adapt this principle to potential new cases of new scales in new contexts, thereby exploring its potential variations.

1.7.1.4 Methods for developing the assessment framework

In this research, the assessment framework is developed through a combination of literature review, agent-based simulation, coding, and a case study ([Chapter 6](#)). The framework is designed to assess design performance as indicated by user satisfaction. It comprises multiple indicators and a set of digital mapping tools ([Figure 6.7](#)). The indicators are selected based on findings from the literature review. The digital tools include both existing software programs—such as MassMotion and Rhino—and custom Python scripts developed in this research. Agent-based simulation is used to simulate the station system to measure the values of indicators. The assessment framework is tested for effectiveness through its application to the case of Rotterdam Central Station.

1.7.1.5 Methods for developing the visual assessment model

In this research, a visual assessment model ([Chapter 7](#)) is developed as a component of the overall assessment framework. The model is constructed using image segmentation and statistical analysis. It draws on the PlacePulse 2.0 dataset ([Saleses, 2012](#)), which contains street images rated by humans for scene qualities such as ‘liveness’. Image segmentation is applied to extract street elements from these images. Then, machine learning models are used to analyze the statistical relationship between the extracted elements and corresponding ‘liveness’ scores.

1.7.1.6 Methods for assessing the design principles

To validate the design principles, this research employs two methods: expert interviews and assessment using the assessment framework ([Chapter 4](#); [Chapter 5](#)). During expert interviews, experts are introduced to the research context and invited to examine the developed design principles. They provide feedback on these principles, identifying potential use scenarios and limitations. The principles are also assessed using the developed assessment framework. In this assessment, through research-by-design, the principles are applied to generate four design proposals for a virtual case—Station Xtreme. These proposals are subsequently assessed using the assessment framework, and the results are analyzed to evaluate each principle's effectiveness.

1.7.2 Theoretical model

A theoretical model provides a structured way to analyze problems and develop solutions. Overcrowding and underutilization (O&U) arise from temporal fluctuations in station usage ([subsection 1.2.2](#)), yet existing theoretical models largely overlook the temporal dimension ([subsection 1.3.4](#)). To address this gap and promote flexible use as a solution for mitigating O&U, this research proposes the Flexible Use model of stations ([Figure 1.29](#), right).

This model stands in clear contrast to the widely established Node-Place model proposed by [Bertolini \(1999\)](#) ([Figure 1.29](#), left). Bertolini's framework approaches station areas from a spatial planning perspective, positioning them based on a combination of structural, operational, and socioeconomic indicators—such as daily transit service frequencies, the number of neighborhood residents, and sectoral employment densities ([Bertolini, 2008](#)). Bertolini's approach evaluates these indicators as static, time-invariant values (e.g., using total daily service frequencies or static census counts). By flattening these metrics into static daily averages, his model overlooks the variations in station use. Under this static approach, traditional spatial planning of railway stations targets the central 'balance' zones as permanent ideal states, where the dual identities of transport connectivity and urban density are intended to be equally and permanently co-developed.

In contrast, the Flexible Use model shifts the analytical lens from temporally smoothed, static averages to the dynamic, temporal uses of stations. By explicitly emphasizing the temporal dimension, this model accounts for multi-weekly to yearly use fluctuations and recognizes that a station's operational reality and functional identity are highly dynamic. Instead of striving for a static equilibrium in the matrix's center, an ideal flexible station is conceptualized as deliberately oscillating along a diagonal trajectory between two distinct states: operating with a node-dominated identity during peak times to efficiently process high transit volumes, and transitioning into a

place-dominated identity during non-peak times to foster local urban vitality. Rather than measuring fixed capacities or daily aggregate totals, the Flexible Use model captures dynamic flow and space use, evaluating the shifting temporal-spatial occupancies by various human activities at different times. This new theoretical foundation directly guides the investigation of spatial relevance ([Chapter 3](#)) and establishes the baseline for the subsequent assessment framework ([Chapter 6](#)).

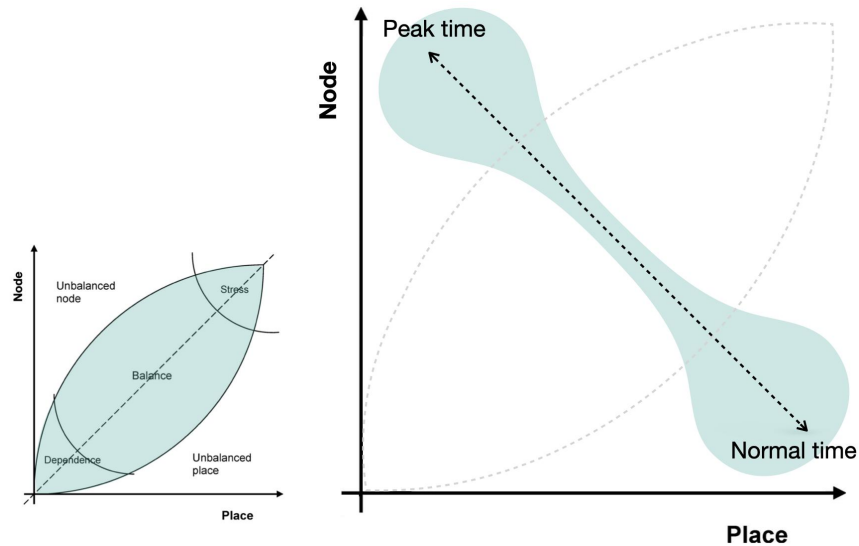


FIG. 1.29 Node-Place model vs Flexible Use model. (Source: Author)

1.7.3 Assessment criteria for positive solutions

To evaluate whether spatial interventions are effective, this research develops a set of assessment criteria, including reducing overcrowding and underutilization, adding socio-economic values to the station or the city, and improving user experience ([Table 1.4](#)).

User experience encompasses a broad meaning that requires contextual adaptation to railway stations. As transport infrastructure, stations primarily serve passengers; however, following [Bertolini and Spit's \(1998\)](#) conceptualization of stations as urban places, they should also accommodate non-passengers for non-transport users. For passengers, [Van Hagen \(2011\)](#) identifies five core needs: safety, speed, ease, comfort, and experiential quality. [Enshan et al.'s \(2025b\)](#) subsequent research operationalized these needs through quantifiable spatial and behavioral/perceptual metrics. 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.

TABLE 1.4 Assessment criteria for positive spatial interventions

Assessment criterion	Exemplary spatial interventions
(1) Reduce/ease overcrowding and/or underutilization; Support flexible use	Widening bottleneck corridors; Applying reconfigurable layouts to underused spaces to support leisure gatherings and markets
(2) Add socio-economic values to the station or the city	Introducing retail kiosks adds commercial revenue to stations
(3) Improve user experience	Designing the station plaza with greenery makes it climate-comfortable during the summer

These criteria are developed mainly based on the research objective—Advancing flexible use of stations through spatial design, promoting station-city integration (see subsection 1.5.1). First, the emphasis on flexible use is aimed at reducing overcrowding and underutilization (O&U). Second, for typical spatial design and the flexible use of stations as public spaces, improving user experience is a central priority. Third, for station-city integration, any added positive benefits would be desirable (Figure 1.30).

Notably, cultural values, although closely related to architectural design and users’ perceptual/experiential experience, are not included in the criteria, because cultural values are overly broad and subjective for this research, and their importance can be easily surpassed by other factors during the discussion of O&U.

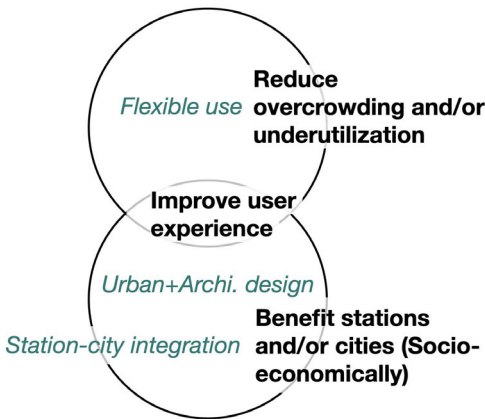


FIG. 1.30 Values derived from the research objectives. (Source: Author)

Regarding the temporal dimension, these criteria vary. First, different user experiences have different priorities or even different meanings during the peak and non-peak times. Considering safety, speed, ease, comfort, and experience as user needs (Van Hagen, 2011), speed, comfort, and experience are relevant during non-peak times, while less relevant during peak times. Ease suits the opposite scenarios. During peak times, overcrowding is a safety concern, while during non-peak times, empty dark spaces are a safety concern, as people will fear being attacked there.

Second, flexible use and station-city integration can provide different potential benefits at different times. During peak time, reducing overcrowding and increasing the station's accommodating capacity are the relevant benefits. During non-peak time, increasing the space usage and providing proximal retail are the relevant benefits. Figure 1.31 incorporates these temporally varied criteria into the Flexible Use model—which emphasizes the temporal dimension.

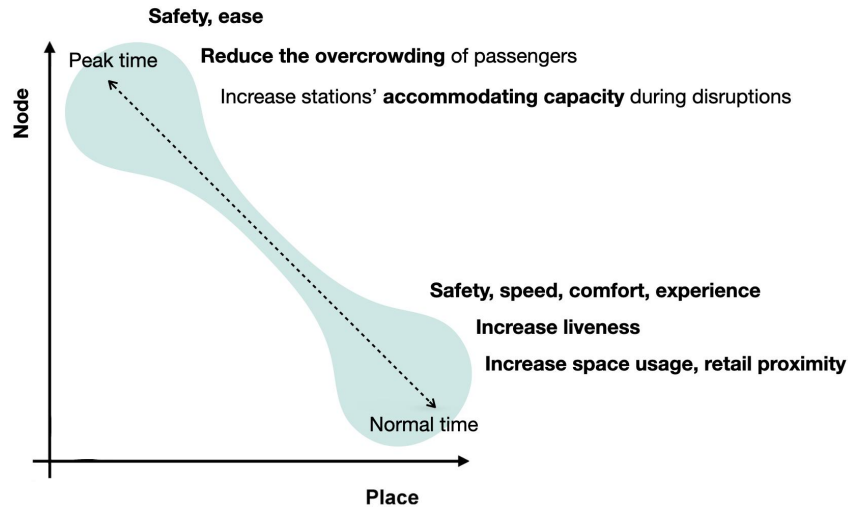


FIG. 1.31 Embed the indicators into the theoretical Flexible Use model. (Source: Author)

1.8 Thesis outline

The thesis is organized as follows: This introduction Chapter ([Chapter 1](#)) presents the research question: How to **spatially understand, design, and assess** railway station areas that support **flexible use** aimed at reducing overcrowding and underutilization and promote **station-city integration**? This research question is based on the problem statement and the knowledge gap. Chapter 2 provides an extended literature review revealing the knowledge gap. Chapters 3–7 answer the research question by describing the spatial relevance, building an assessment framework, and developing a set of design principles. Specifically, [Chapter 3](#) describes the problems in detail, [Chapter 2](#) investigates the extent to which solutions have been developed in existing literature, [Chapter 6](#) develops an assessment framework to assess station performances that are indicated by user experience, using agent-based simulation; [Chapter 7](#) specifically explains the visual experience assessment within the assessment

framework; [Chapter 4](#) establishes design principles; [Chapter 5](#) tests the design principles using the assessment framework; and [Chapter 8](#) discusses and concludes ([Figure 1.32](#)). Except for the first and last chapters, each chapter is a published paper or a manuscript that can be read independently.

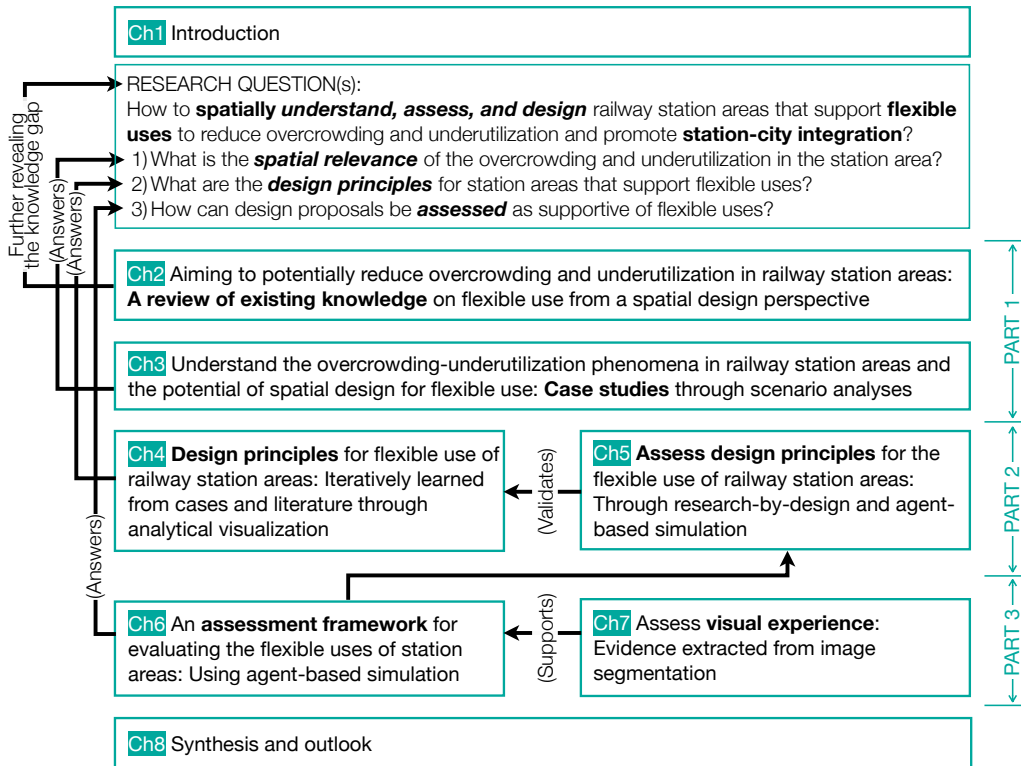


FIG. 1.32 Thesis outline. (Source: Author)

PART I

Contextual Foundation

This part, comprising **Chapters 2 and 3**, establishes the contextual foundation of the research by demonstrating both the academic necessity and spatial relevance of flexible station use.

Chapter 2 presents a systematic literature review that builds upon the broad academic context mapped in Chapter 1. It investigates existing solutions for the flexible use of station areas, revealing that relevant knowledge remains fragmented across disciplines, with critical gaps in spatial layout strategies and design-oriented toolsets. These gaps underscore the necessity of the research presented in this thesis.

Chapter 3 establishes the relevance of spatial design to the flexible use of stations. While overcrowding, underutilization, and flexible use are inherently linked to events and operational management, how they are shaped by spatial configurations remains poorly understood. This chapter explicitly evaluates these spatial influences, demonstrating the significant potential of spatial design in enabling flexible station use.

2 Literature review

A review of existing knowledge on flexible use from a spatial design perspective

ABSTRACT As described in [Chapter 1](#), this thesis promotes flexible use as a strategy to mitigate overcrowding and underutilization (O&U) in railway stations, with spatial design serving as a key enabler. However, the relevant knowledge—of railway stations, overcrowding, underutilization, flexible use, and spatial design—is scattered across disciplines, limiting a comprehensive understanding of the issue. Therefore, a comprehensive review across disciplines is required. Meanwhile, a reflection from the spatial design perspective is necessary for potential design solutions. This chapter addresses the **questions**: to what extent has flexible use been spatially addressed by existing literature? A systematic literature review across multiple disciplines (e.g., spatial design, transport planning, and management) is **conducted** in this chapter, examining four types of knowledge: design measures, user knowledge, theoretical insights, and relevant technologies. The **results** present the relevant existing knowledge, with four knowledge gaps: (1) an explicit definition describing the flexible use of railway station areas to reduce O&U, (2) spatial layouts supporting flexible use, (3) knowledge integration, and (4) design-oriented toolsets.

KEYWORDS Spatial design, urban design, architecture, flexible use, railway station

2.1 Introduction

As described in [Chapter 1, section 1.2](#), the **overcrowding-underutilization (O&U)** phenomena happen in railway stations that have fluctuating passenger numbers or in case of railway system disruptions, raising safety concerns and wasting space resources ([subsection 1.2.2](#)). **Flexible use** is a potential solution to address O&U, as the word 'flexible' linguistically means being 'able to change or be changed easily according to the situations', and flexible use has been seen in real-world cases like Shanghai Railway Station and Rotterdam Central Station ([subsection 1.2.4](#)), where station areas are flexibly used for transport and non-transport activities. Within the research context of station-city integration ([section 1.1](#)), this thesis sees flexible use as a new positive value of station-city integration ([subsection 1.5.1](#)).

Spatial design is of crucial relevance to the overcrowding-underutilization phenomena, flexible use, and station-city integration due to several reasons: first, the overcrowding-underutilization (O&U) phenomena are associated with spatial configurations, as shown in cases like Beijing West Railway Station ([subsection 3.3.3](#)), indicating the potential of spatial design; second, flexible use is enabled by proper spatial layouts, as shown by case comparisons between the current and the former Rotterdam Central stations ([subsection 3.3.4](#)); and third, station-city integration has long been discussed within the discourse of spatial design ([subsection 1.3.4](#)). Spatial design is one discipline among several (like urban planning, transport planning, and management) that address station-related issues. In this thesis, flexible use is expected to be realized through tangible spatial design interventions ([Figure 2.1](#)).

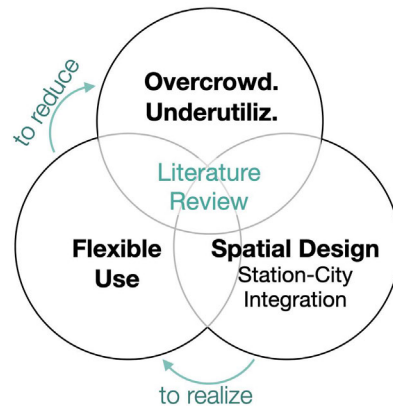


FIG. 2.1 Spatial design is assumed by this thesis as a means to realize flexible use to reduce overcrowding and underutilization. (Source: Author)

The relevant knowledge—of railway stations, overcrowding, underutilization, flexible use, and spatial design—is fragmented across different disciplines and fields. For example, within the spatial design discipline, in the architecture field, studies have

addressed the design of station buildings (Ross, 2000; Edwards, 1997; Da Conceição, 2015); In the urban design field, studies have investigated people's activities in public space (Gehl, 1987; Whyte, 2001); and in the transport planning discipline, studies have concentrated on pedestrian movement, linked to overcrowding (Fruin, 1971; Heuvel, 2022).

Such a fragmented knowledge distribution limits a comprehensive understanding of the complex issue of flexible use and the current state of research. Therefore, it is necessary to examine existing research across disciplines. Meanwhile, with this thesis's intention of pursuing potential design solutions, it is necessary to reflect on the multidisciplinary knowledge from a spatial design perspective. Regarding these necessities, this chapter provides a systematic literature review, guided by two frameworks (section 2.2): one defines the ideal solutions' characteristics to guide the searching and screening of the literature (subsection 2.2.1); the other defines the knowledge types to guide the reviewing and reflecting on the literature (subsection 2.2.2). Through the systematic literature review, this chapter addresses the following main research question:

Aimed at seeking solutions to reduce overcrowding and underutilization in railway station areas, and from a spatial design perspective, ***to what extent has flexible use been addressed by existing literature?*** [Answered by subsections 2.4.3-2.4.6.]

The scope of 'to what extent' in this main research question is specified by the following sub-questions:

- 1) What spatial content has been addressed, at what spatial scales? [Answered by subsections 2.4.4 and 2.5.1.]
- 2) What user activities have been addressed, and are they comparable to station users' transport and non-transport activities? [Answered by subsections 2.4.5, and 2.5.2.]
- 3) What technologies have been developed that can potentially support the flexible use of stations? [Answered by subsections 2.4.6 and 2.5.3.]
- 4) What limitations of flexible use solutions have been reported? [Answered by subsection 2.4.7.]

This chapter is written for designers in mind and is also relevant to researchers, planners, managers, developers, and other stakeholders who are interested in station planning, design, development, and management. The research results contribute to a comprehensive understanding of the existing knowledge as well as the current knowledge gaps. Within this thesis, this chapter supports Chapter 1 by underpinning the knowledge gap, and supports Chapter 4 by providing spatially relevant literature as input. Comparing to the literature review (section 1.3) in Chapter 1, which is a high-level overall review of relevant topics on the problems, assessment, and solutions, this chapter specifically inquires about solutions.

The remainder of this chapter is structured as follows: [section 2.2](#) develops two frameworks for searching and analyzing the literature; [section 2.3](#) describes the detailed criteria and processes of literature searching and screening; [section 2.4](#) presents the findings and interpretations; [section 2.5](#) concludes by outlining the knowledge gaps and suggesting future research directions.

2.2 Frameworks for the literature review

Two frameworks are developed in this chapter: one to support searching and screening the literature ([subsection 2.2.1](#)), and the other to support reviewing and reflecting on the literature ([subsection 2.2.2](#)).

2.2.1 Framework defining the ideal solutions' characteristics

For systematically searching and screening literature, this chapter builds Framework One ([Figure 2.2](#)), defining six characteristics of the ideal spatial design solutions (and the selected literature should have these features):

- 1) Addressing station-city integration, or describing railway stations and their surrounding areas;
- 2) Addressing overcrowding, underutilization, or events;
- 3) Providing flexible use solutions relevant to spatial design—either directly proposing prescriptive spatial interventions, or providing descriptive knowledge with spatial implications;
- 4) (Optional) Addressing problems or solutions at the district level within a range of around 250 meters, or at the building level (in the spatial dimension);
- 5) (Optional) Addressing events that occur on temporal scale cycles ranging from multiple weekly to yearly (in the temporal dimension);
- 6) (Optional) Providing solutions that are achievable through the design of spatial elements and layouts.

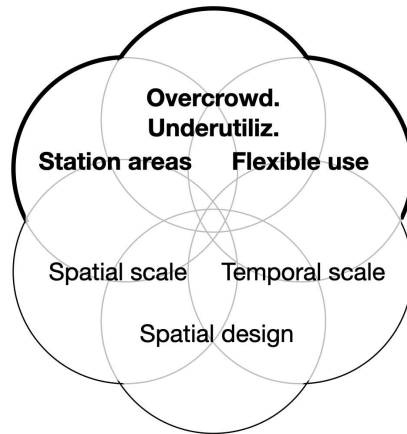


FIG. 2.2 Framework One: primary (in bold text) and optional characteristics (in light text) of ideal solutions. (Source: Author)

These characteristics are determined based on the following considerations: (1) the research context of station-city integration (see [section 1.1](#)); (2) the overcrowding-underutilization phenomena's nature relating to events (see [subsection 1.2.2](#)); (3) the expected flexible use strategy (see [subsection 1.2.4](#)); (4) the station areas' spatial scale ([subsection 1.6.6](#)); (5) events and their temporal scale (see [subsection 1.6.1](#) and [subsection 1.6.2](#)); and (6) the spatial design content (see [subsubsection 1.6.4.1](#)).

2.2.2 Framework defining the knowledge types

For systematically reviewing and reflecting on the literature, this chapter builds Framework Two ([Figure 2.3](#)), categorizing knowledge into four types:

- 1) Knowledge of design measures for flexible use;
- 2) Theoretical insights conceptually addressing spaces or users related to flexible use;
- 3) User knowledge, associated with user behaviors or psychology, in transport and non-transport activities;
- 4) Relevant technologies (e.g., crowding monitoring and simulation) that support user analysis or intervention assessment.

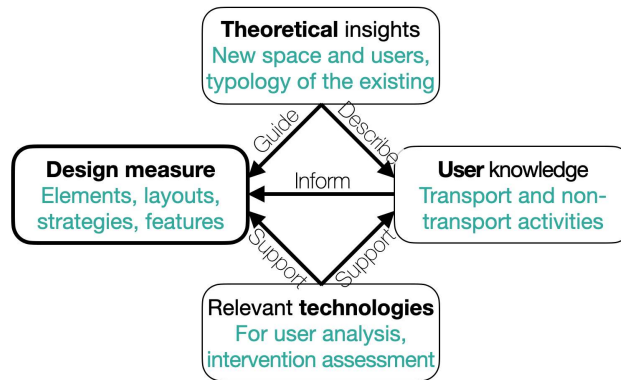


FIG. 2.3 Framework Two: the knowledge types. (Source: Author)

These four knowledge types are determined based on two considerations: (1) their relevance to spatial design, and (2) their differences in research philosophical natures. First, these four types of knowledge are relevant to design. The primary type of knowledge this chapter expects is design measures—tangible interventions that can be directly applied by designers, such as spatial elements, layouts, strategies, and features of buildings or urban areas. However, this type of knowledge is relatively limited in literature, and design measures are usually specific to the context, limiting generalizability. To gain a broader understanding, the chapter also examines the other three types of knowledge—user knowledge, theoretical insights, and relevant technologies—that contribute to design measures. User knowledge, which deepens the understanding of how people interact with spaces, provides evidence to inform appropriate design measures that better facilitate user activities. Theoretical insights, which summarize existing practice at a high level or provide visions for flexible development, can guide design measures. Relevant technologies (e.g., crowd monitoring and simulation) can enhance design measures, making them more effective.

Second, design measures, theoretical insights, and user knowledge are fundamentally different from a research philosophical perspective—they are means-end knowledge, descriptive knowledge, and theories. According to [Zwart and De Vries \(2016\)](#), different research projects produce different knowledge, including descriptive knowledge, means-end knowledge, and other types. Means-end knowledge gives prescriptive guidance on the means under certain contexts to achieve specific goals, and design measures are means-end knowledge. Descriptive knowledge aims to explain and document phenomena as they are, without necessarily providing guidance for action, and user knowledge is descriptive. Theories which are more intangible and abstract ([Sutton and Staw, 1995](#)), providing conceptual frameworks or explanatory logics, synthesizing existing practices or envisioning future possibilities; and this chapter seeks theoretical insights.

2.3 Literature searching and screening

Based on the six characteristics defined in the first framework (subsection 2.2.1, Figure 2.2), inclusion and exclusion criteria are developed for literature searching and screening (subsection 2.3.1 and subsection 2.3.2). Additionally, literature based on experts' suggestions is also added in the end (subsection 2.3.3). Figure 2.4 provides an overview of the whole process of searching and screening.

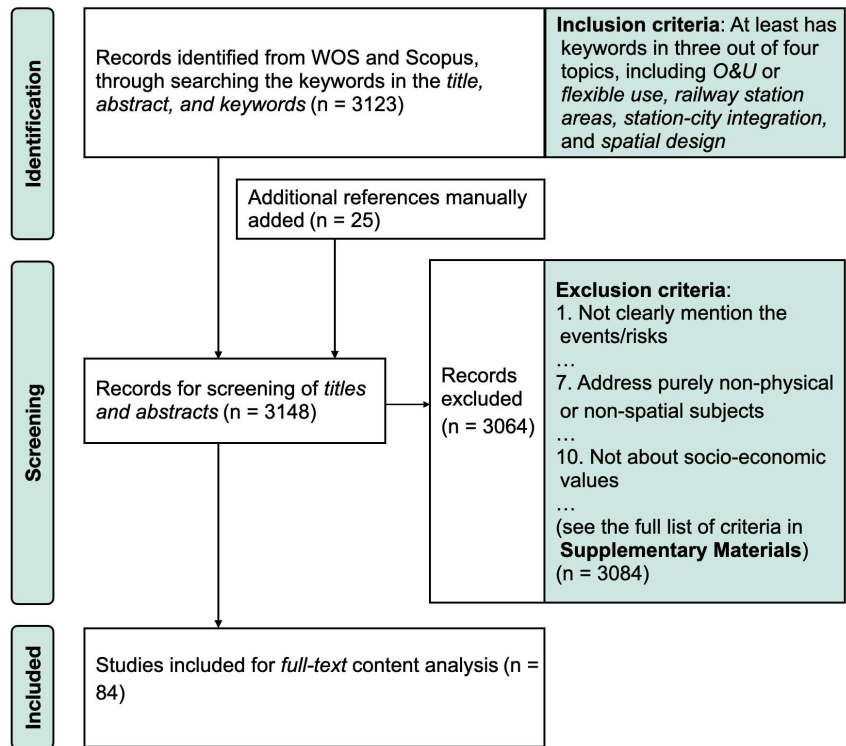


FIG. 2.4 The searching and screening processes and the corresponding criteria. (Source: Author)

2.3.1 Searching strategy (Inclusion criteria)

2.3.1.1 Expand five clusters of keywords

This chapter expects the literature to be relevant to ‘railway station areas,’ ‘overcrowding and underutilization,’ ‘flexible use,’ ‘spatial design,’ and ‘station-city integration.’ These keywords cover the primary characteristics defined in Framework One in [subsection 2.2.1](#). Each keyword is expanded into a larger cluster of more words to ensure enough papers are retrieved ([Figure 2.5](#)), as described below.

‘Railway stations,’ according to [Bertolini and Spit \(1998\)](#), are ‘nodes’ of the transport networks and ‘places’ of the cities. Therefore, stations are fundamentally ‘transport infrastructures’ for transportation activities and ‘public spaces’ for other leisure activities. ‘Station areas’ include the ‘station buildings’ and the outdoor ‘spaces,’ therefore, ‘open/urban/public space’ and ‘landscape’ are relevant.

‘Overcrowding’ is a type of ‘risk’ to the station system ([Weng et al., 2023](#)), and ‘resilience’ is a quality of systems to address risks ([Bešinović, 2020](#)). ‘Underutilization’ is a lack of use of spaces as resources ([Chen and Wei, 2013](#); [Hwang and Lee, 2020](#)), with spaces be ‘empty’ during certain periods. The shift in station status between overcrowded and underutilized is partly due to ‘fluctuation’ in passenger numbers and space usage, and is affected by ‘events’ such as holidays.

‘Flexible use’ requires systems to change at different times. Similarly, terms like ‘dynamic,’ ‘adaptive,’ ‘robust,’ ‘movable,’ ‘reconfigurable,’ ‘multi-functional,’ ‘temporary,’ ‘kinetic’ ([Johnson et al., 2019](#); [Parametric Architecture, 2024](#)), and ‘demand-responsive’ ([Hunkin and Krell, 2018](#)) typically also require systems to change at different times. Due to their shared essence that incorporates time and changes, these words often co-appear in the same papers.

‘Spatial design’ typically includes fields of ‘urban design,’ ‘architecture,’ or ‘landscape architecture,’ and deals with the ‘built environment’ in a broader sense ([De Jong and Van Der Voordt, 2002](#)). ‘Spatial design’ is closely associated with ‘urban planning.’

‘Station-city integration’ is commonly mentioned in literature about ‘station areas,’ ‘station development,’ ‘catchment areas,’ ‘station AND urban,’ and so on ([Cheng et al., 2021](#); [Yang, 2021](#); [Shikata et al., 2013](#); [Martínez et al., 2016](#)).

2.3.1.2 Search with keyword combinations

Literature searches are conducted using combinations of keyword clusters. When all five clusters were combined, no articles were retrieved, suggesting that this topic has not been explicitly discussed in the literature. Alternatively, looser combinations were applied by including only four or three clusters at a time (Figure 2.5; see documented search queries in the [Supplementary Materials](#)).

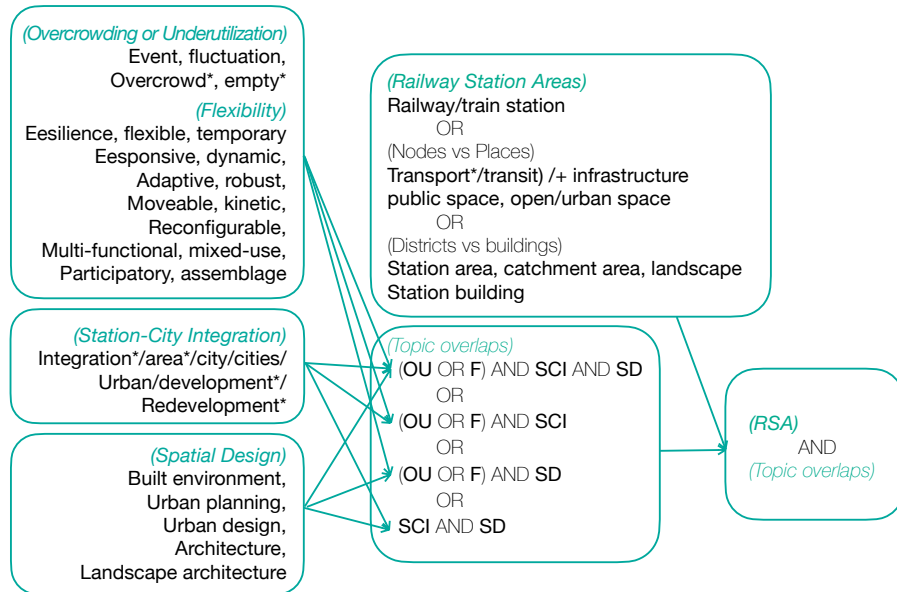


FIG. 2.5 Using keyword clusters and their combinations for searching literature. (Source: Author)

2.3.2 Exclusion criteria

Multiple exclusion criteria are developed, based on the last three optional characteristics defined in Framework Two in [subsection 2.2.1](#) (i.e., within spatial scale of around 250m, temporal scale between multi-weekly to yearly, relevant to spatial design), as well as the insights gained during the screening process (see the full list of exclusion criteria in [Supplementary Materials](#)). The following paragraphs present three exemplary exclusion criteria.

First, regarding events or activities, this chapter seeks solutions for regular human transport and non-transport events or activities, with temporal scales between multi-weekly to yearly. Articles addressing non-human events or rare events at large temporal scales—such as climate, weather, water, flood, food, ecology, disasters, or

COVID-19—are excluded. Articles addressing events of terror, violence, and protest are also excluded, as these events are calamities and less common in normal daily life.

Second, regarding the subjects, this thesis focuses on the physical content of spatial design, treating station areas as physical spatial layouts and elements, as described in [subsubsection 1.6.4.1](#). Therefore, articles focusing purely on non-physical aspects—such as planning processes, management, production, or teaching and design methodologies—are excluded.

Third, regarding values, this chapter expects flexible use of stations to intensify the use of space resources, generating direct socio-economic value. Articles purely aimed at cultural, artistic, heritage, or philosophical values are excluded.

2.3.3 Additional references suggested by experts

The above literature search and screening were conducted in the databases WOS and Scopus. However, for the design and practice of railway stations, a wealth of documents and books—with abundant empirical knowledge—are not indexed in these science-driven databases. To overcome this database limitation, additional documents and books are added based on recommendations from station experts ([Table 2.1](#)).

TABLE 2.1 Additional references included based on expert recommendations

References	Relevance
Jones and Meagher 2015; Leupen et al. 2005	Books addressing architecture with movement or time
Ross 2000; Edwards 1997	Books addressing the planning, design, and management of railway station buildings
Fruin 1971	A classic book on pedestrian movement
Carmona et al. 2003; Gehl 1987; Whyte 2001; Jacobs 1961	Classic books on public spaces, urban places, and people's activities
Networkrail n.d.; Spoorbeeld n.d.; UIC n.d.	Official websites of companies or organizations developing design principles for architectural and urban design of stations
Sheng 2019	An article on station classifications
Bertolini and Spit 1998; Calthorpe and Poticha 1993; Cervero 1998	Books addressing the development of station areas, proposing the Node-Place model and Transit-Oriented Development (TOD)
De Wilde 2006	A thesis on the multiple use of spaces and railway infrastructure
Heuvel 2022; Zhao and Siu 2014; Van Hagen 2011; Van Hagen and Bron 2014	Thesis or article addressing user behavior, perceptions, or emotions, in transport spaces
Van Hagen 2009; Van Hagen et al. 2022; Dallen 2007	Articles on user classification
Holder and Tapamo 2018	An article addressing the technology of facial expression recognition for crowd monitoring
Gifford 2001	A book about environmental psychology

2.4 Results and interpretations

This section presents the observations from the full-text screening of the selected references. The following [subsection 2.4.1](#) presents the general overview of the included articles. Subsections [2.4.4–2.4.6](#) report the detailed findings in four types of knowledge, answering this chapter's main research question. These findings are interpreted from a design perspective, with attention to their applicability at different spatial scalar levels—building level, district level (within a range of around 250m, see [subsection 1.6.6](#)), or both. In relation to stations' flexible use, these findings are examined in terms of their relevance to reducing overcrowding, reducing underutilization, or promoting flexibility. Subsection [2.4.7](#) synthesizes the challenges or limitations of flexible use mentioned by the literature. Broader observations from the abstract and title screening of both the selected and excluded references are incorporated into [section 2.5](#).

2.4.1 General overview of the included articles

After examinations of titles, abstracts, and full texts, 59 articles were shown to be relevant to this chapter's inquiry. As shown in [Figure 2.6](#), in the selected articles, the frequently addressed subjects include public spaces, architecture, and train stations. The frequently addressed properties include kinetic, responsive, and sustainability, among others. This keyword occurrence analysis shows these selected articles are indeed centered around this chapter's inquiry that lies in the discourses about railway stations, flexible use, and spatial solutions. (See [Supplementary Materials](#) for the full data of selected articles.)

Reflecting the strict screening and inclusion criteria detailed in the previous section, [Figure 2.7](#) illustrates the chronological distribution of the final 59-article sample. The number of publications has been increasing over time, showing a growing research interest in addressing related topics.

2.4.2 The literature distribution in relation to disciplines

After reviewing the full text of the included literature, it becomes evident that multiple disciplines are represented, which shows that this chapter is indeed a multidisciplinary literature review. (Figure 2.8 presents the disciplines and fields involved, based on the literature for each knowledge type. The relationship between the knowledge types and disciplines contributes to the later understanding of existing knowledge (see Table 2.2, last column), and the reflection of knowledge gaps—some gaps exist within disciplines, while others span across disciplines (see section 2.5, Figure 2.11).

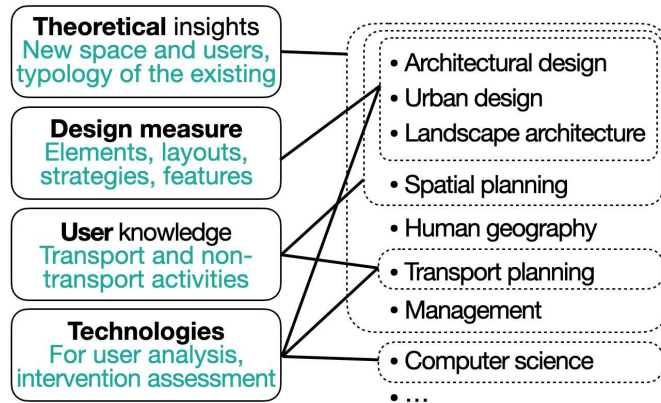


FIG. 2.8 The selected literature's distribution in relation to disciplines or fields. (Source: Author)

2.4.3 Theoretical insights

In the reviewed literature, two types of studies provide theoretical insights (Table 2.2), including:

- 1) studies that envision new types of environment, space, or buildings that support flexible uses; and
- 2) studies that synthesize typologies of existing content related to flexible use.

2.4.3.1 Envision new types of environments, spaces, and buildings

Addressing different necessities or values, studies have envisioned new types of environments, spaces, and buildings that support flexible uses, with descriptions of

their key features. For example, [Roggema \(2014\)](#) proposed a '**dismantable city**,' in which both functional and physical parts are seen as temporary, allowing them to change location and/or function. Three directions of development strategies are provided, such as multiple layers for urban activities ('multi-layer urbanism'), easy construction ('light urbanism'), or reusing abandoned spaces ('transformable urbanism'). In explaining these development strategies, the study provided an illustrative conceptual design as well as real-world community practices in the Netherlands.

By reviewing existing literature and proposing her own arguments, [Thompson \(2002\)](#) conceptually envisioned the evolving roles and features of **urban open spaces** (such as parks and streets) toward the 21st century, repeatedly implying flexible use. For example, in the information age, taking advantage of new information and telecommunication technologies, the landscape should be designed as more responsive and intelligent to facilitate real-world social interactions. 'Loose-fit' places are also needed, allowing for a variety of functions, rich experiences, and even risk, as well as for less conventional activities to arise. In Thompson's research, open space is treated as part of the solution to satisfy diverse user and societal needs. In contrast, in a study by [Ivers \(2018, pp. 54–57\)](#), open space is framed as a problem of ongoing maintenance, which necessitates flexible activities—especially income-generating ones—as the solution.

[Carr and Dionisio \(2017\)](#) proposed '**flexible spaces**' as a 'third way' in urban planning to overcome the limitations of traditional expert-led and participatory models, such as elite dominance, undemocratic input, and NIMBYism ('NUMBY' stands for 'not in my back yard'), particularly in post-disaster or socio-economically disrupted cities like Christchurch and Detroit, where they enable resilient, inclusive 'planning by doing.' These spaces are expected to have the following features: short and non-renewable tenancies, shared and reconfigurable uses with modular materials, minimal regulations for safety and fairness, novel successor activities, impromptu use provisions, low-cost access for marginalized groups, and potential off-site scaling fostering innovation and community empowerment.

[Qian \(2020\)](#) argues that the intellectual landscapes of **public space** research have moved beyond conventional definitions focused on physical accessibility and presence. He categorized three theoretical approaches that conceptualize public space: (1) as a situated and lived experience, (2) as an assemblage of human and non-human elements, and (3) as a liminal zone where inclusion and exclusion are co-constituted, respectively. Qian's article mapped the permutations of new theoretical and conceptual developments in the research of public space, and pointed out public space and publicness as more open-ended, processual, and ambivalent.

Considering the development and management of city districts, [Coppens et al. \(2021\)](#) transformed the 'real options' concept from the finance field into **a real options framework** for adaptive urban design. In this framework, ideal development projects have options to defer or stage, grow, scale, switch use, and even abandon or temporarily suspend, providing flexibility to deal with future uncertainty.

Katsikakis (2017) noted that due to the increasing online communication, there will be less need for conventional physical office space, necessitating the flexible use of the resulting redundant space. In this context, the **flexible workspaces** were envisioned as loose-fit, socially oriented, technology-enabled environments, embracing incompleteness and user participation. The associated real estate becomes a service industry focusing on people rather than on assets, and the associated design and management of buildings become less about the ‘hardware’ and more about the ‘software.’

2.4.3.2 The synthesis of existing types of spaces or uses

Other studies have synthesized typologies of existing content that are related to flexible use or stations—such as city events, spaces, buildings, and users, which provide theoretical frameworks for analysis or for systematizing knowledge. For example, Smith et al. (2021) classified nine types of city events in public spaces, aiming to explore associated issues, and reduce negative impacts and user conflicts. Based on the accessibility of the events and the movement freedom of participants, these events are classified as: large indoor arenas, concerts and screenings, pleasure gardens, parades and street races, roadshows, markets and fairs, mass gatherings, micro-performances, and marches and street parties. Ardeshiri et al. (2016) categorized flexibility in urban spaces into three types, namely spaces with versatility, convertibility, and expansibility, aiming to accomplish flexibility in its complete meaning.

Megahed (2017) proposed a framework for classifying kinetic architecture, in which buildings are categorized according to different factors like spatial vs non-spatial, function vs aesthetics, movement, and materials. This framework enables architects to think about the major aspects of kinetics and explore their potential for architectural applications. Alkhansari (2018) established a framework synthesizing tactics and principles for flexible housing, aiming for convergence of existing knowledge.

TABLE 2.2 Theoretical insights on spaces and uses related to flexible use

Key concepts or subjects ▼	Necessities or values ▼	Key ideas or content ▼	References and disciplines ▼
Envision new types of spaces			
(D) (U) 'Dismantable' city	Overcome limitations of urban metabolism model, increase resilience during transformations	Multiple layers for urban activities, easy construction, or re-using abandoned spaces	Roggema 2014 (Urban planning and design)
(D) (F) Urban open space in the 21st century	Satisfy diverse user and societal needs in the information age	Using technologies, responsive and intelligent; 'Loose-fit' (support diverse functions; associated with the sense of touch; provides places of escape; emphasizes real uses)	Thompson 2002 (Landscape architecture)

Continued on next page

(D) ($\overline{F}$) 'Staging urban landscape'	Solve ongoing maintenance problems for open spaces	Income-generating activities as a solution to sustain the maintenance of open spaces	Ivers 2018, pp. 54-57 (Landscape architecture)
(D) ($\overline{F}$) Flexible spaces	Overcome limitations of traditional & participatory planning models	Tenancies (fixed, non-renewable, shared, and of free or minimal cost); minimal regulations; reconfigurable spaces; unscheduled uses, off-site expansion	Carr and Dionisio 2017 (Urban planning)
(D&B) ($\overline{F}$) New conceptions of public space and publicness	Move beyond conventionally narrow definitions of publicness and show the emerging understandings	Public space as (1) a situated and lived experience, (2) an assemblage of human and non-human elements, and (3) a liminal zone where inclusion and exclusion co-constitute	Qian 2020 (Human geography)
(D) ($\overline{F}$) A 'real-options' framework for adaptive urban design	To guide the design of master plans that might be deployed in the face of uncertainty.	Options to defer or stage, grow, scale, switch use, and even abandon or temporarily suspend	Coppens et al. 2021 (Urban design and management)
(B) ($\overline{F}$) Flexible architecture for working spaces	Adapt to decreased need for conventional offices due to online communication	Flexible use of redundant space, high-quality offline communication environments	Katsikakis 2017 (Architectural design)
Synthesize typologies of existing spaces or uses			
(D) ($\overline{F}$) Typology of city events	Explore associated issues, and reduce negative impacts and user conflicts	Nine types of events based on access and mobility	Smith et al. 2021
(D) ($\overline{F}$) Typology of flexibility in urban spaces	To accomplish flexibility in its complete meaning	Three types of flexible spaces: versatility, convertibility, and expansibility.	Ardeshiri et al. 2016
(B) ($\overline{F}$) Typology of kinetic architecture	To enable architects to think about the major aspects of kinetics and explore their potential for architectural applications	Based on: spatial vs non-spatial, function vs aesthetics, movement, materials, etc.	Megahed 2017
(B) ($\overline{F}$) Typology of tactics and principles for flexible houses	Provide a framework toward convergence for the existing knowledge	(As described in subsection 2.4.4 and Table 2.4)	Alkhansari 2018

Note: Notations for spatial scales— (*B*) = applicable at the building level, (*D*) = applicable at the district level, (*B&D*) = applicable at both the Building and District levels.
Notations for topic relevance— (*Q*) = potentially guide practice to reduces overcrowding, (*U*) = potentially guide practice to reduces underutilization, ($\overline{F}$) = potentially guide practice to increases flexible use.

2.4.3.3 Theoretical insights specifically on station-related content

Studies have envisioned new types of stations or developments. To analyze the complexities of railway station redevelopment, Bertolini and Spit (1998) conceptually proposed railway stations as both nodes in transport networks and places in cities, highlighting stations' dual identities. Aimed to curb the urban sprawl, Calthorpe and

Poticha (1993) proposed transit-oriented development (TOD) around stations, with high density and mixed-use as features. In an ideal TOD community, residents are encouraged to use public transit instead of cars, and the communities are lively during the day and night due to their mixed commercial and residential functions. If the temporal dimension is considered, from this chapter’s perspective, both node-place and TOD theories support flexible use of stations, allowing for different functions—like transport, commercial, and residential uses at different times—at different times. Highlighting the importance of stations, Cavallo (2008) explored the roles of railway stations in city development, and the transformation issues stations and cities encounter. Recognizing the need to expand railway infrastructure and the need for urban development, De Wilde (2006) explored railway infrastructure, through multiple (or mixed) use of space, surface, and land, as well as prolonged use over time. His research focuses on technical aspects that affect safety and financial aspects.

Studies have synthesized typologies of station-related content, such as station types and user types. Clarifying station types is particularly important because stations are a particular type of building that have numerous variations (Richards and Mackenzie, 1986, p. 52). Studies have attempted to classify railway station types based on the following aspects: the layout relationship between the station building and the railway tracks (Meeks, 1956), the project driving factors (Peters and Novy, 2012), the number of passengers (UIC, 2025), the station-city relationships (Sheng, 2019), mobility types (Ross, 2000), and so on. Studies have attempted to classify normal railway passengers based on passengers’ psychological preferences (Van Hagen, 2009), or particularly classify tourists and leisure visitors using trains based on their behavior and attitudes (Dallen, 2007).

TABLE 2.3 Theoretical insights on station-related content

Key concepts or subjects ▼	Necessities or values ▼	Key ideas or content ▼	References and disciplines ▼
Envision new types of stations or developments			
Stations are nodes and places	To analyze the complexities of railway station redevelopment	Railway stations as both nodes in transport networks and places in cities, highlighting stations’ dual identities	Bertolini and Spit 1998
Transit-oriented development (TOD)	To curb urban sprawl, to reduce car use, and to promote public transport	Development around stations, with features including: high density, mixed-use, etc.	Calthorpe and Poticha 1993; Cavallo 2008
Multiple use of railway infrastructure	The need to expand railway infrastructure and the need for urban development	Multiple (or mixed) use of space, surface, land; prolonged use over time; Focusing on technical aspects (related to safety) and financial aspects	De Wilde 2006
Synthesize existing types of stations or users			
(B) (F) Typologies of railway stations	(Clarify station types for precise analysis and clear applicability of findings, given stations’ numerous variations)	Based on: relationship between the station building and the railway tracks; the project driving factors; the number of passengers; station-city relationships; mobility types; and so on	Meeks 1956; Peters and Novy 2012; UIC 2025; Sheng 2019; Edwards 1997; Ross 2000

Continued on next page

(<i>D&B</i>) (<i>F</i>) Typologies of railway users	(Clarify user types for precise analysis)	Based on: psychological preferences; behavior and attitudes	Van Hagen 2009; Dallen 2007
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Note: Notations for spatial scales— (*B*) = applicable at the building level, (*D*) = applicable at the district level, (*B&D*) = applicable at both the Building and District levels.
Notations for topic relevance— (*Q*) = potentially guide practice to reduces overcrowding, (*U*) = potentially guide practice to reduces underutilization, (*F*) = potentially guide practice to increases flexible use.

2.4.4 **Design measures**

This subsection presents the results on the design measure in three stages: First, design books on time and movement—which are fundamental for flexible use—are briefly presented; Then, articles addressing design measures for flexible use are presented (Table 2.4); Lastly, studies specifically addressing the design of railway stations are presented.

Studies have explored time and movement in urban and architectural design. For example, Carmona et al. (2003) described urban design in six dimensions, including the temporal dimension. Leupen et al. (2005) explored how architecture can respond to time and changing patterns of use, presenting design strategies and conceptual approaches for creating spaces or buildings that accommodate flexible use.

2.4.4.1 **Design measures for the flexible use of buildings or urban spaces**

Towards flexible use, studies have investigated many spatial aspects, including:

- 1) spatial elements (including indoor and outdoor elements),
- 2) spatial layouts,
- 3) design strategies, and
- 4) spatial features.

Addressing buildings or indoor spaces, studies have examined *indoor elements* to support flexible use. Soft, removable elements such as light (Crocì, 2008), AR projection or VR wearable devices (Elkhouly et al., 2023; Barry et al., 2012), curtains (Coffman, 2018), and tents (Trisno et al., 2023). In addition, studies have addressed mechanically powered, removable elements like moving robotic walls (Nguyen et al., 2022; Johnson et al., 2019). From a design perspective, these elements can be designed separately and added to existing buildings, activating empty spaces during non-peak times and distributing pedestrian flows more evenly during peak times to support flexible use.

Buildings with particular hard and non-detachable elements allow reconfigurations and therefore support flexible use. ‘The Shed’ building (Holden, 2019), in Hudson Yards, Manhattan, New York, for example, with its lightweight building envelope and mechanical bogie wheels, allows reconfiguration between an open-air plaza and an enclosed performance hall, enabling flexible use for public outdoor events and indoor cultural performances. The Center Pompidou, Paris, with its structural elements positioned to the exterior, achieves a large free internal floor space, which can be reconfigured on various time scales, enabling programmatic flexibility and supporting diverse uses (Akgün et al., 2022).

Addressing outdoor spaces, studies have shown a variety of **outdoor elements** that support flexible use. These include soft or easily removable elements, such as giant temporary inflatable installations, movable urban furniture, temporary structures, and potted plants (Ivers, 2018; Loo and Fan, 2023; Preston and Bank, 2012; Appel, 2015), as well as mechanically powered elements that enable dynamic adaptation, such as rotatable benches and boards for partitioning spaces, liftable bollards for controlling vehicle traffic, foldable umbrellas or movable roofs for weather protection, and movable stages (Dąbrowska-Żółtak et al., 2021).

In comparison to spatial elements, spatial **layouts** (Figure 2.9) are less examined by studies. A rare study by Heathcott (2019) analyzed Mexico City’s street markets and identified five typologies of layouts—linear, circuit, cluster, contour, and hybrid—which relate to the geometry of the streets.

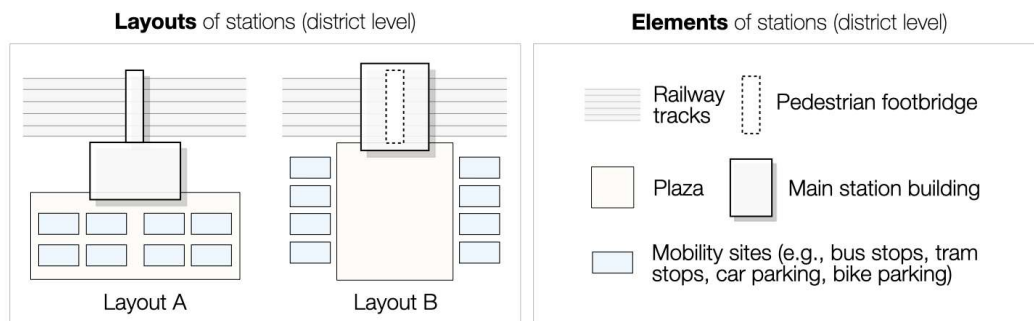


FIG. 2.9 ‘Layouts’ vs ‘elements.’ (Source: Author)

Beyond individual elements and certain types of layouts, studies also use more overarching design **strategies** to enhance flexibility in public spaces. At the district scale, for example, in a design proposal for an old city in Guangzhou, China, Bai et al. (2023) applied the ‘plug-in city’ concept, originally developed by the Archigram group, to activate public spaces through modular and adaptable interventions. At the building level, buildings with modular components can be dismantled and reassembled, enabling flexible use of the site. Stadium 974, for instance, was constructed from 974 shipping containers, allowing it to be disassembled and relocated. Inspired by this approach, a design proposal by Smith (2023) explored the possibility of designing stadiums with modular units that can similarly be shipped and reassembled. Together,

these examples illustrate that buildings and outdoor spaces can support a variety of uses and activities when their elements are strategically designed or arranged to enable flexible use.

Beyond concrete design elements, layout, and strategies, studies also examined the general **features** that characterize flexibility in buildings and outdoor spaces. At the building level, [Geraedts \(2008\)](#) proposed four indicators for assessing buildings' flexibility—partitionability, adaptability, extendability, and multi-functionality. [Alkhansari \(2018\)](#) illustratively analyzed 33 examples and identified eight tactics for designing flexible buildings, including open plan, pre-fabricated modules, similar spaces, extendable unit, attachment and detachment of adjacent units, common space between adjacent units, portable walls, and retractable furniture in a multifunctional space. From these tactics, she extracted three broader fundamental principles: soft connection, diversity and multiplicity of spaces, and multi-functional space. At the district level, [Ardeshiri et al. \(2016\)](#)—through vivid illustrations—explained three prerequisites followed by main requisites for achieving urban spaces that can be flexibly used. The three prerequisites include permeability, adaptability, and legibility, and the main requisites include positive outdoor spaces, spaces with multimodal behavioral patterns, multiuse buildings, active frontages, and fine amenities. Along similar lines, [Roggema \(2014\)](#) proposed the concept of a 'dismantable city', in which urban objects are detachable from their environment and building components are dismantable, allowing them to be reused in other configurations. This idea challenges the conventional assumption that design must be specific or even fixed to a given context.

TABLE 2.4 Design measures for flexible use

Design measures	Detailed content	References
Indoor design elements	(B) ($\overline{F}$) Soft, removable elements: light; AR projection and VR wearable devices; curtains; tents.	Croci 2008 ; Elkhouly et al. 2023 ; Barry et al. 2012 ; Coffman 2018 ; Trisno et al. 2023 ; Johnson et al. 2019
	(B) ($\overline{F}$) Mechanically powered, removable elements: moving robotic walls.	Nguyen et al. 2022
	(B) ($\overline{F}$) Non-removable elements that support reconfigurations: (The Shed, New York) lightweight hall driven by mechanically powered wheels, enabling space reconfiguration; (Center Pompidou, Paris) large free internal floor with structures positioned externally, and lightweight internal building parts, enabling floor layout reconfigurations	Holden 2019 ; Akgün et al. 2022
Outdoor design elements	(D) ($\overline{U}$) Soft elements: giant inflatable installations. Removable elements: removable Ferris wheels, removable urban furniture, potted plants; temporary structures.	Ivers 2018 ; Loo and Fan 2023 ; Preston and Bank 2012 ; Appel 2015
	(D) ($\overline{F}$) Mechanically powered elements: rotatable benches, foldable umbrellas, movable roofs, movable stages	Dąbrowska-Żółtak et al. 2021
Spatial layouts	(D) ($\overline{U}$) Five typologies of streets (layout) in Mexico City: linear, circuit, cluster, contour, and hybrid supporting street markets.	Heathcott 2019

Continued on next page

Design measures	Detailed content	References
Design strategies	(D) (<u>U</u>) 'Plug-in city' strategy to activate public spaces in an old city area.	Bai et al. 2023
	(B) ($\bar{F}$) Design buildings with modular units (e.g., containers) to be reassembled and transported.	Smith 2023
Features of building or outdoor spaces	(B) ($\bar{F}$) Assess buildings' flexibility through four indicators: partitionability, adaptability, extendibility, multifunctionality.	Geraedts 2008
	(B) ($\bar{F}$) Achieve architecture flexibility through eight tactics: open plan, pre-fabricated modules, similar spaces, extendable unit, attachment and detachment of adjacent units, common space between adjacent units, portable walls, and retractable furniture in a multifunctional space; and three principles: soft connection, diversity and multiplicity of spaces, and multifunctional space.	Alkhansari 2018
	(D) ($\bar{F}$) Urban flexibility requires three prerequisites: permeability, adaptability, legibility; and multiple body requisites: positive outdoor spaces, spaces with multimodal behavioral patterns, multiuse buildings, active frontages, and fine amenities.	Ardeshiri et al. 2016
	(B&D) ($\bar{F}$) Detachable urban objects and dismantable building components.	Roggema 2014

Note: Notations for spatial scales— (*B*) = applicable at the building level, (*D*) = applicable at the district level, (*B&D*) = applicable at both the building and district levels.

Notations for topic relevance— (*Q*) = this solution potentially reduces overcrowding, (*U*) = this solution potentially reduces underutilization, ($\bar{F}$) = this solution potentially increases flexible use.

2.4.4.2 Spatial design of railway stations

The following paragraphs present station-specific studies that addressed the design of station building components, station buildings, and the broader station areas. These studies are not necessarily dealing with flexible use, but reviewing them provides an opportunity to understand how much (or how little) flexible use has been addressed by existing station-specific design literature.

First, **station building components** like bi-directional ticket gates and escalators, with mechanical and digital interventions, can adjust their directions dynamically to changing pedestrian flows, supporting efficient peak-time transport use. Studies have examined the impact of changing gates from unidirectional to bidirectional in stations (Lai et al., 2024; Yamada and Utaka, 2023).

Second, beyond building components, the design of the whole railway **station buildings** has been explored by studies in the design discipline. For example, Ross (2000) provided a comprehensive overview of the planning, design, and management of railway stations. Her book described the functional requirements of stations, including the flexibility of station elements (Ross, 2000, p. 213), and briefly introduced management issues related to station development and maintenance. Edwards (1997) presented different perspectives to view station architecture, discussed stations' roles

as urban gateway and landmark, categorized railway stations into different types based on their status in the railway networks, and described station buildings' layout, design, and technical issues. [Da Conceição \(2015\)](#) explored how architecture can contribute to the improvement of spatial performance of station areas, analyzing the layouts of station buildings regarding railway tracks and the city ground. The edited volume by [Triggianese et al. \(2019\)](#) explored the role of stations in future metropolitan areas through a series of case studies and design studios that illustrate design proposals.

Third, beyond the station buildings, studies have addressed the broader **station areas** (See the scale and content of 'station areas' explored in this thesis, [Chapter 1, subsection 1.6.6](#)). For example, Du has revealed and defined the 'place quality' of railway stations, by literature review, expert interviews, and user surveys ([Du et al., 2021](#); [Du, 2023](#)). In his definition, the place quality of station areas consists of aesthetic qualities of urban spaces (the spatial dimension), experienced 'sense of place' (the socio-cultural dimension), and the agglomeration of economic activities (the economic dimension). Peters did a series of case studies, examining design measures in station cases such as Rotterdam Central Station, Utrecht Central Station, Stuttgart 21 Station, Berlin Central Station, London King's Cross Station, Penn Station ([Peters, 2009](#); [Peters and Novy, 2012](#); [Novy and Peters, 2012](#); [Peters and Tolkoff, 2016](#); [Loukaitou-Sideris et al., 2017](#)).

Companies like [Sporbeeld](#) (a Dutch company specializing in developing design guidelines for Dutch Railways) and [Networkrail](#) (a British company that owns and operates some of Britain's biggest and busiest railway stations), and organizations like [UIC](#) (International Union of Railways), publish a variety of station-related guidance, including design principles for architectural and urban design of stations (see [Networkrail n.d.](#); [Sporbeeld n.d.](#); [UIC n.d.](#)).

TABLE 2.5 Design measures for railway stations

Design measures	Detailed content	References
Station building components	(B) ($\overline{F}$) (Non-removable elements) Bi-directional ticket gates and escalators adjust to changing pedestrian flow.	Lai et al. 2024 ; Yamada and Utaka 2023
Station buildings	The planning, design, and management of railway stations; the functional requirements of stations, including flexibility of station elements; briefly introduced management issues related to station development and maintenance.	Ross 2000
	Perspectives on station architecture: the politics of railway, station types, station layouts and design (with clarifications on generic functional requirements, and building/space elements), and technical issues; Exemplary cases.	Edwards 1997
	Design strategies and guidance manuals address station buildings and building components (e.g., lighting, vertical circulations, facilities, retail), encompassing generic station qualities such as safety, comfort, sustainability, efficiency, identity, etc.	See documents in Networkrail n.d. , Sporbeeld n.d. , and UIC n.d. , e.g., Networkrail 2024 , Sporbeeld 2025
	Examine spatial performance regarding the vertical position of railway tracks: ground level, elevated level, or underground level.	Da Conceição 2015

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	Explore the role of railway stations in future metropolitan areas	Triggianese et al. 2019
Station areas	Define the ‘place quality’ of station areas and its dimensions: aesthetic qualities of urban spaces (spatial dimension); experienced ‘sense of place’ (socio-cultural dimension); and the agglomeration of economic activities (economic dimension).	Du et al. 2021; Du 2023
	Case studies on stations, addressing diverse urban design aspects such as the spatial layouts of station areas, the cost and benefits of station (re)development, and the politics and power struggles during project development.	Peters 2009; Peters and Novy 2012; Novy and Peters 2012; Peters and Tolkoff 2016; Loukaitou-Sideris et al. 2017
	Guidance on the urban design of station areas or public spaces in station areas, covering diverse objectives, such as enhancing stations’ identity, improving public spaces’ attractiveness.	See documents in Networkrail n.d., Spoorbeeld n.d., and UIC n.d. e.g., Networkrail 2023, Networkrail 2022, Spoorbeeld n.d.

Note: Notations for spatial scales— (*B*) = applicable at the building level, (*D*) = applicable at the district level, (*B&D*) = applicable at both the building and district levels.

Notations for topic relevance— (*Q*) = this solution potentially reduces overcrowding, (*U*) = this solution potentially reduces underutilization, (*F*) = this solution potentially increases flexible use.

2.4.5 User knowledge

Studies have developed user knowledge that describes behavioral or psychological patterns of users in the following activities:

- 1) transport user activities (e.g., waiting and moving);
- 2) non-transport user activities (e.g., leisure activities like playing in parks, participating in events like open-air markets, and ‘informal use’ like sleeping on the streets)

Aiming at flexible use of stations, this chapter treats knowledge of both transport and non-transport activities as relevant, for the following three reasons. First, user knowledge in transport activities potentially informs design measures that improve efficiency to reduce overcrowding. Second, user knowledge in non-transport activities, such as activities during leisure events and informal use, potentially guides the creation of pleasant spaces that accommodate such activities to reduce underutilization. Finally, by combining user knowledge in transport and user knowledge in non-transport activities, stations can be designed to flexibly serve multiple functions.

Classic studies such as those by Fruin (1971), Jacobs (1961), Gehl (1987), Whyte (2001), and Jones and Meagher (2015) continue to inform understandings of how people move through space and use space. Fruin (1971) quantitatively defined individual pedestrians’ physical and perceptual characteristics in movement, outlined

flow patterns like the relation between flow volumes, density, and speed, and transferred the level-of-service (LOS) concept from the field of highway design to the design of transport spaces that passengers use.

Jacobs (1961) described how people use community spaces for activities like daily interactions, children playing, local businesses, and so on. She suggested districts to have features like mixed primary uses, short blocks, aged buildings with varying conditions, and high densities of people, to promote diverse uses towards safe and lively urban environments. Gehl (1987) differentiated three types of outdoor user activities: necessary activities, optional activities, and social activities, and generally described the spatial features that emphasize pedestrian comfort, social interaction, and sensory experience. Whyte (2001) further observed detailed behaviors and described the practical design details like sitting space that facilitate diverse user needs, considering factors like the sun, wind, trees, water, and food. In studying the interaction between humans and the environment, a field called ‘environmental psychology’ has been established and continuously contributed new insights on space users (Gifford, 2001).

Jones and Meagher (2015) brought together a series of articles that examine architecture through the lens of bodily movement, temporality, and lived experience. They discussed how buildings and landscapes are encountered dynamically, emphasizing sequences of perception, shifting viewpoints, and the ways in which users’ actions shape spatial meaning. These foundational studies are commonly referenced by later studies. Beyond these studies, more recent research has expanded knowledge with more empirical findings on transport and non-transport user behavior, as described below (Table 2.6).

2.4.5.1 Transport activities

First, for **transport activities**, at the building level, studies have examined how different passenger behaviors are affected by varying conditions and factors. Such studies are conducted in various spatial settings, including across the entire railway station buildings, within specific areas inside the building, and/or on the platforms. For example, with multiple Dutch railway station **buildings** as the spatial setting and with field and laboratory experiments, Van Hagen (2011) systematically studied how passengers’ waiting experience is influenced by three dimensions of waiting environments—ambient, design, and social dimensions. In his research, the ambient (intangible) dimension was manipulated with music and light intensity, the design (tangible or visible) dimension was manipulated with color, advertising, and infotainment, and the social (people) dimension was manipulated with varying degrees of crowd density on the platform. The results show that it is necessary to add the right environmental stimuli at the right moment, avoiding too much or too little for passengers. Negative stimuli should first be eliminated or neutralized before adding positive ones. Additionally, a user need pyramid was constructed in the study,

specifying the priorities of different user needs from fundamental to high-level needs, ranging from safety and reliability, speed, ease, comfort, to experience (Van Hagen, 2011, p. 211). Van Hagen also conducted related studies investigating the experience of users traveling in stations or trains, regarding user emotional experiences (Van Hagen and Bron, 2014), and user types with different psychological preferences (Van Hagen, 2009; Van Hagen et al., 2022).

In a railway station, Haghani and Sarvi (2016) investigated pedestrian route choice differences between normal egress and emergency evacuation, highlighting several key differences in passenger priorities: (1) In nonemergency egress, the proximity of the exit points to the passenger's destinations is a dominant factor. (2) In emergencies, passengers place a much higher priority on avoiding crowded exits. (3) Directional flows of pedestrians are not a significant factor in a normal egress, and (4) are a negative utility factor for most individuals, depending also on visibility of the exits.

Harding (2024b) analyzed the user experience of inclusivity in a railway station. He observed passengers' behaviors such as moving, waiting, and queuing, and reflected on the station's design details like the number and positions of lifts and escalators, the hazard warning marks, the lack of seating in 'paid' and 'unpaid' areas, and so on. The observations revealed detailed user needs, such as needing seating areas that define comfortable waiting zones, to avoid being anxious. The research method Harding (2024b) used is a qualitative and rigorous one called auto-ethnography, which involves immersing himself in the daily use of this station. Relatedly, Zhao and Siu (2014) conducted a study in a similar qualitative way, observing and analyzing the behavioral and perceptual boundaries of public space in metro stations. The findings provide nuanced insights into people's perceptions of space boundaries, as influenced by hard facilities, soft signs, other people's presence and activities, and so on. For example, old ladies selling newspapers result in a boundary of the area, as passengers generally want to avoid them. Qualitative studies like the two by Harding (2024b) and Zhao and Siu (2014) are relatively scarce in research on transport passengers' behavior, where quantitative research dominates.

With two particular **areas**—one ingress area and one egress area—in a station, Fang et al. (2015) extracted data from camera footage and analyzed the passenger movement in catching trains and leaving the station. The results showed that, on average, passengers catching trains, due to time pressure, walk faster than passengers leaving the station. Regarding passengers who carry baggage, surprisingly, within a certain range of baggage quantity, the more luggage the passengers carry, the faster they walk. This phenomenon is possibly due to passengers' increasing psychological pressure to catch the trains with increasing luggage. In addition, a 'dislocation phenomenon' sometimes happens—some passengers stop walking to stow their luggage or wait for their companions, then the passengers behind are blocked and need to change their walking lanes. Therefore, Fang et al. (2015) suggest adding a probability of pausing in the simulation of pedestrian movement.

With a concourse area in front of station gates as the spatial setting, Sukor (2019) also extracted data from camera footage and studied the pedestrian flows during three peak times—morning, afternoon, and evening peak hours, in normal working days. The

results show that during these three periods, for the same paths, there are varying volumes of pedestrians, with varying density and walking speeds, demonstrating the heterogeneity of the movement associated with space.

With station **platforms** as the spatial setting, [Heuvel \(2022\)](#) defined a measurable capacity of platforms as limited by three aspects: arriving passengers queuing or walking in undesirable areas, boarders waiting in the danger zone along the platform edge, and train dwell times prolonged. These are related to passengers' boarding and alighting behavior, escalators' capacity, and trains' dwell time. The study revealed detailed passenger behavior patterns with associated factors by analyzing the quantitative measurements of passengers. For instance, a queue of 20 or more persons forms an obstacle for persons attempting to pass it, the platform crowding increases the number of persons and their time spent in the buffer zone (i.e., the danger zone alongside the platform edge), the 0.8m width of the buffer zone is ineffective at high crowd densities, passenger service time (for boarding and alighting processes) is a reason leading to trains' delayed dwell time.

With a mock-up station platform in laboratory experiments as the spatial setting, [Küpper and Seyfried \(2023\)](#) investigated the effects of waiting time, number of pedestrians, and obstacles on the distribution of waiting passengers. The findings show that interpersonal distance varies surprisingly little regardless of obstacles or crowd density, suggesting a strong collective optimization when searching for waiting positions. In this collective optimization, passengers chose shorter distances to each other, ranging from 1.0 to 1.2 meters, which fall within the classical 'personal space' zone ($0.45 < d < 1.2$ m), rather than the 'social' zone ($1.2 < d < 3.6$ m).

2.4.5.2 Non transport activities

Second, for **non-transport** activities like leisure use and informal use, in outdoor and indoor spaces at the district and building levels, studies have examined how different user behaviors and psychology are affected by physical and non-physical factors. A few studies examined how **installations** in urban spaces or buildings affect user behavior or psychology. For example, in a public square setting, [Paukaeva et al. \(2021\)](#) showed that installations set up during a temporary winter event attract 40–60% more participants and encourage longer stays, more even use of space, and greater participation in place-based activities, illustrating temporary design interventions' effectiveness in shaping user behavior and engagement, even in an extremely cold climate. Similarly, in an urban park setting, [Loo and Fan \(2023\)](#) showed that movable urban furniture significantly attracts pedestrians. Also, both the fixed landmark and movable furniture attract people by forming visible edges, confirming the 'edge effects' ([Gehl, 1987](#); [Whyte, 2001](#)) in public space. Both studies ([Paukaeva et al., 2021](#); [Loo and Fan, 2023](#)) call for combining flexible elements with fixed elements in the design of public spaces. In an indoor room setting with an autonomously moving robotic wall, a study by [Nguyen et al. \(2022\)](#) explored user perception, showing that if spatial,

situational, and subjective qualities are balanced, the wall generates positive experiences, enhancing privacy, noise reduction, and a refreshed view. Conversely, poor balance results in negative feelings of confinement or unrest.

Studies in the planning and design fields have examined activities like street vending, markets, homeless people sleeping rough, which are often seen as **‘informal’ use** (Koster and Nuijten, 2016; Lutzoni, 2016) because they involve informal or unregistered occupations of spaces designed for ‘formal’ uses. For example, Flock and Breitung (2016) studied street vending in Guangzhou, China, showing a complex social production of public space, with the dynamics between migrant street vendors and public security forces, the government’s multifaceted considerations on city image and people’s livelihood, and the evolving policies involving zones and periods of control over vending in public spaces. Similarly, Heathcott (2019) studied street markets in Mexico City, Mexico, and mentioned that there are constant struggles between vendors and residents over parking, sidewalks, spaces, blocked access to buildings, and so on. Entities and dynamics at different operational levels, such as governments, government delegations, vendors’ associations, gangs, district laws, economic restructuring, and international trade agreements, make the street markets more complicated and dynamic. With a spatial setting of a railway station building, Lenhard 2022 studied homeless people’s sleeping rough. During the process of homeless people seeking access to the hot air vents for warmth in winter, dynamic interactions happen both internally between homeless people and externally with the security forces. Also, building elements like hot air vents, spikes, and fences during construction affect homeless people’s use of space in a prolonged or permanent way.

TABLE 2.6 User knowledge in transport and non-transport activities

Spatial settings ▼	User behaviors or psychologies ▼	Physical or non-physical factors involved ▼	References ▼
In transport activities			
(B_{indoor}) Railway stations	User perception of stations and waiting	Intangible, tangible, and social elements; the number of elements at different moments; user psychological preferences, emotional experiences	Van Hagen 2011; Van Hagen and Bron 2014; Van Hagen 2009; Van Hagen et al. 2022
(B_{indoor}) A railway station	(Q) Route choice differences between normal egress and emergency evacuations.	Different priorities on proximity to exits, avoiding crowded exits, and maintaining directional flow;	Haghani and Sarvi 2016;
(B_{indoor}) A railway station	Passenger movement and waiting	The number and position of escalators and lifts, warning marks, and seating that signify waiting areas	Harding 2024b;
(B_{indoor}) Metro stations	User behavior indicating their perception of the boundaries of space	Hard facilities, soft signs, other people’s presence and activities, etc.	Zhao and Siu 2014

Continued on next page

(<i>B</i>) An ingress area and an egress area in a station	(<i>O</i>) Movement efficiency of passengers with baggage;	Baggage size.	Fang et al. 2015;
(<i>B</i> _{indoor}) A concourse area in front of the station gates	(<i>O</i>) Pedestrian movement.	Speed, density, oblique movement	Sukor 2019; Harding 2024a
(<i>B</i> _{indoor}) Station platforms	Pedestrian queuing and waiting	Queues' sizes, escalators' capacity, the width of the buffer zone, trains' dwell time, measurement accuracy related to the platform segment size	Heuvel 2022
(<i>B</i> _{indoor}) A station platform (a mock-up platform in laboratory experiments)	(<i>O</i>) Passengers' waiting behavior, measured by crowd density, spatial positions, and distance between individuals.	Number of pedestrians, waiting time, and obstacles; a a superposing effect during collective optimization	Küpper and Seyfried 2023;
In non-transport activities			
(<i>D</i>) A city square, with event installations	(<i>U</i>) 40–60% more participants, longer stays, more even space use, greater participation	Temporary installations, temporary and permanent design, day and night	Paukaeva et al. 2021
(<i>D</i>) An urban park, with movable furniture and fixed landmarks	(<i>U</i>) Playing, group forming and interaction	Spatial edges, moveable furniture, and visual landmarks.	Loo and Fan 2023
(<i>B</i> _{indoor}) A room, with a moving robotic wall	(<i>F</i>) Positive perception: enhanced privacy, noise reduction, and a refreshed view; negative perception: confinement or unrest.	Balance of spatial, situational, and subjective qualities	Nguyen et al. 2022
(<i>D</i>) Two streets and a station square	(<i>U</i>) Street vending	Zones and periods of control by administration; street elements like the signs and flowerpots.	Flock and Breitung 2016
(<i>D</i>) Streets	(<i>U</i>) Street markets	Street spatial layouts (as described in Table 2.4); different entities and policies at different operational levels.	Heathcott 2019
(<i>B</i> _{outdoor}) A railway station	(<i>U</i>) Homeless people sleeping rough	Building elements like hot air vents, spikes, fences; personnel interventions.	Lenhard 2022

Note: Notations for spatial scales— (*B*) = at the building level, (*B*_{indoor}) = indoor settings at the building level, (*B*_{outdoor}) = outdoor settings at the building level, (*D*) = at the district level.

Notations for topic relevance— (*O*) = this knowledge potentially help reduces overcrowding, (*U*) = this knowledge potentially help reduces underutilization, (*F*) = this knowledge potentially help enhance or increase flexible use of space.

2.4.6 Relevant technologies

In the reviewed literature, multiple studies have applied different technologies to support transport and design research. The following text first introduces three clusters of technologies (Table 2.7), and then presents their applications in studies (Table 2.8).

2.4.6.1 Three clusters of technologies

In the reviewed literature, three clusters of technologies emerged, including:

- 1) user data collection technologies (which are applicable at the collective level or individual level),
- 2) user virtual reality (VR) experiments, and
- 3) user simulation.

First, **user data collection** at the **collective level**, which captures groups of pedestrians in shared spaces, has been facilitated by technologies such as Bluetooth, Wi-Fi, GPS, sensors, phone signals, cameras, or comparisons of ticket or chip-card check-in and check-out data (Heuvel, 2022; Wu et al., 2020; Elhamshary et al., 2019; Pouw et al., 2024). They have adapted rapidly alongside developments in computer science; for instance, methods for automatically counting pedestrian numbers in camera footage have evolved from early texture-based algorithms (Marana et al., 1998) to modern neural network object-detection algorithms (Wong and Law, 2023; Zhao et al., 2022). Similarly, in Dutch railway stations, Bluetooth tracking was replaced by Wi-Fi tracking, which was subsequently superseded by OV-chipcard data (Heuvel, 2022, p. 72). Each of these technologies carries trade-offs in terms of accuracy, user privacy, and cost (Heuvel, 2022, p. 70).

At the **individual level**, user data collection has been facilitated by multiple types of technologies such as biotechnologies, neurotechnologies, and human-computer interaction technologies, including more specific technologies like eye tracking and electroencephalogram (EEG) (Schneider et al., 2023; Egger, 2016; Schrom-Feiertag et al., 2016). These technologies enable the collection of detailed biometric and neural data from participants. Combined with mathematical models, such as structural equation modeling, which can uncover latent factors (Cheng et al., 2018), and discrete choice modeling, which quantifies the effects of observable variables (Yang et al., 2024a,b), these data provide detailed insights into pedestrians' decision-making.

Second, virtual reality (VR) technology enables **user VR experiments**, providing multiple advantages over experiments in real-world scenes (Zhu and Li (2021); Egger (2016); Armougum et al. (2019); Yang et al. (2024a,b)). VR environments offer easier control over the elements to be investigated, allowing researchers to include elements

of interest while excluding irrelevant real-world elements. They also enable research that otherwise would be dangerous to conduct in real-world settings. For instance, research on pedestrian perception of running vehicles. VR environments also offer a cost-effective way to design and test experiments that would be prohibitively expensive in real-world settings. With these advantages, VR experiments are increasingly adopted in both the transport and spatial design fields (E.g., see VR labs in [civil engineering](#) and [architectural](#) faculties at TU Delft.) Technologies for user data collection at the individual level are commonly applied in VR experiments to extract detailed user data.

Third, based on user data and the patterns derived from them, **user simulation** enables simulating users' behavioral and perceptual abilities, including the abilities to navigate and move, to see the scene or even feel the visual quality, to conduct tasks, and so on. Simulation of users' movement, or traditionally called crowd movement, has long been developed through diverse algorithms, approaches, and software programs ([Duives et al., 2013](#); [Yang et al., 2020](#)). Algorithms, for example, physics-based Social Force Model, simulate pedestrian movements by modeling repulsive and attractive forces between individuals and obstacles. Discrete methods, including Cellular Automata, represent space as a grid and update pedestrian states in discrete time steps. Utility models focus on decision-making, where agents select actions to maximize a utility function based on factors such as travel time, congestion, or comfort, and are often integrated within agent-based modeling frameworks. Machine learning algorithms, such as Support Vector Machines or neural networks, are increasingly used for trajectory prediction, parameter calibration, or behavior recognition. These algorithms are frequently implemented within broader modeling approaches such as agent-based modeling, rule-based simulations, or vision-based modeling ([Yang et al., 2020](#)), and applied at micro, meso, and macro spatial levels, providing flexible choices to capture complex pedestrian behaviors in both normal and emergency scenarios. Based on these algorithms and approaches, software programs—both commercial and open-source—have been developed ([Dubroca-Voisin et al., 2019](#); [Richards, n.d.](#)), such as MassMotion and SUMO, to support the simulation of complex projects like railway stations.

Comparatively, simulation of other types of user abilities has been less developed. Traditional methods like 'Isovist' analysis enable the simulation of the user's seeing ability in scenes ([Benedikt, 1979](#)). Recent studies have applied computer vision technologies, with mathematical models to simulate user visual perception, to be able to recognize elements in the scenes and even tell the visual quality of the scenes ([Enshan et al., 2025b](#); [Schrom-Feiertag et al., 2016](#)). Based on agent-based modeling, which enables the simulation of users as agents to interact with environments, studies have expanded the simulation of other user behaviors and abilities, like wayfinding and conducting tasks ([Schrom-Feiertag et al., 2016](#); [Brunnhuber et al., 2012](#); [Kim et al., 2023](#)). Equipped with new technologies like multimodal large language models (MLLMs), agents in simulation are becoming more intelligent with more advanced cognitive abilities to understand the world ([Noyman et al., 2025](#)).

TABLE 2.7 Three clusters of user-based technologies

User-based technologies	Technology, software, or data
User data collection	Collective level. Bluetooth, WIFI, GPS, sensors, phone signals, camera footage, data of check-in and check-out; neural-network-based object-detection algorithms (Heuvel, 2022; Wu et al., 2020; Elhamshary et al., 2019; Pouw et al., 2024; Wong and Law, 2023; Sukor, 2019; Loo and Fan, 2023; Zhao et al., 2022).
	Individual level. Biotechnologies, neurotechnologies, and human-computer interaction technologies, such as eye tracking, and electroencephalogram (EEG) (Schneider et al., 2023).
User VR experiments	Virtual reality (VR) (Zhu and Li, 2021; Egger, 2016; Armougum et al., 2019; Yang et al., 2024a,b).
User simulation (see also sub-section 6.1.2)	Movement simulation—algorithms (e.g., social force model, Cellular Automata, Utility models, machine learning models), approaches (e.g., agent-based simulation, rule-based simulation, vision-based simulation), and software programs (e.g., MassMotion, SUMO) (Duives et al., 2013; Yang et al., 2020; Dubroca-Voisin et al., 2019; Richards, n.d.).
	Visibility or visual perception simulation—approaches (e.g., Isovist analysis, mathematical models like linear regression models for visual quality, visual attention modeling) (Benedikt, 1979; Enshan et al., 2025b; Schrom-Feiertag et al., 2016).
	Simulation of other abilities—like wayfinding, conducting tasks, and cognitive abilities based on large language models (Schrom-Feiertag et al., 2016; Brunnhuber et al., 2012; Kim et al., 2023; Noyman et al., 2025).

Note: The references cited in this table encompass both the literature reviewed in this chapter and additional sources from the author’s broader knowledge.

2.4.6.2 Applications of these technologies in transport or design research

As presented in the following paragraphs, studies have applied the above technologies to support transport or design research on:

- 1) user analysis (of both passengers and non-passengers),
- 2) stations’ dynamic daily operations and users’ route choices, or
- 3) assessing management or design interventions (Table 2.8).

For **user analysis**, user data typically serves as a basis, and it has been collected at the collective level using technologies like WiFi, sensors, and object-detection algorithms. These technologies monitor pedestrian presence, movements, and conditions—for example, counting pedestrian numbers, detecting crowd density, tracking trajectories, distinguishing between waiting and moving, identifying interactions between people in groups, and capturing facial expressions that indicate moods (Heuvel, 2022; Wu et al., 2020; Elhamshary et al., 2019; Loo and Fan, 2023; Pouw et al., 2024; Holder and Tapamo, 2018). The corresponding user analysis typically reveals collective user behavioral patterns. User data collection has also been conducted at the individual level through VR experiments, together with technologies like eye-tracking and electroencephalogram (EEG), supporting user analysis that reveals in-depth user psychology or decision-making mechanisms (Schneider et al., 2023; Egger, 2016;

Yang et al., 2024b; Schrom-Feiertag et al., 2016; Yang et al., 2024a,b).

Studies have addressed the monitoring of pedestrian flows (e.g., detecting crowd density and congestion), which inform decision-making in **stations' operations** (Dai et al., 2024; Pouw et al., 2024; Trivedi and Pandey, 2020; Wong and Law, 2023; Wu et al., 2020; Yasufuku and Takahashi, 2024; Zhao et al., 2022). The monitoring of the systems can provide a basis for mobile applications to inform users' decision-making of **route choices and trip scheduling** (Mayr et al. 2023; see also the application of planning users' trips to-and-from Schiphol Airport, <https://www.schiphol.nl>)

The decision-making can also be earlier informed through real-time simulation (also called 'online' simulation), as simulation provides predictions on future pedestrian flow (Yasufuku and Takahashi, 2024; Hänseler et al., 2016). The monitoring, simulation, and data exchange between real-world and digital systems is forming a trending practice of 'digital twins' (Li et al.).

Since simulation provides predictions of systems' future status, it can be used to enable the assessment of future interventions on the systems. For example, studies have applied simulation to **assess management interventions**—like adopting mobile phone apps to inform passengers (Elkhoully et al., 2023; Mayr et al., 2023).

Studies have applied simulation to **assess design interventions**. For example, studies have applied agent-based simulation to assess design schemes (Enshan et al., 2025b), design principles (Enshan et al., 2025a), and existing spatial configurations (Harding, 2019). For assessing design proposals at the design stage, a unique challenge is that the (offline) simulation should be free from the constraint of existing data, as the project is not built and existing data is lacking (Enshan et al., 2025b). In contrast, simulation on existing spatial configurations often heavily involve existing data (e.g., see Hänseler et al., 2016; Pu et al., 2022).

Notably, the inputs, outputs, and settings of different simulations are different, determined by research aims. For example, in simulations for design intervention assessment (e.g., see Enshan et al., 2025b), the inputs are designed interventions (in the form of different spatial configurations), the outputs are performances of the transport or spatial systems, and the fixed settings are agent parameters. In contrast, in model calibration studies of simulations (e.g., see Davidich and Köster, 2013), the inputs are varying agent parameters, the outputs are the agent behaviors or the model's performance, and the fixed settings are the spatial configurations.

TABLE 2.8 New technologies applied in the studies of users and interventions

Usage	Specific usage	Methods	References
Support user analysis	(<i>D&B</i>) (<i>O</i>) Monitor pedestrian presence, movements, and conditions (e.g., to count pedestrian numbers, detect crowd density, track pedestrian trajectories, and detect the status of waiting or moving), for user analysis.	User data collection at the collective level .	Heuvel 2022; Pouw et al. 2024
	(<i>D&B</i>) (<i>F</i>) Cost-effectively and safely conduct experiments, and extract detailed biometric and neurologic data, for user analysis.	User VR experiments , with user data collection at the individual level .	Schneider et al. 2023; Egger 2016; Schrom-Feiertag et al. 2016
Support stations' operations and users' route choices	(<i>D&B</i>) (<i>Q</i>) Real-time monitoring pedestrian flows to inform stations' flow management and mobility supply, or users' route choices and trip scheduling.	Conduct user data collection at the collective level, (optionally) run real-time simulations generating timely predictions of future crowd status, to inform flow management or mobility supply.	Dai et al. 2024; Trivedi and Pandey 2020; Wong and Law 2023; Wu et al. 2020; Yasufuku and Takahashi 2024; Zhao et al. 2022; Hänseler et al. 2016; Elhamshary et al. 2019
Support assessing management or design interventions	(<i>D&B</i>) (<i>Q</i>) Assess management interventions (e.g., adopting mobile phone apps that inform passengers; using partition line to split passengers according to their baggage)	Run offline simulation , with and without management interventions, and predict interventions' effects on pedestrian flows.	Mayr et al. 2023; Elkhoully et al. 2023; Fang et al. 2015
	(<i>D&B</i>) (<i>F</i>) Assess design interventions (e.g., new design proposals, different spatial configurations)	Run offline simulations to evaluate the spatial configurations' effects on pedestrian flows and user visual perceptions.	Enshan et al. 2025b,a; Harding 2019

Note: Notations for spatial scales— (*B*) = applicable at the building level, (*D*) = at the district level, (*B&D*) = applicable at both the Building and District levels.

Notations for topic relevance— (*Q*) = potentially support reducing overcrowding, (*U*) = potentially support reducing underutilization, (*F*) = potentially support increasing flexible use.

2.4.7 Limitations of flexible use solutions

Design with flexibility has been explored by architects for over a century, yet it is still marginal to the profession at large (John Habraken, 2008). Therefore, it is necessary to be mindful of the challenges or limitations of flexible use solutions. This subsection synthesizes and reports the practical challenges and limitations identified in the literature (Table 2.9), which also answer this chapter's research sub-question 4 (i.e., What limitations of flexible use solutions have been reported?). Synthesizing the

challenges and limitations in this dedicated section helps form a comprehensive picture of barriers across scales and highlights their practical relevance.

As described in the above subsections, towards flexible use, studies have addressed design measures regarding **flexible buildings, urban spaces, or cities**. These studies also pointed out multiple challenges or limitations. At the building level, for instance, [Meagher \(2014\)](#) noted that flexible buildings are typically more expensive to construct and maintain, as their mechanical components are prone to failure (Therefore, the author suggests prioritizing low-tech elements in flexible buildings). [Holden \(2019\)](#) pointed out that the radical open floor plan in the Center Pompidou, while offering flexibility, also imposes a burden on curators—they must completely rearrange the interiors for each exhibition. In promoting flexible office spaces that support dual use for living, [Katsikakis \(2017\)](#) mentioned that there is a risk of generating affordable but uncomfortable living spaces. In the case of Chesterfield House, [Madanipour \(2018\)](#) revealed that temporary use has pitfalls of perpetuating precarity and displacement for users. The multivalent practice of temporary use, driven by economic crises and neoliberal globalization, serves as a stopgap to manage empty spaces but often normalizes inequality, accelerates gentrification, and prioritizes investor gains over long-term community benefits. At the district or city levels, in envisioning 'dismantable city,' [Roggema \(2014\)](#) outlined current technical, social, and regulatory constraints; for example, in most current cases, many city elements or buildings are difficult to move or reassemble, and current land use is regulated in a fixed manner with determined uses.

Towards flexible use of space, this thesis suggested **adding non-transport activities** ([subsection 1.2.4](#)), with this chapter reviewing literature on leisure events, street markets, vending, and homeless people's sleeping rough. However, as shown or mentioned in the literature, such activities have certain limitations. First, street markets and vending may negatively influence the city's image, as they often involve selling unhealthy food, creating dirty scenes, and causing traffic problems. They usually require significant management effort from administrators or other entities ([Flock and Breitung, 2016](#); [Heathcott, 2019](#)). Similarly, homeless people sleeping rough, as the more radical type of informal use, raises even more concerns about safety for the pass-by pedestrians. The radical strategy of using vacant community spaces for homeless people to counter gentrification ([Carr and Dionisio, 2017](#)), if situated in the context of railway station areas, may be largely questionable for the same concerns. Second, flexible activities in public spaces, particularly revenue-generating ones, may result in exclusion: for example, by occupying spaces, by creating gated and paid areas, or by setting high rental prices that exclude price-sensitive space users, tenants, or event organizers ([Flock and Breitung, 2016](#); [Carr and Dionisio, 2017](#); [Madanipour, 2018](#)). Lastly, specifically for railway stations, non-transport services, such as commercial areas and kiosks, if not properly designed, can result in congestion, causing travel experience degradation. (E.g., [Ross \(2000\)](#) mentioned stations congested by kiosks paying hundreds of pounds a year in rent, despite having millions of pounds in ticket revenue; Beijing West Railway Station's egress area historically was congested by the clothing wholesale stalls ([Sinanews, 2006](#)).)

TABLE 2.9 Challenges or limitations of flexible use solutions

Category by solutions	Limitations or challenges	References
(<i>F</i>) Limitations of flexible buildings, spaces, or cities	(<i>B</i>) Mechanical components prone to damage.	Meagher 2014
	(<i>B</i>) Burden of over-flexibility for exhibition curators using the open floor plan.	Holden 2019
	(<i>B</i>) Affordable but disagreeable living space in dual-use living-and-office spaces.	Katsikakis 2017
	(<i>B</i>) Temporary use perpetuates precarity and displacement for users; the related practice normalizes inequality, accelerates gentrification, and prioritizes investor gains.	Madanipour 2018
	(<i>D</i>) 'Dismantable city' faces current technical, social, and regulatory constraints	Roggema 2014
(<i>U</i>) Challenges of adding non-transport activities	(<i>D</i>) Street vending and markets—may negatively affect the city's image; Require significant management efforts.	Flock and Breitung 2016
	(<i>D</i>) Causing exclusive use or tenancy	Flock and Breitung 2016; Carr and Dionisio 2017; Madanipour 2018
	(<i>B</i>) Significant travel experience degradation due to non-transport use	Ross 2000, p. 317? Sinanews 2006

Note: Notations for spatial scales— (*B*) = relevant at the building level, (*D*) = relevant at the district level. Notations for topic relevance— (*U*) = relevant for practice to reduces underutilization, (*F*) = relevant for practice to increases flexible use.

2.5 Knowledge gaps and future research directions

Based on the existing knowledge as presented above (section 2.4), and the broader observations during the review process, this section outlines four knowledge gaps concerning the spatial design for the flexible use of stations, including:

- 1) an explicit definition of the flexible use of stations;
- 2) knowledge of spatial layouts supporting flexible use;
- 3) integrated knowledge of transport and non-transport activities; and
- 4) design-oriented toolsets.

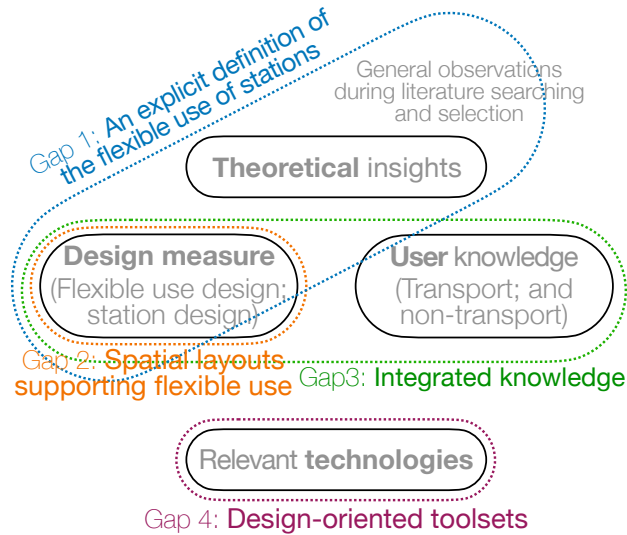


FIG. 2.10 Knowledge gaps (in colored texts) regarding existing knowledge (in gray texts). (Source: Author)

In relation to the research questions posed in this chapter, [subsection 2.5.1](#) answers sub-question 3 (i.e., What spatial content has been addressed, at what spatial scales?).

2.5.1 Spatial layouts supporting flexible use

Existing literature on design measures for flexible use has dealt mostly with elements, while barely investigating layouts ([subsection 2.4.4](#), [Table 2.4](#)), leaving a gap in knowledge on spatial layout supporting flexible use ([Figure 2.10](#), Gap 2). Elements and layouts are two key considerations in spatial design ([De Jong and Van Der Voordt, 2002](#); [Carmona et al., 2003](#); [Liu, 2020](#)). In design projects, designers typically need to first understand the basic elements and their characteristics, then organize these elements in suitable layouts. Layouts are important because they define the overall structure and spatial organization, shaping how users experience the environment at a global scale. Crucial user experiences in stations, such as user paths, transfer distances, and wayfinding, are largely determined by the station layout. For the successful implementation of flexible use in stations, which directly impacts these user experiences, a deeper understanding of layouts is essential. Therefore, this knowledge gap in station layouts needs to be addressed.

2.5.2 Knowledge integration

Regarding design measures and user knowledge, integrations are needed both within and across disciplines (Figure 2.11, Gap 3).

First, as shown by subsection 2.4.4, within the design discipline, there is design knowledge of flexible use (of non-station buildings and space), and design knowledge of stations; yet there is a lack of integrated design knowledge on the flexible use of stations (Figure 2.11-①).

Second, as shown by subsection 2.4.5, across disciplines and fields, there is knowledge of users in transport activities (developed in transport planning field), and knowledge of users in non-transport activities (developed in fields like urban design and environment psychology); yet there is a lack of integrated knowledge of users in both activities with dynamic user needs (which is relevant in the context of station flexible use) (Figure 2.11-②).

In the existing literature, studies of users in transport activities primarily focus on safety-related factors and capacities, while studies on users in non-transport activities usually investigate other higher-level user needs and spatial qualities related to leisure experience. Integrating both will facilitate a more comprehensive understanding of user needs and station design.

Third, it would be helpful if there were an integration between design measure knowledge and user knowledge, where scientific evidence on users can be substantially translated into design interventions (see Figure 2.10, the green box). Yet this integration is relatively lacking.

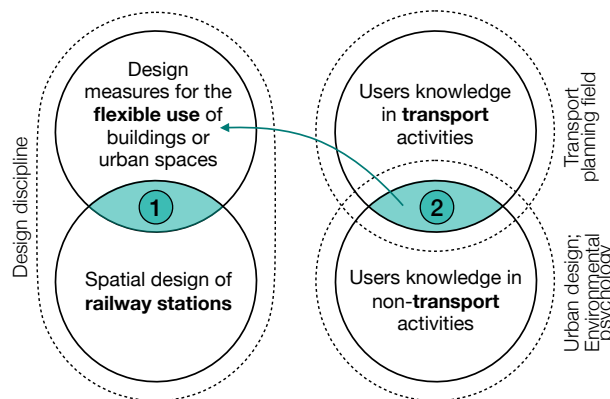


FIG. 2.11 Knowledge integrations needed. (Source: Author)

2.5.3 Design-oriented toolsets

Reflecting on the related technologies, a gap in design-oriented toolsets is identified. Stations are complex projects, involving many spatial elements in complex spatial configurations. The flexible use of stations further involves more dynamics, such as varying space uses and user needs in different scenarios during different time periods. Considering this complexity, in the design practice, technical toolsets are needed for the quantitative assessment of design proposals, enabling designers to make better-informed design decisions. However, in the existing literature, design-oriented toolsets are scarce ([Figure 2.10](#), Gap 4).

To fill the above four knowledge gaps, future research is suggested to:

- 1) develop explicit definitions of the flexible use of stations,
- 2) integrate knowledge of crowd movement and public space, and integrate knowledge of station design and flexibility design,
- 3) develop spatial layouts knowledge (see [Chapter 4](#)), and
- 4) develop design-oriented toolsets (see [Chapter 6](#)).

As an initial step toward more precise definitions, this chapter proposes the term ‘fluctuation-supportive’ to describe the flexible use aimed at reducing overcrowding and underutilization in railway stations. To maintain inclusive language, however, this term is intentionally not used widely throughout the text.

For knowledge integration and developing knowledge of spatial layout, this chapter suggests synthesizing and visualizing knowledge ([Liu, 2020](#)), with designers’ analytical drawings and practical interpretations ([Haoxiang, 2025](#)).

3 Spatial relevance

Case studies through scenario analyses

ABSTRACT The phenomena of overcrowding and underutilization (O&U) in railway station areas raise concerns about safety during peak times and waste of space during non-peak times. Preliminary observations suggest that at least two dimensions—the physical spatial configurations and social-cultural national contexts—impact the overcrowding-underutilization phenomenon. This chapter aims to systematically understand these two dimensions' influence on the O&U phenomena, providing an explanation and informing future design solutions. Acknowledging the existing literature's insufficiency in doing so, this chapter addresses the following **questions**: (1) How do spatial configurations affect the overcrowding-underutilization phenomena in railway stations, and hence, what is spatial design's potential? (2) How do national contexts affect the overcrowding-underutilization phenomena in railway stations? **Methodologically**, the chapter sets five types of scenarios—stations during disruption, peak times, non-peak times with commercial use, with leisure activities, and with leisure events, and applies these scenarios to four cases—Beijing West Railway Station (RS), Shanghai RS, and the previous and current Rotterdam Central RSs. The **results** reveal that national contexts affect O&U through distinct pathways: internal operational factors (security checks, ticketing-seating rules) directly determine spatial performance, while external factors (events, travel patterns) challenge station performance. Counterintuitively, passenger numbers alone do not explain the significant size differences between Chinese and Dutch stations. Spatial configurations, including spatial elements, layouts, and qualities, significantly affect overcrowding and underutilization.

KEYWORDS Flexible use, assumptions, urban design, architectural design, station-city integration

3.1 Introduction

As described in [Chapter 1, section 1.2](#), **overcrowding and underutilization (O&U)** phenomena happen in railway stations that have fluctuating passenger numbers or in case of railway system disruptions, raising safety concerns and wasting space resources ([subsection 1.2.2](#)). **Flexible use** is a potential solution to reduce O&U, because the word ‘flexible’ linguistically means being ‘able to change or be changed easily according to the situations.’ Within the research context of station-city integration ([section 1.1](#)), this thesis also sees flexible use as a new positive value to enrich station-city integration ([subsection 1.5.1](#)). O&U are the phenomena examined and explained in this chapter.

This chapter examines two key dimensions that affect the overcrowding-underutilization phenomena in railway stations—spatial configurations and national contexts. **Spatial configurations** refer to the relational arrangements of spaces and their connections, which give rise to patterns of accessibility, visibility, and movement ([Hillier and Hanson, 1989](#); [Hillier, 1995](#)). Rather than describing isolated spatial units, configurations capture the structural relationships between them, shaping how spaces are perceived, navigated, and used.

Based on the author’s preliminary observations, spatial configurations affect the overcrowding-underutilization phenomena ([subsection 1.2.3](#) and [subsection 1.2.4](#)). For example, comparing Beijing West Railway Station (RS) and Shanghai RS, Shanghai RS experiences less overcrowding and less underutilization with more non-transport uses—e.g., neighborhood residents dancing on the station squares in the night (observed by the author). These two stations share similarities as they are both major stations in megacities facing the same national holiday challenges, while they differ significantly in spatial configurations. Therefore, it is reasonable to attribute this performance difference to their different spatial configurations. Considering urban and architectural design (or briefly referred to as spatial design) deals with spatial configurations, it has the potential to address O&U and flexible use ([Figure 3.1](#)).

National contexts refer to overarching social, cultural, institutional, and systemic environments that differ between countries or regions. While the context itself is a broad construct that is hard to observe directly, it gives rise to specific, observable factors. National-context-associated factors across railway stations nationwide, such as ticketing, security checks, and travel patterns ([Dai et al., 2019](#)) affect station operations and spatial configurations, hence affecting the overcrowding-underutilization phenomena. For instance, security checks in Chinese stations pose a greater bottleneck effect on pedestrian flows, necessitating the design of additional spare spaces to prevent overcrowding.

On the one hand, the above insights are preliminary, as they arise from the author’s scattered experiences. On the other hand, railway stations as complex systems involve

many spatial aspects (e.g., space, elements, layouts) and non-spatial aspects (e.g., human activities, pedestrian flows, functions, operational factors), which are in complex interplays (Ross, 2000; Edwards, 1997). Given this complexity, it is necessary to systematically examine how spatial configurations and national contexts affect the overcrowding-underutilization phenomena (Figure 3.1).

In the design field, a variety of PhD theses have studied railway stations, examining different spatial aspects to achieve diverse aims. These studies successfully link spatial aspects to critical values such as transfer efficiency (Van Der Spek, 2003), economic development and urban synergy (Peter, 2002; Peek, 2006; Chorus, 2012), place quality and urban integration (Trip, 2007; Da Conceição, 2015; Du, 2023; Dai, 2015), and the architectural resolution of railway-city interfaces (Cavallo, 2008) (See also Chapter 2, subsection 2.4.4).

However, a significant gap remains. First, while these works provide a strong foundation for understanding stations as nodes or places, none explicitly address the overcrowding-underutilization phenomena or flexible use. The thesis by De Wilde (2006) on the multiple use of space is the most conceptually relevant to flexible use, yet its content focus is on structural, managerial, and financial feasibility for building over railways, leaving the causal relationship of spatial configuration on flexible use unexplored, and the national contexts and their associated factors largely untouched. Therefore, the complex interplay between national contexts, spatial configurations, and the overcrowding-underutilization phenomena constitutes the core knowledge gap this chapter aims to fill.

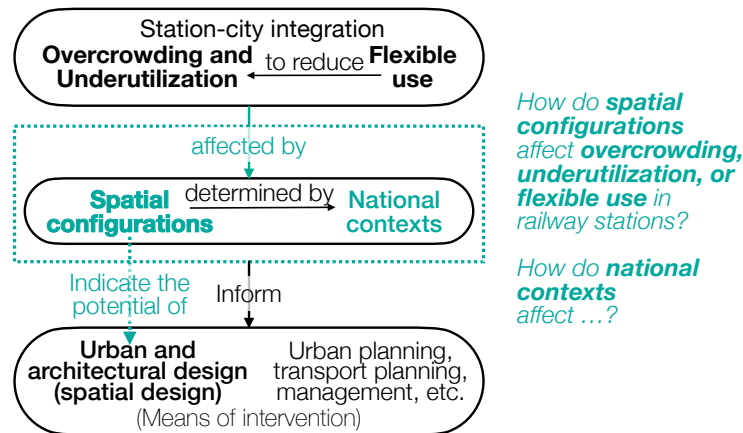


FIG. 3.1 To understand the influence of spatial configurations and national contexts. (Source: Author)

3.1.1 Research questions and contributions

In light of the above insights and knowledge limitations, this chapter adopts a descriptive and exploratory approach to map the complex, real-world station system. Following a research tradition that uses case studies (Yin, 2002) to understand relationships in complex systems (e.g., Rizal, 2007), this chapter is guided by the following research questions:

- 1) How do national contexts affect the overcrowding-underutilization phenomena in railway stations?
- 2) How do spatial configurations affect the overcrowding-underutilization phenomena in railway stations, and hence, what is spatial design's potential?

The central aim is to describe and analyze the relationships between these influencing factors and the resulting phenomena. In this chapter, the national contexts and spatial configurations of railway stations are defined in more detail as follows:

- **Spatial configurations** of railway stations: relational arrangements of spatial elements and their connections, encompassing both the physical spatial layout—the tangible arrangement of spatial elements like platforms, circulation areas, ticket sales and retail space, and station forecourt (Edwards 1997, pp. 50-83; See also the detailed listing of spatial elements in [subsubsection 1.6.4.1](#))—and physical-associated aspects, such as connectivity, flow potential, and the affordances that spaces provide for movement and interaction (Van Der Spek, 2001). Rather than describing isolated spatial components, configurations capture the structural relationships between them, shaping how spaces are perceived, navigated, and used. In this thesis, stations are analyzed at a spatial range of around 250m ([subsection 1.6.6](#)).
- **National contexts and their associated factors:** The institutional, cultural, and systemic environments that differ between countries and give rise to specific, observable factors influencing station performance. In this study, the national context (e.g., of China vs. the Netherlands) is operationalized through a set of systemic and operational factors, such as events, prevalent travel patterns, security checks (Dai et al., 2019), and ticketing processes.

This chapter conducts exploratory case studies to answer the research questions, producing descriptive knowledge as research outcomes, and it makes the following contributions:

- For designers: It provides a detailed, evidence-based explanation of how spatial configurations affect station performance, thereby confirming the significant potential of spatial design as a key intervention means for mitigating overcrowding and underutilization and supporting flexible use.
- For international practice: It elucidates how national contexts affect performance outcomes, thereby supporting the transfer of knowledge and design strategies across cases in different countries.

The remainder of this chapter is organized as follows: [section 3.2](#) describes the methodology, [section 3.3](#) presents the results, and [section 3.4](#) discusses and points out future research directions.

3.2 Methodology

The chapter conducts case studies to analyze how spatial configurations and national contexts affect the overcrowding-underutilization phenomena in stations. As illustrated in [Figure 3.2](#), four cases of railway stations are chosen, compared ([subsection 3.2.1](#)), and analyzed. The cases are tested under different scenarios (during peak and non-peak times) ([subsection 3.2.2](#)), to see their performance in supporting pedestrian flow, small user activities, and large user events. Technically, the cases are analyzed through three methods: either observe during the author's site visits, review relevant literature and website news, or hypothetically apply unseen scenarios on the case. Combining these methods provides comprehensive data sources to gain insights into both past occurrences and future possibilities ([Figure 3.3](#)). Analytical visualization is conducted to present the final results.

While this research is case studies, it also can be seen as scenario analyses, in which the settings are scenarios; the inputs are cases, their spatial configurations, and national contexts; and the outputs are (the possibility of) the phenomena of overcrowding and underutilization, which indicates the station performance. This research is also empirical research, in which the station performance variables are dependent variables, and others are independent variables ([Figure 3.2](#)).

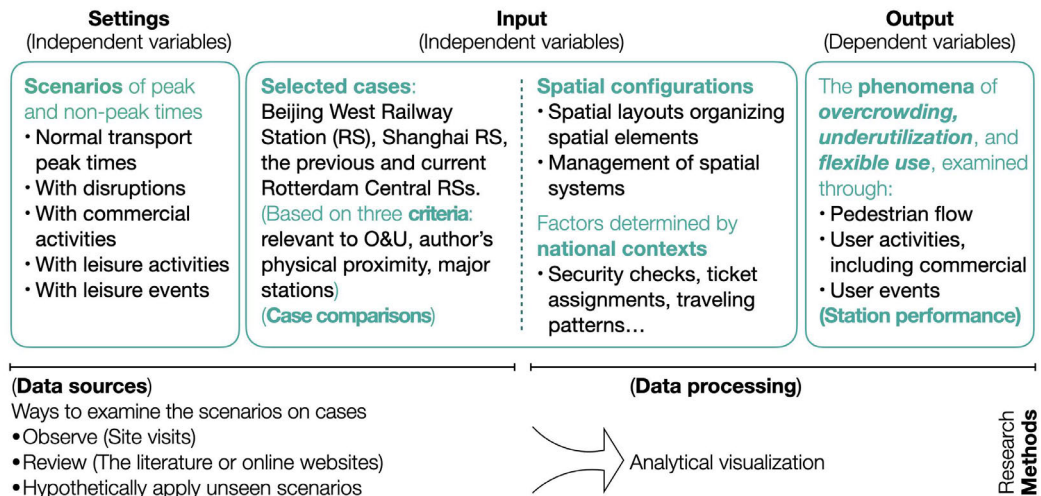


FIG. 3.2 Research methodology of this chapter. (Source: Author)

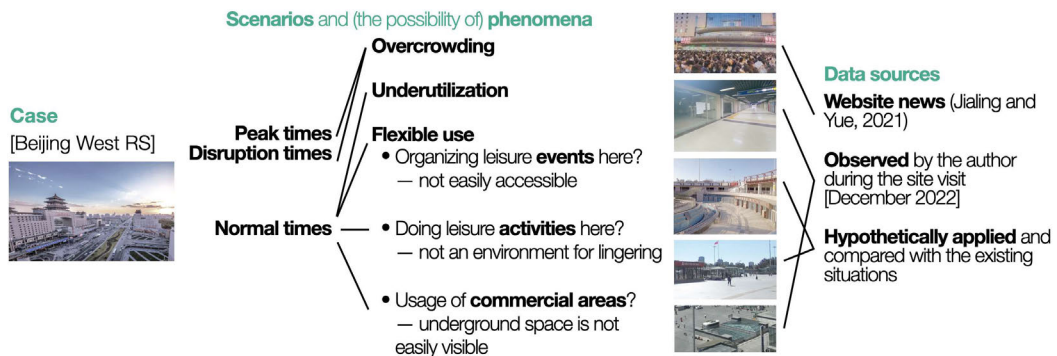


FIG. 3.3 Scenarios are observed, reviewed, or hypothetically applied to cases (using Beijing West Railway Station as an example. Source: meipian.cn, wiki.com, and photoed by the author)

The site visits include a five-day on-site observation at Beijing West Railway Station in December 2021, a five-day on-site observation at Shanghai RS also in December 2021, a site visit during the Rotterdam Summer Carnival in 2022, and frequent use of Rotterdam Central RS. The following subsections provide more details on case selection and comparisons, and the assumptions of flexible use in different scenarios.

3.2.1 Selected cases and case comparisons

This chapter selects Beijing West Railway Station (RS), Shanghai RS, the former Rotterdam Central RS, and the current Rotterdam Central RS for case studies, based on the following criteria (See also [Chapter 1, subsection 1.6.5](#)):

- The cases are either relevant to overcrowding, underutilization, or non-transport uses that are useful for reducing underutilization;
- The cases suit the author's physical proximity, allowing for site visits;
- The cases are major stations in their respective countries, enabling the findings to have a significant impact.

Beijing West RS is often seen on social media as being congested ([Jialing and Yue, 2021](#); [Bilibili, 2021](#)), and large parts of its underground commercial spaces are underutilized ([Yu, 2018](#)). In comparison, Shanghai RS is hardly seen on social media as congested or underutilized. It has a vibrant surrounding commercial environment. Its North Plaza is used by elderly people dancing during non-peak days.

The current Rotterdam Central RS has a large capacity, and congestion is not a major issue; leisure events happen on its front plaza, which reduces underutilization. In comparison, the former Rotterdam Central Station did not support leisure activities on the plaza because all transport facilities occupied it. The former station's surrounding environment was unsatisfactory due to heavy traffic ([Loukaitou-Sideris et al., 2017](#)) ([Table 3.1](#)).

TABLE 3.1 Cases selected considering their relevance with overcrowding and underutilization

Relevance ▼	Beijing West RS	Shanghai RS	The current Rotterdam Central RS	The previous Rotterdam Central RS
Relevance to overcrowding during transport peak times	Overcrowding happens from time to time	No obvious overcrowding	–	–
Relevance to (reduce) underutilization during non-peak times	Large underutilized commercial spaces	• Vibrant commercial environment; • North Plaza used by elderly people dancing during non-peak days	Leisure events on the plaza (e.g., crowd dancing during Rotterdam Summer Carnival)	No Leisure events on the plaza

The cases within the same countries provide comparisons for investigating the influence of spatial configurations. The cases in different countries provide comparisons for investigating the influence of national contexts ([Figure 3.4](#)).

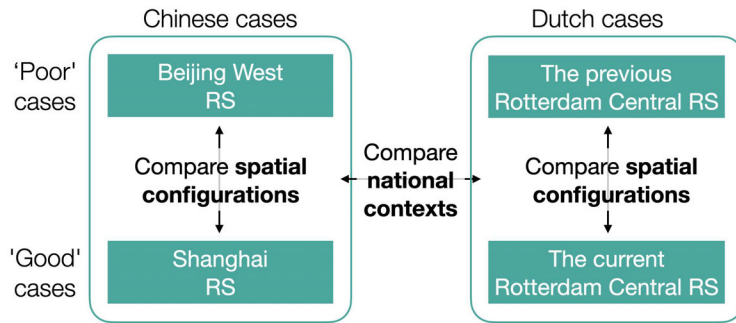


FIG. 3.4 Case comparisons planned in this chapter. (Cases are noted as 'poor' and 'good' in a relative sense: 'good' cases resolve overcrowding and underutilization and support flexible use, while 'poor' cases do not. Source: Author)

3.2.2 Assumptions of flexible use in different scenarios

This chapter makes the following assumptions about stations supporting flexible use in different scenarios. In these assumptions, words like 'can' and 'should' are used, which seem inappropriate for academic writing, but this is due to the nature of design research—Design research develops normative mean-end knowledge (Zwart and De Vries, 2016) for achieving certain goals under certain conditions, and uses words like 'can' and 'should' to suggest better future versions (Nijhuis and Bobbink, 2012).

- [Scenario 1-a] During event times when large volumes of passengers come and are delayed before bottlenecks, or [Scenario 1-b] during railway disruption times when many passengers are stranded,
[Assumption 1] stations supporting flexible use should be able to effectively use the city areas adjacent to stations, as spare space, to enlarge the capacity of accommodating passengers.
- [Scenario 2] During non-peak times when stations are underutilized,
[Assumption 2] stations should support non-transport use. This assumption is further specified into three sub-assumptions:
 - [Assumption 2-a] Stations' commercial areas should be used by leisure users (i.e., non-passengers) beyond passengers to avoid underutilization.
 - [Assumption 2-b] spaces should have spatial qualities that initiate self-motivated leisure activities (or 'optional activities' as noted by Gehl 1987)—e.g., wandering in the station areas, enjoying outdoor dining—to avoid being underutilized.
 - [Assumption 2-c] It should be possible to organize leisure events (e.g., open markets, air music concerts, dancing) in underutilized spaces to enliven the spaces.

Assumptions 2-a, 2-b, and 2-c all relate to non-transport uses of stations, differing in

usage duration and space requirements. Commercial and leisure activities (e.g., dining, wandering) use space for extended periods, resulting in higher usage rates, while leisure events (e.g., markets, concerts) require significant preparation and are less frequent, leading to lower usage rates. Commercial and leisure activities can occur in smaller spaces, while leisure events need larger, coherent areas. Despite events typically requiring larger spaces and resulting in low space utilization, they remain an important part of diverse city life. Combining all the above assumptions allows for a more comprehensive investigation of station cases.

This chapter examines the assumptions (embedded in scenarios) on the selected cases in three ways: through site visits, reviews of literature, online websites, or hypothesizing. Some scenarios in certain cases are directly observable (e.g., Youtubers' dancing activities on the plaza of Rotterdam Central RS during non-peak times); some scenarios are documented in literature or on news websites (e.g., an event of crowd dancing in front of Rotterdam Central RS during Summer Festival in 2022); Other scenarios are hypothetical (e.g., hypothetically organizing a square dancing on the square of Beijing West RS). Testing hypothetical scenarios is a practice in which design has an advantage ([Zevenbergen et al., 2024](#)). All observations, reviews, and scenario hypothesizing are processed using analytical visualization.

The scenarios and assumptions are employed as analytical instruments in this chapter. According to [De Jong and Van Der Voordt \(2002, p. 258\)](#), a scenario is 'the description of a possible future, partly designed, that corresponds partly to prognoses and perspectives.' Therefore, it integrates existing phenomena and intended futures—and not only the futures that are possibly to spontaneously happen, but also the futures that are actively driven by policies or intentions (In this research, the intention is to promote flexible use). An assumption here is a normative proposition about a desired use that a station's performance should fulfill. These assumptions are treated as logically valid premises for this design-oriented analysis. This approach is methodologically analogous to simulation, where simplifying assumptions are necessary to model a complex system (e.g., see the assumptions used in studies by [Marzouk and Mohamed 2019](#); [Hassannayebi et al. 2020](#)). Assumptions do not claim universal applicability; specific contexts, such as stringent safety requirements, may override assumptions of flexible use. Notably, assumptions are not hypotheses to be statistically tested for truth or falsehood. Instead, they are design criteria used to evaluate and understand how different spatial configurations can support the goal of flexible use under varied conditions.

3.3 Results

This section presents the research results. The first five subsections combined reveal how the phenomena of O&U or flexible use are affected by complex aspects, including national contexts, national-context-associated factors, and spatial configurations. The first five subsections serve as the basis for the sixth subsection, and the first six subsections serve as the basis for the seventh subsection (Figure 3.5).

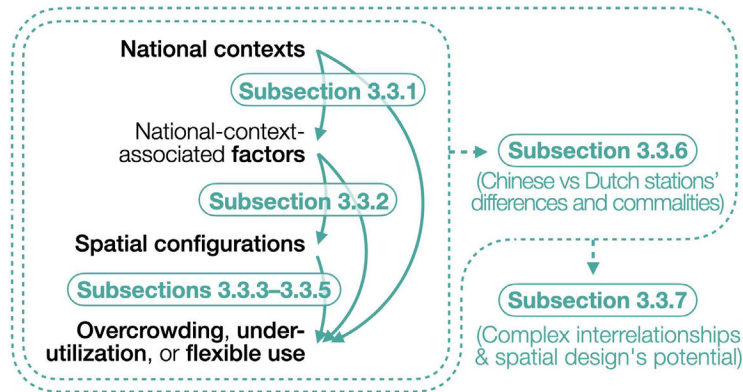


FIG. 3.5 The underlying logic of organizing subsections in this section. (Source: Author)

More specifically, [subsection 3.3.1](#) reveals multiple factors associated with national contexts, and how they affect overcrowding and underutilization (O&U); [subsection 3.3.2](#) explains how these factors affect spatial configurations, which, in turn, influence O&U; [subsection 3.3.3](#) explains how spatial configurations affect overcrowding, at a detailed level with case examples; [subsection 3.3.4](#) explains how spatial configurations affect flexible use that reduces underutilization, at a detailed level with case examples; [subsection 3.3.5](#) synthesizes the spatial configurations' influence on overcrowding and underutilization, at an abstract level. [subsection 3.3.6](#) outlines the differences and commonalities between Chinese and Dutch stations; and [subsection 3.3.7](#) synthesizes the complex interrelationships and highlights spatial design's potential.

3.3.1 National contexts' influence on overcrowding and underutilization

Several factors, associated with national contexts, affect stations, including events, passenger numbers, security checks, ticketing-seating rules, and travel patterns. The

following paragraphs explain how overcrowding and underutilization in stations are affected by these factors, and why these factors are hard to change, as they typically relate to broader social contexts.

First, **events**—such as national holidays in China, or sports matches and King’s Day in the Netherlands—challenge railway station in terms of overcrowding. During event times, large numbers of passengers come to railway stations, potentially resulting in overcrowding. In China, the most extreme event affecting stations is the Chinese New Year, during which stations are challenged by massive numbers of passengers traveling to or from their hometowns (Mccarthy, 2018). It is a cultural tradition for Chinese people to return home during the Chinese New Year, and long-distance travel occurs due to the uneven distribution of jobs between cities (where people work) and rural areas (where many people’s hometowns are). Therefore, it is hardly possible to change this recurring pattern of surging passengers during the Chinese New Year solely to reduce station overcrowding; instead, it presents a contextual challenge that tests stations’ capacity and operational resilience. In the Netherlands, events such as large football matches, concerts, or a combination of these, as well as King’s Day, create surges in the number of passengers, similarly challenging certain stations’ capacity and operational resilience (Aseniya, 2019; Times, 2015).

Second, **security checks, ticketing-seating rules, and travel patterns (e.g., long-distance travel on a monthly or yearly basis, lack of traveling experience, irregular trains causing long wait)** affect stations in terms of overcrowding. In the Netherlands nowadays, most passengers simply check in and out using their OV-chipcard, take any one of the relevant trains towards their destinations, and travel without assigned seats; many people take trains on a daily basis, for relatively short-distance travel. In China (and in Europe, international high-speed railway services like Eurostar running between London to Paris), the check-in process in railway stations is similar to that of airports, with security and ticket checks that causes longer waiting times (Chen and Wei, 2013); each ticket is tied to a specific train and assigned seat, so passengers tend to come to stations early to avoid missing their scheduled trains, results longer waiting time and quire more waiting area; Chinese railway passengers typically use the railway for long-distance traveling, often carrying large luggage, and are less familiar with the travel processes as they use the railway on a monthly or yearly basis. The combination of strict security checks, early arriving passengers due to rigid ticketing-seating rules, and inexperienced passengers with bulky luggage decreases the efficiency of the passenger transfer processes in Chinese stations, potentially increasing overcrowding. Historically, Dutch stations also featured large waiting areas to accommodate travelers who often had to wait days for irregular trains to arrive.

Preventing overcrowding during peak times necessitates stations to be designed with generous capacities, which often become underutilized during non-peak times. Therefore, overcrowding and underutilization are closely related. The very factors described above that affect overcrowding also affect underutilization, through the same mechanism.

Reflecting on these factors, they differ in how they relate to and express national

contexts. Events and travel patterns (i.e., long-distance travel on a monthly or yearly basis, lack of traveling experience, irregular trains causing longer wait) function as **external factors** to stations: they originate from broader mobility systems and socio-cultural norms, and test stations' capacity to accommodate temporary surges in passengers, rather than directly altering stations' internal performance mechanisms. In contrast, security checks, and ticketing-seating rules are **internal operational factors**. These are embedded in institutional and systemic settings that directly shape how passengers move, wait, and use space within stations, thereby exerting a more immediate influence on station performance. This differentiation resonates with Da Conceição (2015, p. 33), who distinguishes between internal and external influences on station functioning. These external and internal factors either directly affect station performance or influence the design of stations that, in turn, influence how effectively stations address overcrowding and underutilization, or support flexible use (Figure 3.6).

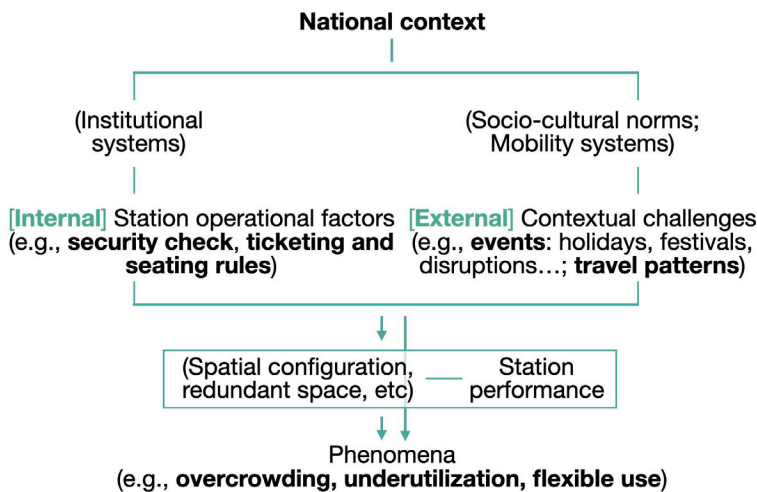


FIG. 3.6 National contexts' influence on overcrowding and underutilization. (Source: Author)

3.3.2 National-context-associated factors' influence on spatial configurations

The above subsection reveals several factors associated with national contexts—events, passenger numbers, security checks, ticketing-seating rules, and travel patterns. This subsection further analyzes how these factors affect spatial configurations, which, in turn, influence overcrowding and underutilization. The analysis follows abductive reasoning (Cross, 1990), and treats pedestrian flow as the primary focus. The analysis resulted in two illustrative diagrams—Figure 3.7 and Figure 3.8. Three key analytical concepts are employed to guide the analysis. These

concepts—circulation space, bottlenecks, and spare spaces—are defined below.

Circulation space denotes any physical area through which pedestrians move, such as halls, corridors, platforms, and squares (Designing Building, n.d.), whose geometry affects pedestrian flow and bottleneck formation (Liao et al., 2014; Li et al., 2022a).

Bottlenecks refer to locations with reduced capacity to process pedestrian flow and can cause congestion (Schadschneider et al., 2012, p. 4). Finally, in this thesis, **spare space** denotes additional area in stations designed to accommodate excess pedestrian flow during peak times, and it is additional to what is required for ordinary use. It is also logical to call it '**redundant space**' because during non-peak times, this space is underutilized, presenting redundancy.

Notably, overcrowding—and in its most extreme form, stampedes—is a complex phenomenon influenced by factors beyond the physical spaces, such as crowd behavior and psychology (e.g., people tend to concentrate in certain areas and do not redistribute themselves automatically for fear of missing trains), as well as managerial interventions (e.g., on-site personnel guiding the crowd) (Almeida and Schreeb, 2019). Nevertheless, this study focuses on circulation space and spare space, as they are prerequisites for accommodating pedestrians and preventing overcrowding.

Figure 3.7 is a basic diagram illustrating the relationship between spatial configurations and national-context-associated factors. In stations, pedestrians' transfer journeys can be seen as moving from origins to destinations. Along the journey, the pedestrians pass through various **circulation spaces**, such as pedestrian squares, passages, tunnels, paths, footbridges, etc.

If any of these circulation spaces, or facilities within them, have insufficient capacity to process the passenger flow, they act as **bottlenecks** (e.g., gates for **security and ticket checks** often present bottlenecks in stations). Adding **spare space** is a direct solution to increase the capacity of accommodating stranded passengers before bottlenecks to prevent overcrowding. However, spare space is typically underutilized during non-peak times.

More spare space is needed if bottlenecks become more significant, capacities at destinations drastically decrease (e.g., due to **railway disruptions**, no running trains accepting passengers), or travel demands at origins drastically increase (e.g., due to **events** like the Chinese New Year, massive numbers of Chinese passengers come to the stations). However, increasing spare space also raises the risk of underutilization.

The basic pattern of passengers moving from origins to destinations influenced by bottlenecks and spare spaces (Figure 3.7) appears repeatedly, in its variant forms, in stations, as illustrated in Figure 3.8. During a journey, a passenger repeatedly moves from one point (origin) to the next point (destination), such as from a bus station to the railway station, from a building entrance to an exit, from a hall to a train; the bottlenecks can be gates, stairs, or narrow passages; the spare spaces can be station squares, halls, platforms, or other spaces.

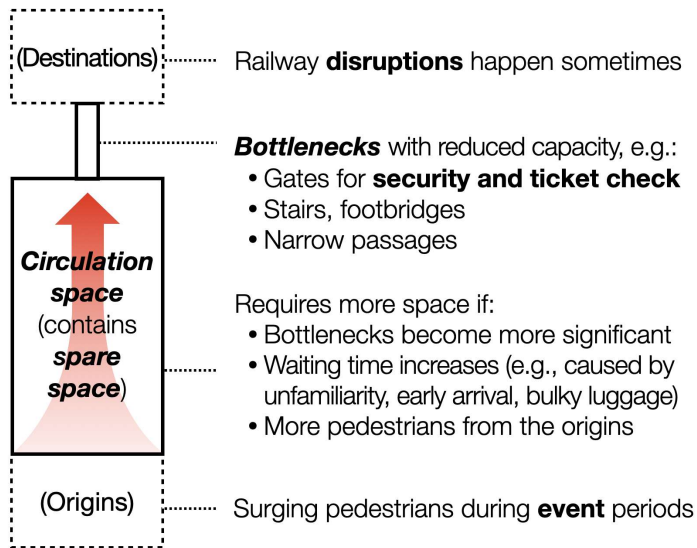


FIG. 3.7 A conceptual basic unit of passenger flow. (Source: Author)

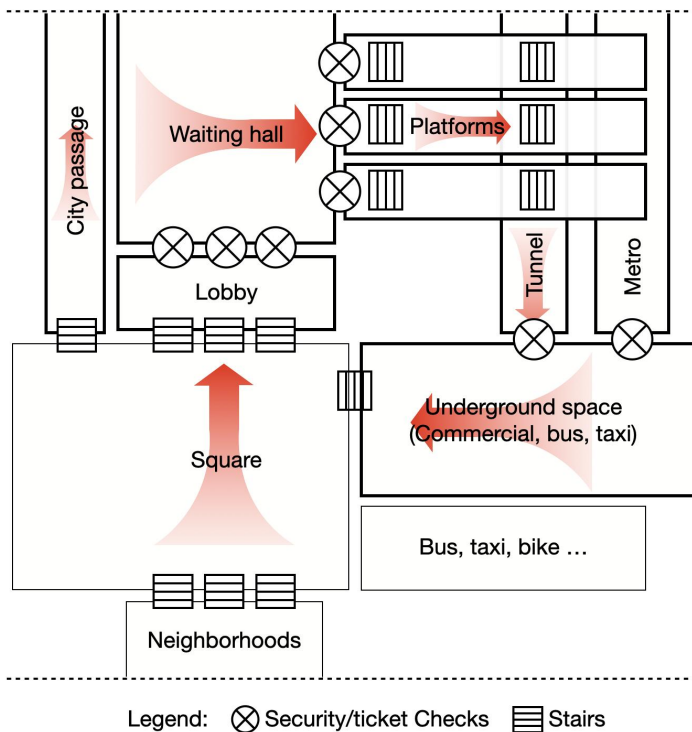


FIG. 3.8 A topological mapping of the spatial configuration of Beijing West Railway Station. (Source: Author)

3.3.3 Spatial configurations' influence on overcrowding

[Scenario 1-a] During event times when large volumes of passengers are coming and delayed before bottlenecks, or [Scenario 1-b] during railway disruption times when many passengers are stranded, [Assumption 1] stations should be able to effectively use the adjacent city areas, as spare space, to enlarge their capacity in accommodating passengers (subsection 3.2.2). Case analyses show the influence of the following spatial aspects: **stations' connections with neighboring city districts, and elements potentially forming barriers to the pedestrian flow** (Table 3.2, row 1).

In the current Rotterdam Central Railway Station (RS) case, the station plaza is connected to the adjacent city areas through pedestrian-friendly walkable paths (Figure 3.10-①), enabling the station to effectively utilize the neighboring plaza to accommodate delayed or stranded passengers during peak or disruption times. This potential of effectively using the neighboring plaza was indicated by a similar real-world scenario—during the opening ceremony of the current station, people accumulated all across the station plaza (Figure 3.10-②) and expanded to the neighboring plaza in the adjacent area. In comparison, the previous Rotterdam Central RS was physically isolated from the neighboring areas by a fast road acting as a barrier, rendering it unable to utilize the neighboring areas for passenger buffering (Figure 3.15-①).

In the Shanghai RS case, a neighboring city pedestrian street on the north side is connected to the main station square by a zebra crossing, enabling easy pedestrian movement (Figure 3.16); consequently, this street can serve as a spare space for accommodating pedestrians. In comparison, in the Beijing West RS case, the station is isolated from adjacent city areas by arterial roads acting as barriers (Figure 3.18). On the north side, although neighboring sunken plazas exist, their connections to the main station plazas are weak: passengers must navigate to either footbridges or underground tunnels, whose presence is hard to notice. Consequently, the neighboring sunken plazas do not serve as spare space for the station for peak time use (Figure 3.19).

3.3.4 Spatial configurations' influence on non-transport uses

3.3.4.1 Spatial configurations' influence on the use of commercial areas

[Scenario 2] During non-peak times when stations are underutilized, [Assumption 2-a] stations' commercial areas should be used by leisure users (i.e., non-passengers) beyond passengers to avoid underutilization (subsection 3.2.2). Case analyses show the influence of the following spatial aspects: **stations' connections with neighboring city districts, commercial areas' relative locations to gated zones that affect accessibility, spatial layouts that affect commercial areas' visibility, and bike**

parking that affect station areas' accessibility (Table 3.2, row 2-a).

In the current Rotterdam Central Railway Station (RS) case, the station and its neighboring city districts are well connected at the street level, thanks to the previous traffic-intensive road being submerged into the underground tunnel. Neighboring residents can easily walk or cycle to the station, visiting its stores located outside the gated zones. If having railway chip cards, users can go inside the gated zone for free within 30 minutes to explore more stores (Figure 3.11). In comparison, in the previous Rotterdam Central RS case, to visit the stores in the station, neighboring residents need to take detours and cross a traffic-intensive road, which is not pleasant to do for those with leisure purposes (Figure 3.12).

In the Shanghai RS case, most stores are located at the front of the station building and outside the gated zones, so they are accessible to both passengers with train tickets and non-passengers without tickets (Figure 3.17). In the Beijing West RS case, a substantial number of stores are located within the ticketed area, accessible only to passengers with tickets. Additionally, numerous stores are situated in the underground spaces on both the south and north sides of the station, which are hardly noticeable unless one ventures downstairs (Figure 3.21). In the South Station Plaza, two atriums above the underground commercial areas are designed like equipment facilities, making the expansive commercial spaces below almost invisible to passersby on the plaza (Figure 3.19 and Figure 3.21-⑤). Access to these stores is also challenging for residents from the neighboring city districts: the south side lacks clear walking paths, and the north side relies on footbridges or tunnels (Figure 3.18). Furthermore, there is no designated bike parking, making cycling impractical. Commercial shared bikes were discarded haphazardly in the station area.

3.3.4.2 Spatial configurations' influence on leisure activities

[Scenario 2] During non-peak times when stations are underutilized, [Assumption 2-b] spaces should have spatial qualities that initiate self-motivated leisure activities—e.g., wandering in the station areas, enjoying outdoor dining—to avoid being underutilized. Case analyses show the influence of the following spatial aspects: ***spaces of human scale, mobility sites' constellation that reduces negative influence on human perception, traffic elements' arrangement that reduces negative influence on human perception, and stations' connections with neighboring city districts*** (Table 3.2, row 2-b).

In the current Rotterdam Central Railway Station (RS) case, it is comfortable to hang around on the plaza, in the weather-protected gray spaces under the large roof, and inside the building. The human-oriented environment supports staying. The plaza is covered with red marble tile, extending to the station hall. When the weather is fine, many people sit idle on the grass areas' edges that are designed for seating (Figure 3.10-③), and various activities happen, such as social media video creators

dancing using the station as a background. The station is designed proportionally according to its neighborhoods' characteristics—the south side is grand, showing itself as a gateway for the high-rise urban center; the north side is designed in a humble manner, aligning with southern historical districts (ArchDaily, 2015). There are also installations and exhibitions held in the station hall from time to time. In comparison, the previous Rotterdam Central RS, according to Peters and Tolckoff (2016, p. 88), was 'architecturally drab,' not easy to find from the city center, and had its' plaza cluttered with vehicles (Figure 3.15).

In the Beijing West RS case, the main station building, its many sub-buildings, and its spaces are so large that they are out of human scale (e.g., the south facade is 720m long). The huge dimension of buildings and spaces makes walking experiences lengthy and boring, as experienced by the author. Many underutilized underground spaces are shabby and dark due to a lack of maintenance. The ubiquitous facilities on the south plaza and the massive traffic roundabouts on the north plaza constantly remind people that this is a space designed for transit, not for lingering Figure 3.19. In comparison, the Shanghai RS is more favorable for leisure users. The station is huge, but its size is comparable to normal buildings in Shanghai city. The station plazas are large and underutilized during non-peak time, with trees surrounding the edges. So generally, as experienced by the author, it is fine and also a bit boring to stay on the plazas as a leisure user. During the night, the north plaza is used by elderly people dancing Figure 3.16-②. Of note, it is not fair to directly compare user experiences between Dutch and Chinese cases, as typical users from each country may have different traits, such as beauty perceptions, and degree of traffic tolerances when walking from the neighborhoods to stations.

3.3.4.3 Spatial configurations' influence on leisure events

[Scenario 2] During non-peak times when stations are underutilized, [Assumption 2-c] It should be possible to organize leisure events (e.g., open markets, air music concerts, dancing) in underutilized spaces to enliven the spaces. Case analyses show the influence of the following spatial aspects: **coherent large spaces as event venues, and alignment between paths and event venues** (Table 3.2, row 2-c).

In the previous Rotterdam Central Railway Station (RS), the plaza was full of vehicles and not available for any leisure events (Figure 3.15). In comparison, in the current Rotterdam Central RS case, leisure events like dancing and promotions happen on the station plaza. This is possible thanks to the new spatial layout (or composition, Van Der Spek 2001) of the transport facilities—the bus and tram stations have been relocated to the plaza's side areas, the main car parking and the main bike garage have been placed underground, and the tram lines are simplified with reduced tram platforms (Peters and Tolckoff 2016, p. 88; Figure 3.11).

In the Beijing West RS case, large leisure events are not well supported by the station

configuration: The south plaza has many traffic facilities, leaving no coherent space for large events; the south sunken plaza is surrounded by road traffic, not favorable for leisure events; the north plaza is relatively small, and its core area is intensively crossed by walking passengers; although the north sunken plaza is the most suitable space regarding physical features, if hypothetically adding events there, the events will be invisible to the majority of people. In the Shanghai RS case, although no leisure events have been held to the author's knowledge, if such events were to be organized on the station plaza, most people would notice and could easily participate.

TABLE 3.2 Findings of case studies through scenario analyses

Assumptions (in different scenarios) ▼	The current Rotterdam Central RS	The previous Rotterdam Central RS	Beijing West RS	Shanghai RS	Relevant spatial aspects
1. To accommodate delayed or stranded passengers during peak or disruption times	• Large plaza. • Smooth connections, possible to use neighboring plaza	• Plaza for vehicles, people could not use it	• Sunken plazas are underutilized, hardly helpful due to weak connections with main plazas	• Large plazas	• Spare space as pedestrian plazas; • Stations' connections with neighboring city districts
2-a. To let commercial areas be used also by non-transport users during non-peak times	• Easy walk to come. • Stores outside the gated zone—accessible to all; inside the gated zone—only accessible with railway chip cards.	• Take detours and cross traffic-intensive roads to come. • Stores were accessible to all.	• By footbridges or underground tunnels to come. • Atriums' roofs block visibility, hardly noticeable underground commercial areas; stores inside gated zones—only for passengers with tickets. • No bike parking	• Easy walk to come. • Commercial stores at the front, accessible to all.	• Stations' connections with neighboring city districts; • Commercial areas' relative locations to gated zones that affect accessibility; • Bike parking that affect station areas' accessibility; • Spatial layouts that affect commercial areas' visibility

Continued on next page

Assumptions (in different scenarios) ▼	The current Rotterdam Central RS	The previous Rotterdam Central RS	Beijing West RS	Shanghai RS	Relevant spatial aspects
2-b. To motivate leisure users to have leisure activities during non-peak times	• Comfort plaza, materials, roof, edges for seating • Building resembles environments, the hall has exhibitions sometimes • Grass areas' edges serve for seating	• Traffic elements dominate plazas, spaces for vehicles, not for people.	• Huge spaces and buildings, out of human scale, traffic elements dominate plazas, for passing, not for staying.	• Size comparable with city buildings; large plazas, mostly underutilized, with trees surrounding the edges.	• Spaces of human scale; • Traffic elements' arrangement that reduces negative influence on human perception; • Stations' connections with neighboring city districts; • Elements potentially forming barriers to the pedestrian flow; • Seating
2-c. To organize leisure events to enliven spaces during non-peak times	• Station plaza for large events, thanks to the new constellation of mobility nodes	• [Not possible]	• Main plazas, not possible for events; sunken plazas, possible, but invisible.	• Plazas are possible for large events, visible	• Coherent large spaces as event venues; • Mobility sites' constellation that reduces negative influence on human perception; • Alignment between paths and event venues

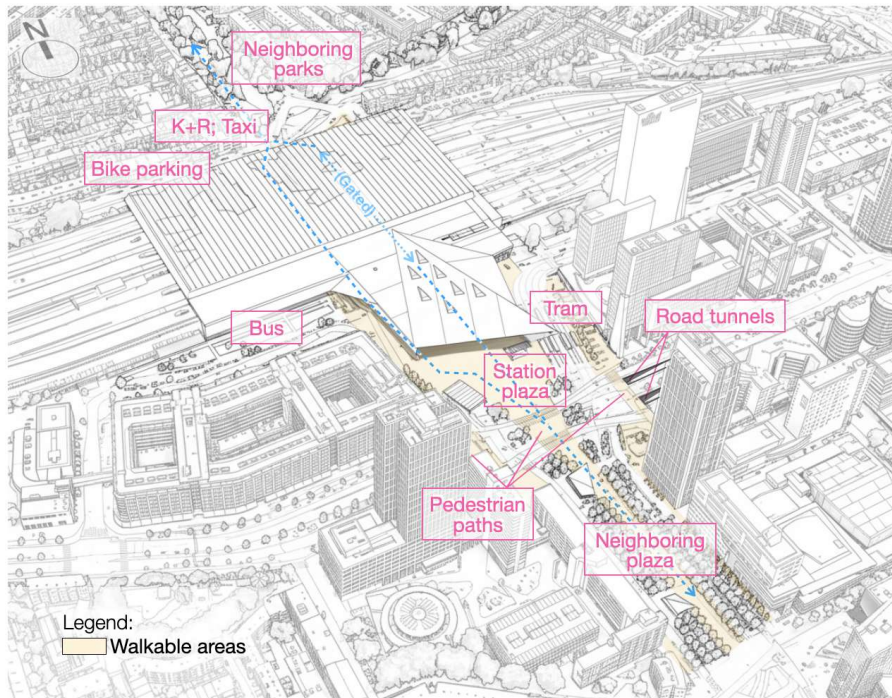


FIG. 3.9 Birdview of the current Rotterdam Central RS (on the district level). (Source: Author)

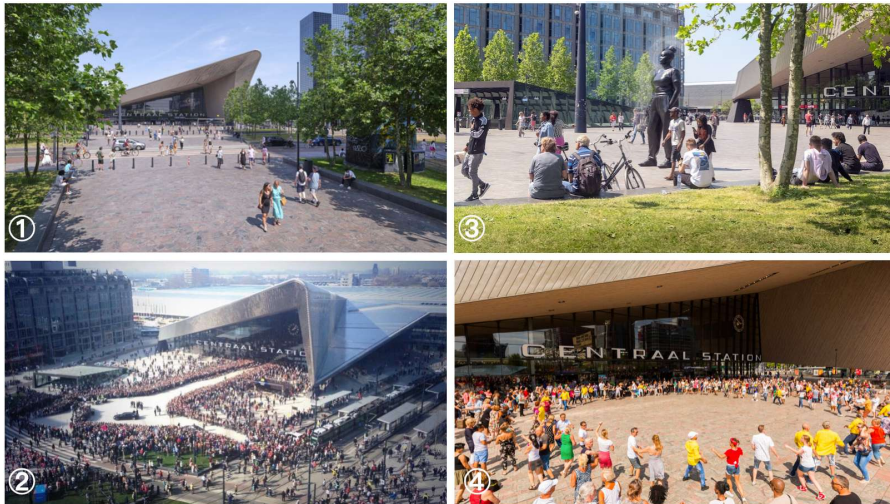


FIG. 3.10 Human-oriented spaces of the current Rotterdam Central RS. [Event in the 2nd image—the station opening ceremony. Event in the 4th photo—Rotterdam Summer Festival. Both events are formally organized.] (Source: up-left and down-left—west8.com; up-right—dutchnews.nl; down-right—Tropicaliente.nl)

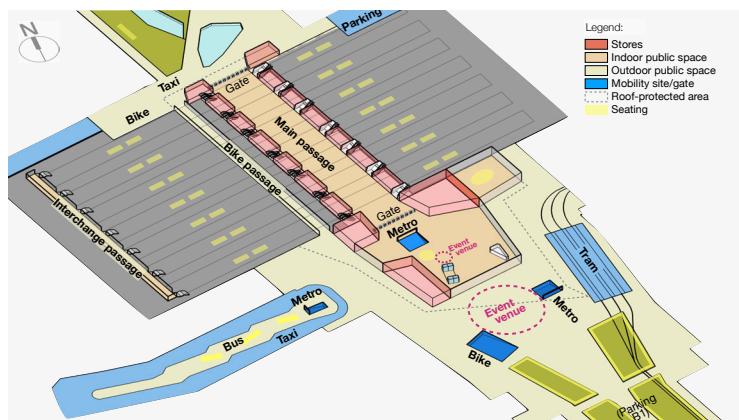


FIG. 3.11 The current Rotterdam Central RS (on the building level). (Source: Author)

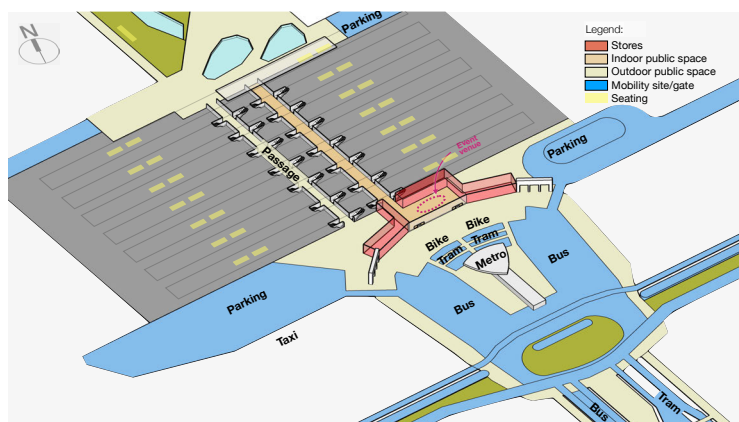


FIG. 3.12 The previous Rotterdam Central RS (on the building level). (Source: Author)

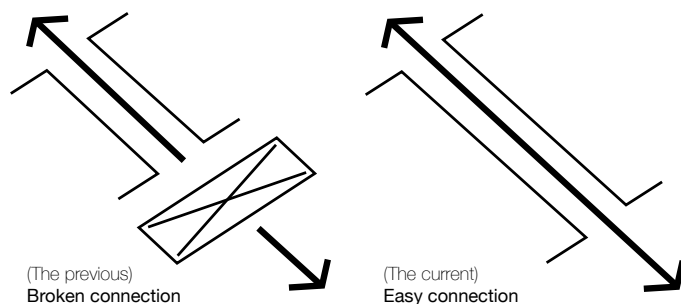


FIG. 3.13 The neighborhood connections of the previous and current Rotterdam Central RSs. (Source: Author)

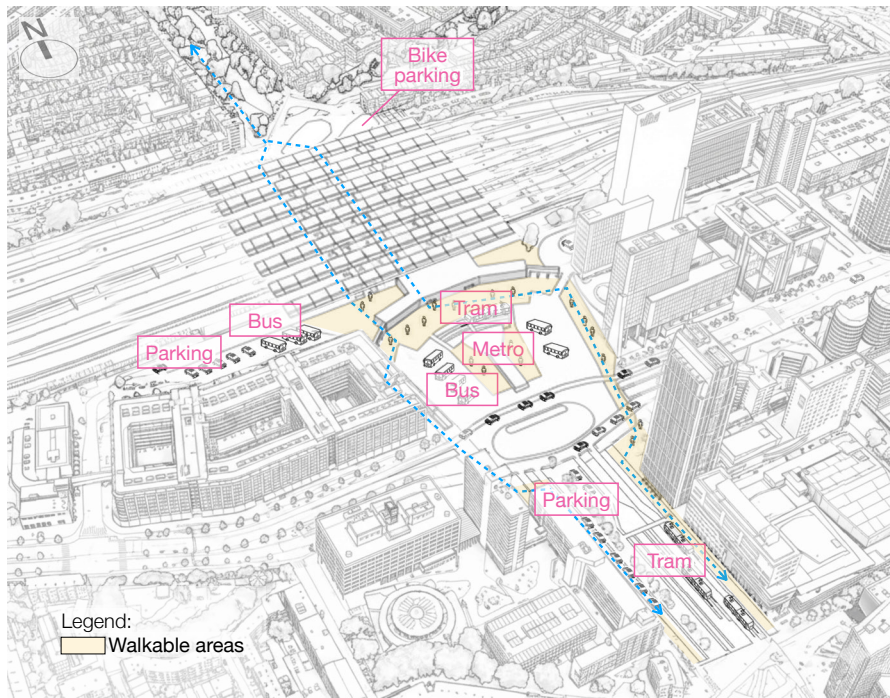


FIG. 3.14 The previous Rotterdam Central RS (on the district level). (Source: Author)

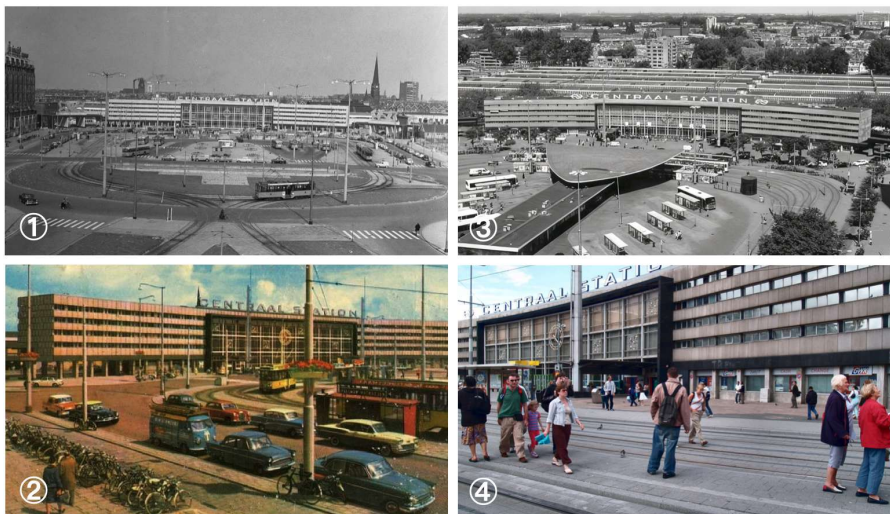


FIG. 3.15 Traffic-oriented spaces of the previous Rotterdam Central RS (Source: Up-left—commons.wikimedia.org; Down-left—fotos.serc.nl; Up-right—fotos.serc.nl; Down-right—commons.wikimedia.org)

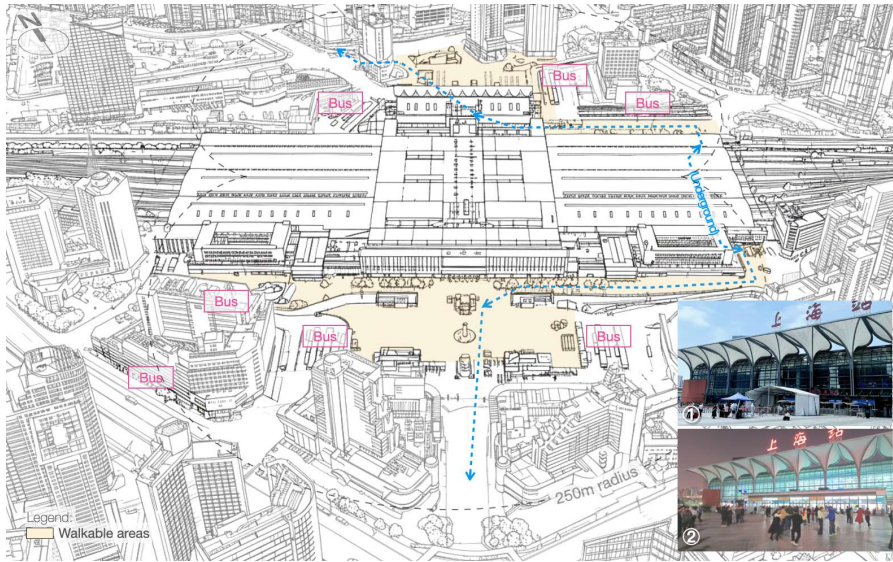


FIG. 3.16 Birdview of Shanghai RS (district level). (Source: Up—douyin.com; Down—photoed by the author)

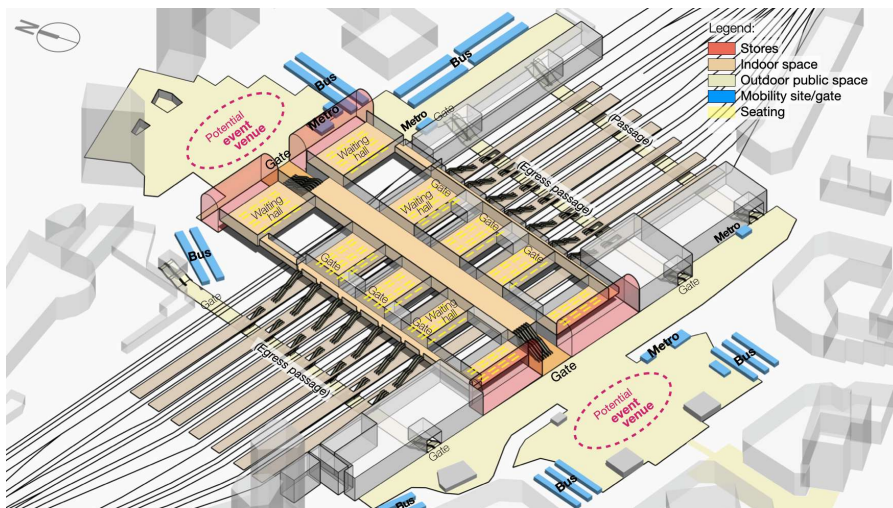


FIG. 3.17 Shanghai RS (on the building level). (Source: Author)

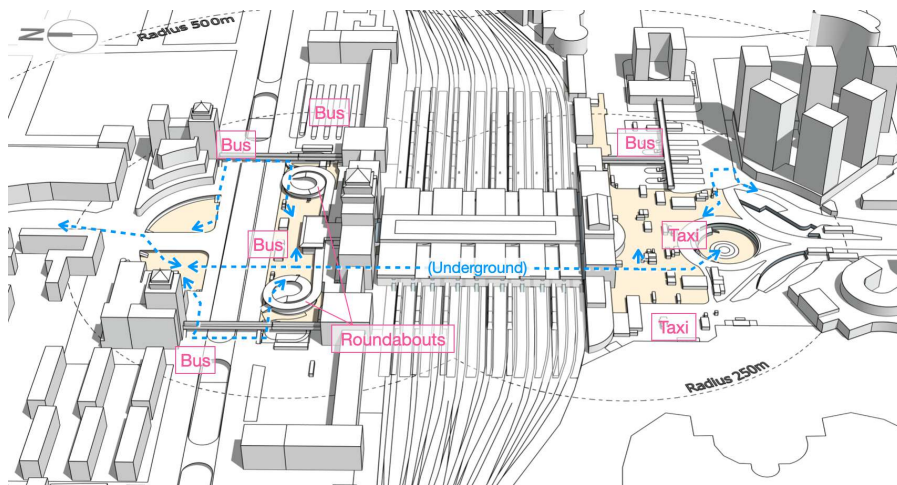


FIG. 3.18 Bird view of Beijing West RS (on the district level). (Source: Author)

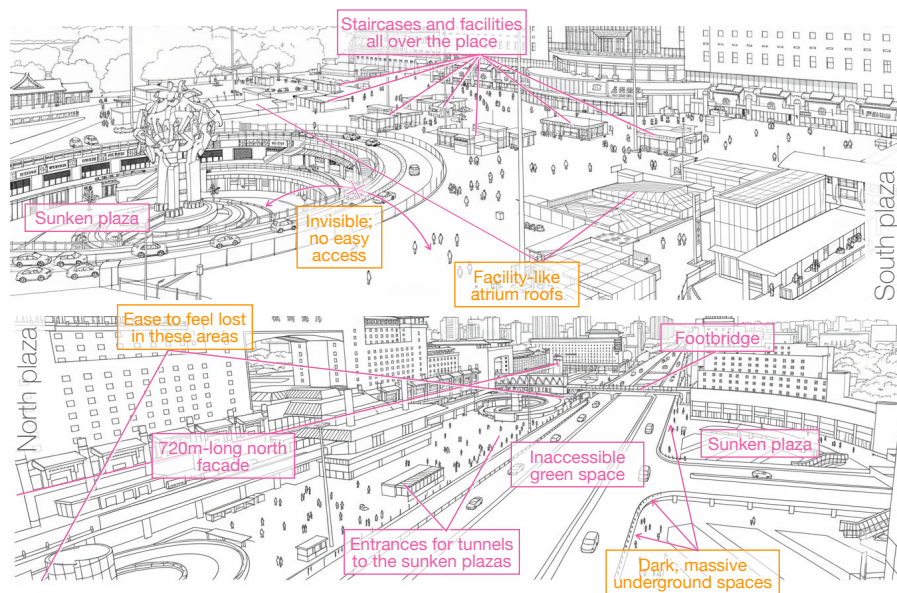


FIG. 3.19 The south and north plazas of Beijing West RS (Source: Author. Note: Texts in pink are descriptions based on observable facts, while texts in orange involve the author's personal experiences and judgments.)

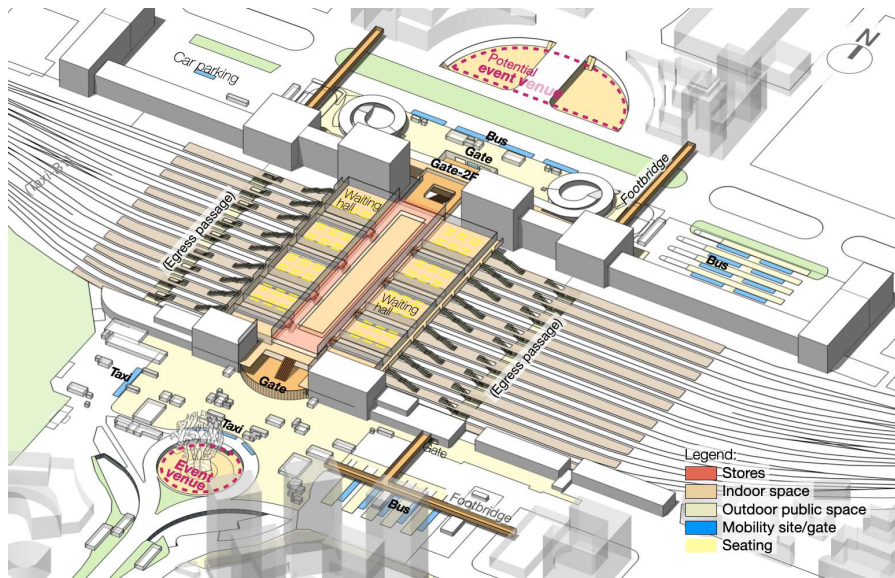


FIG. 3.20 Beijing West RS (on the building level). (Source: Author)

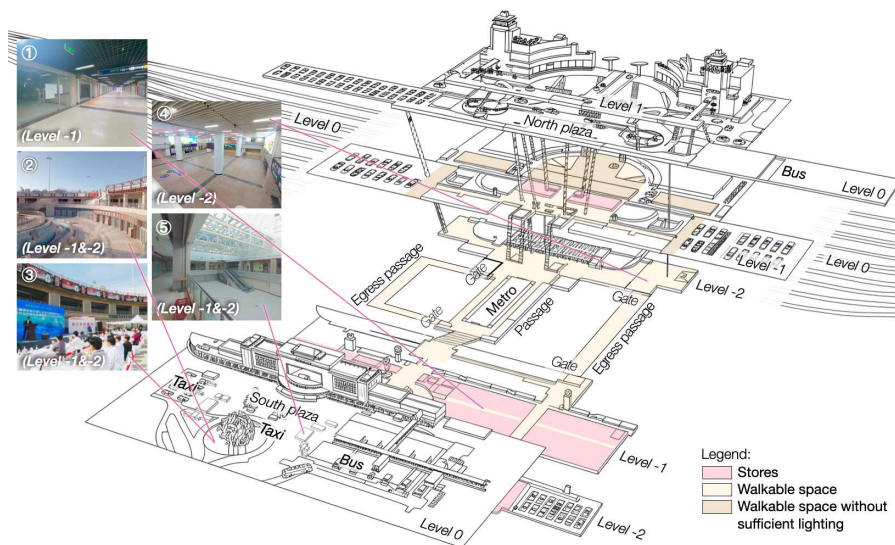


FIG. 3.21 Beijing West RS (building level) with underground floors (Source: Down-left—m.thepaper.cn; Others—photoed by the author)

3.3.5 Synthesize spatial configurations' influence on overcrowding and underutilization

As described in detail by [subsection 3.3.3](#) and [subsection 3.3.4](#), **spatial configurations** affect how pedestrian flows are distributed and managed within stations, thereby affecting both overcrowding and underutilization (See also [Figure 3.23](#)). The following paragraphs synthesize the findings, highlighting spatial configurations across two major aspects: spatial **layouts, elements, and qualities** (See the table embedded in [Figure 3.23](#)).

Spatial layouts affect the overcrowding-underutilization phenomena in stations. The case analyses reveal that the overall arrangement of spaces, paths, and functional zones fundamentally shapes how stations perform under different scenarios. **Stations' connections with neighboring city districts** are crucial, as they are associated with use during peak and non-peak times—strong connections enabling stations to use neighboring city districts' space as spare spaces during peak time, and enabling residents to come to and visit stations' stores or have leisure activities during non-peak time. The comparison between the previous and current Rotterdam Central stations demonstrates how submerging a traffic-intensive road transformed a barrier into a seamless connection, significantly enhancing the station's capacity to handle overflow during disruptions and attracting leisure visitors during quiet periods.

Commercial areas' relative locations to gated zones that affect accessibility, directly influences whether non-passengers can easily access station amenities. When commercial areas are placed outside gated zones and connected to city streets with clear, pleasant paths, as in Shanghai RS and the current Rotterdam Central RS, they become natural extensions of urban commercial environments. Conversely, when stores are hidden underground or locked behind gate barriers, as in Beijing West RS, they remain underutilized assets. Similarly, **spatial layouts that affect commercial areas' visibility** determines whether potential users can even discover these amenities—hidden commercial areas beneath facility-like designed atriums or behind architectural barriers fail to attract leisure visitors, as in Beijing West RS.

The **mobility sites' constellation that reduces negative influence on human perception**—how different transport modes are arranged relative to each other and the station core—profoundly affects space utilization. The current Rotterdam Central RS demonstrates how relocating bus/tram stations to the sides and burying car parking creates a coherent central plaza available for both passenger flow management and leisure events. In contrast, stations where surface transportation dominates the central spaces sacrifice this flexibility. Relatedly, the **traffic elements' arrangement that reduces negative influence on human perception** either creates pedestrian-friendly environments or reinforces the station's identity as purely a transit hub. When traffic roundabouts and vehicle drop-off zones fragment pedestrian spaces, as in Beijing West RS, they discourage leisure use and limit available space for managing peak flows.

The ***alignment between paths and event venues*** ensures that spaces designated for events are naturally encountered and easily accessible. Well-aligned paths bring people past potential event spaces, making events visible, inviting, and enlivening the environments, whereas hidden or detached spaces, like Beijing West RS's sunken plazas, remain underutilized even when physically suitable for events.

A further essential layout feature, which significantly affects station use in all scenarios, will be examined in the middle of the next [subsection 3.3.6: layouts associated with flow organization—unidirectional vs bidirectional](#).

Spatial elements affect the overcrowding-underutilization phenomena in stations. ***Elements potentially forming bottlenecks to the pedestrian flow***, like gates, stairs, footbridges, narrow tunnels, and passages, directly affect the continuity and capacity of pedestrian flow. When the design or capacity of these elements is insufficient, they create bottlenecks that impede movement. When a station's layout includes a high number of such elements, during peak or disruption times, it increases the likelihood of overcrowding in critical areas and demands more spare space elsewhere to accommodate waiting passengers.

Elements potentially forming barriers to the pedestrian flow, like traffic-intensive roads and tracks, typically act as barriers to pedestrian flow. Therefore, they are better to be submerged in underground tunnels or relocated through proper layouts. When barriers are designed on the ground level, footbridges and tunnels are commonly designed to cross barriers. It is important to note that stairs or footbridges—which require vertical movement, and dark tunnels—which feel unsafe to navigate, even when designed with sufficient width, are usually not comfortable for (leisure) users to use, thereby impeding their movement. When a station's layout includes a high number of such elements, it increases the likelihood of underutilization during non-peak times.

Huge spare space—initially designed for transport use during peak time—can also function as ***spare space as pedestrian plazas*** during non-peak times. These large spaces also have potential to be designed as ***coherent large spaces as event venues***, where the challenge lies in designing these large spaces to be coherent and unobstructed by other functional elements, so they can be suitable for event gathering.

Spaces of human scale makes stations inviting for leisure activities rather than intimidating. Oversized spaces and structural elements, as in Beijing West RS, feel institutional and transit-oriented, and do not encourage lingering and spontaneous activities. Elements like ***seating*** support staying and waiting. Notably, large spaces for events may be out of human scale, hence not suitable for spontaneous, small-scale leisure activities. Therefore, it is necessary to limit the amount of large space, or make large space configurable for small activities.

Spatial qualities affect the overcrowding-underutilization phenomena in stations by influencing how people perceive and use station spaces. From the perspective of enhancing users' perception and motivating activities or events, commercial areas and event venues can be considered positive elements. The ***accessibility and visibility of positive elements or activities*** are qualities that work together to determine whether

stations can successfully attract non-transport users. Commercial areas and spaces for leisure activities must be both easy to reach and easy to see to overcome the psychological barrier of entering a primarily transport-oriented environment. These qualities are affected by spatial layouts, mobility facilities (as captured in the lack of **bike parking that affect station areas' accessibility**, in Beijing West RS), and the arrangement of gated zones. Similarly, qualities like 'human scale' of spaces and 'complexity' of scenes emerge from the combination of spatial elements and layouts, making stations feel inviting and vibrant rather than monolithic and boring.

3.3.6 Commonalities and differences between the Chinese and the Dutch stations

Commonalities in fundamental station dynamics. Whether in China or the Netherlands, stations are affected by events. For stations with surging passenger numbers during event times or those experiencing **railway disruptions**, spare spaces are needed to accommodate passengers. The core challenge of managing the mismatch between fixed spatial capacity and fluctuating demand is universal. Consequently, spare space is typically crowded during peak times, while underutilized during non-peak times in both contexts, establishing a common basis for the O&U phenomenon.

Differences in national-context-associated factors. The primary divergence lies in the internal operational factors embedded within each national system. Specifically in China, stations need significantly more spare space to complement the decreased transfer efficiency caused by strict security checks, early arriving passengers due to rigid ticketing-seating rules, and inexperienced passengers with bulky luggage. This operational context, which is less prevalent in the Dutch system, explains why Chinese stations are usually much larger than Dutch stations, even when given similar railway track numbers and comparable daily passenger volumes ([Table 3.3](#)).

Differences in spatial layouts associated with flow organization—unidirectional vs bidirectional. A critical difference in spatial design is found in the fundamental approach to flow organization. In Dutch railway stations, the spatial layout is designed for passengers to use the same paths for ingress and egress, forming bidirectional flows. In contrast, Chinese railway stations often separate these flows—similar to airport designs—creating unidirectional circulation where ingress and egress paths are distinct ([Figure 3.22](#)).

Each layout has advantages and drawbacks. Separated paths allow for higher maximum flow volumes and reduce head-on conflicts between opposite streams of pedestrians ([Zhang, 2012](#)). However, they can also cause pedestrians to become more spatially dispersed, which may result in certain areas being underused. Conversely, shared bidirectional paths concentrate flows, which can intensify overcrowding during peak periods or directional surges.

The choice between unidirectional and bidirectional layouts, therefore, reflects different spatial logics and operational challenges. For example, in Chinese stations—where ingress and egress are spatially separated, and ingress includes additional steps such as security checks—the ingress side is often more prone to overcrowding. In contrast, Dutch stations, which lack such separation, must manage bidirectional flow conflicts within shared spaces.

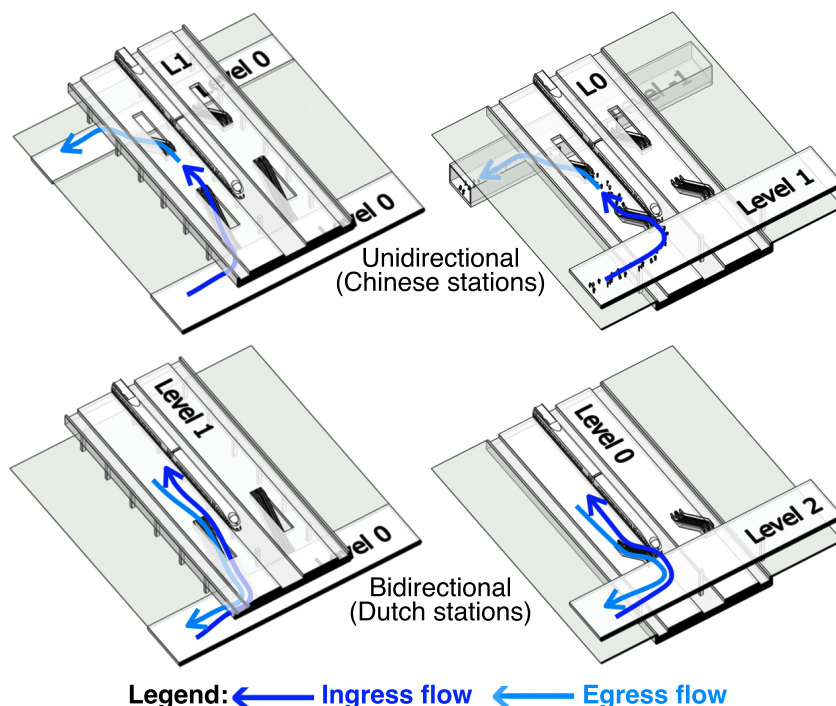


FIG. 3.22 Spatial layouts associated with flow directions (on the building level)

(Source: Author. Note: Corresponding real-world examples: top-left—Shanghai RS, top-right—Jiaxing RS; bottom-left—Rotterdam Central RS, bottom-right—Utrecht Central RS. In this figure, floors are annotated in the form of ‘Level X’—instead of 1F, B1, BG, etc.—to overcome the difference in floor number conventions between the Netherlands and China.)

Reconciling station size with passenger numbers. People commonly assume that Chinese major stations, compared to those in other countries, have much larger passenger volumes and therefore must be much larger to prevent overcrowding. However, the data collected in Table 3.3 contradict this assumption: Beijing West RS handles approximately 150,000–320,000 passengers daily under normal conditions and around 400,000 during the Chinese New Year, while Rotterdam Central RS serves about 110,000 passengers daily, and still functions with 330,000 passengers according to this thesis’s simulation—see section 6.4, Figure 6.18-B-New. Therefore, the passenger number differences are not as substantial as commonly perceived, yet Chinese stations are several times larger in floor area. This suggests that *the number of passengers* does not account for the significantly larger sizes of Chinese stations compared to Dutch ones.

TABLE 3.3 Daily passenger numbers and sizes of the stations

Measurement ▼	Beijing West RS	Shanghai RS	The current Rotterdam Central RS
Daily passenger numbers during holiday peaks	• Ingress+Egress=400,000 [Date not specified] according to (Zhuohetech, n.d.) • Ingress=262,200* [02-02-2019] according to (Baidubaike, n.d.)	• Ingress=191,000* [08-02-2024] according to (Chinanews, 2024) • Ingress=196,000* [2024] according to (Shanghai Municipal Transportation Commission, n.d.)	(330,000, tested in simulation—see section 6.4 , Figure 6.18-B-New)
Daily passenger numbers on normal days	• Ingress+Egress=150,000–180,000 [Date not specified] according to (Zhuohetech, n.d.) • Ingress+Egress=274,000** [2019] according to (China State Railway Group Co., n.d.) • Ingress+Egress=320,000 [2018] according to (Yu, 2018)	Ingress+Egress =191,3000** [2023] according to (Jintainews, 2024)	Ingress+Egress =104,840 [2023] according to (NS, n.d.)
Tracks numbers	20	15	13
Floor area	500,000 m ²	90,000 m ²	45,000 m ²

Note: * No data on egress, but typically, in this pre-Chinese New Year time in major stations in megacities, passenger numbers of egress are less than those of ingress, because many people are traveling from megacities to their hometowns. ** Averaged from the annual passenger number

3.3.7 The complex interrelationships and the potential of spatial design

Synthesizing the above findings, this subsection presents [Figure 3.23](#) to illustrate the interrelationship among key factors. **National-context-associated factors**—including events, travel patterns, passenger characteristics, and operational procedures—directly influence passenger behavior and flow dynamics, creating conditions that lead to overcrowding during peak times.

These factors contribute to **bottlenecks** in pedestrian flow, which can be caused by both non-spatial factors (strict security checks, early arriving passengers due to rigid ticketing-seating rules, and inexperienced passengers with bulky luggage) and spatial elements (narrow passages, insufficient gates, stairs), exacerbating overcrowding.

Spare space emerges as a pivotal concept that connects these aspects of station performance, with its benefits and drawbacks. As shown in the diagram, spare space addresses overcrowding by providing extra capacity to accommodate stranded passengers during peak periods or service disruptions. However, this same spatial resource contributes to underutilization during normal operations, a phenomenon that fundamentally emerges from the mismatch between fixed spatial capacity and fluctuating passenger numbers. The dual nature of spare space—as both essential safety infrastructure during peaks and potential wasted resource during off-peak times—makes it a critical focus for spatial configurations.

In contrast to national-context-associated factors, which are generally difficult to

change due to their roots in broader socio-cultural systems, spatial configurations are more malleable. Spatial configurations affect pedestrian activities, and interact with national-context-associated factors. The substantial content of spatial configuration—encompassing layouts, elements, and qualities—highlights spatial design as an important means of intervention.

This potential can be realized through thoughtful design strategies: by enhancing station connections with neighboring districts, optimizing flow organization patterns, carefully locating commercial areas, and creating human-scaled spaces that encourage diverse activities and serve as coherent event venues. In doing so, spatial design can transform stations from mono-functional transport hubs into vibrant, flexibly-used urban spaces that transition seamlessly between transport accommodation and non-transport uses, thereby maintaining operational efficiency while supporting broader urban vitality.

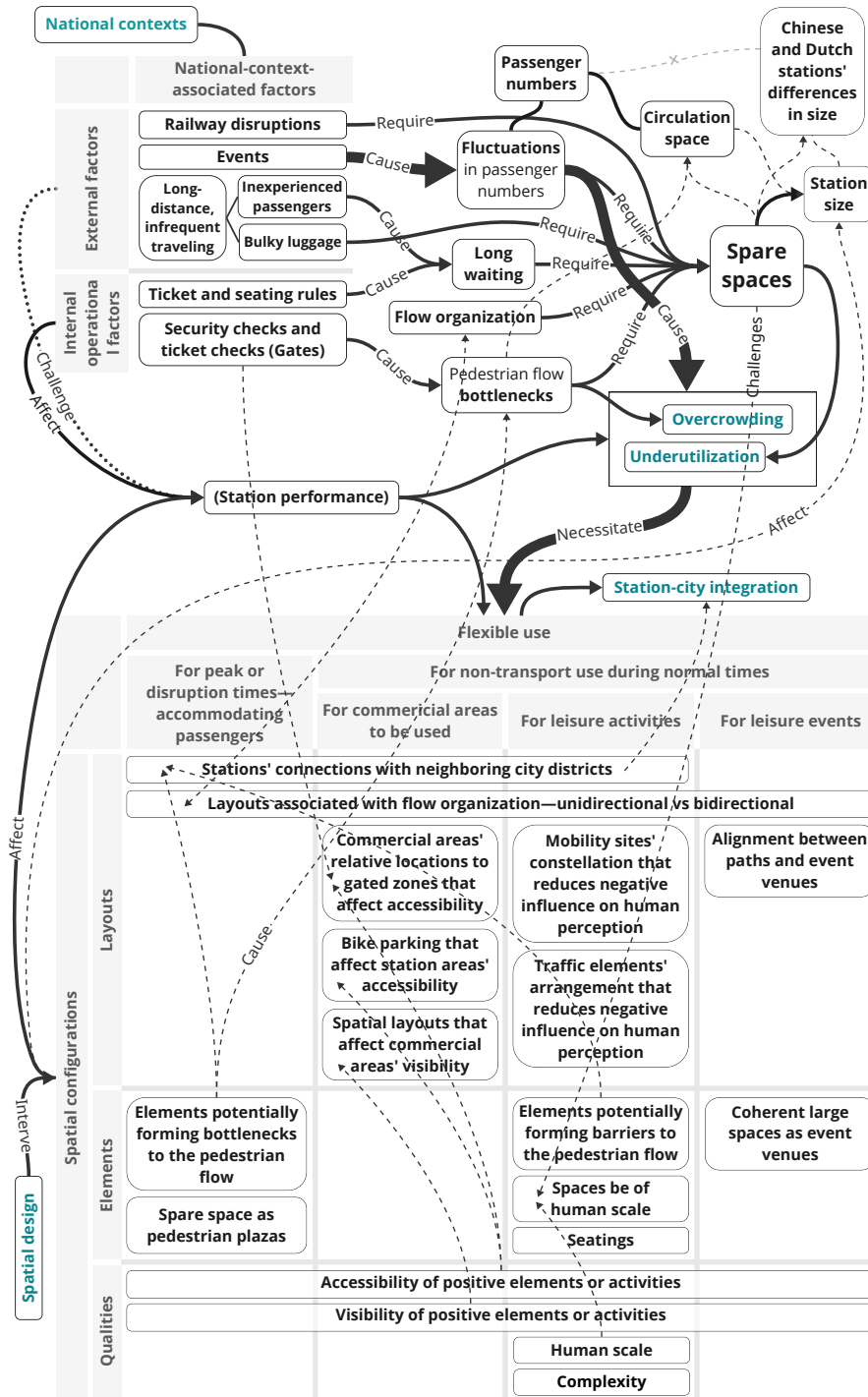


FIG. 3.23 The relationships between aspects related to the overcrowding-underutilization phenomena. (Source: Author)

3.4 Discussions

This section discusses several insights or reflections that emerged from the research, including the potential of static layouts, the nature of elements and layouts in relation to spatial scales, the role of other contextual factors, and experience transfer between different national contexts. The research contributions and limitations are summarized at the end of this section.

3.4.1 The untapped potential of static layouts for flexible use

The findings of this research underscore the significant yet overlooked potential of static layouts. In the previous [Chapter 2, subsection 2.4.4](#), the literature review reveals that existing literature has a strong focus on dynamic—‘reconfigurable,’ ‘flexible,’ or ‘kinetic’—solutions, such as kinetic buildings, moveable walls, retractable seating, potted plants, and other flexible elements, which allow a physical layout to be reconfigured. While these solutions are valuable, this chapter’s findings highlight a complementary and often overlooked strategy: the potential of **static, fixed layouts to enable flexible use**.

A fixed layout, such as the layout of mobility sites and plaza at the current Rotterdam Central Station, does not physically change during peak and non-peak times, but the patterns of use it supports are highly flexible. It provides easy connections, allowing city users to visit the station during off-peak hours, and gives passengers natural overflow routes into the neighboring city plaza during peak times. This approach offers a more permanent and potentially lower-maintenance pathway to mitigating O&U, positioning static layouts as a critical tool alongside dynamic, reconfigurable ones.

3.4.2 The nature of elements and layouts in relation to spatial scales

‘Elements’ and ‘layouts’ are fundamental concepts in design research ([Liu, 2020](#)). According to [Alexander \(1979\)](#), “the element itself is not just embedded in a pattern of relationships, but is itself entirely a pattern of relationships, and nothing else.” While this view powerfully emphasizes the primacy of relationships (or layouts in a physical sense), this chapter’s analysis suggests a more nuanced distinction between an ‘element’ and a ‘layout’ is relative to the scale of analysis ([Figure 3.24](#)). What appears as a singular element at one scale—for instance, a station plaza—is, at a smaller scale, potentially comprising multiple elements such as mobility sites, facilities, and their

interrelationships embedded in layouts, as in Beijing West RS and the previous Rotterdam Central RS. Also, bottlenecks and barriers are rarely isolated elements but are often caused by a specific layout at a larger scale. Designing for the flexible use of railway stations requires a conscious understanding of how interventions at one scale redefine the elements and layouts at another.

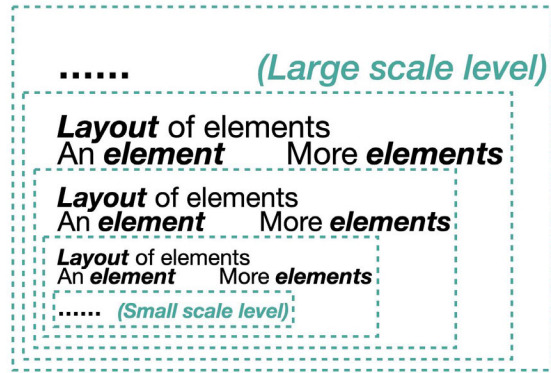


FIG. 3.24 The nature of elements and layouts in relation to spatial scales. (Source: Author)

3.4.3 The role of other contextual factors

Beyond the factors already discussed, stations are also affected by other contextual elements, such as the typical city size and the number of railway stations in a city. For example, the lack of bike parking in Beijing West Railway Station is partially due to the fact that bikes are currently of low priority to its passengers. Large Chinese cities like Beijing and Shanghai, with populations of dozens of millions and with only three to four major railway stations, rely largely on vehicle transportation to transfer their passengers within the cities. In comparison, Dutch cities like Rotterdam, with a population of less than one million, actively utilize bikes and walking as a way of transportation. This research expects future research to continue this exploration of more factors.

3.4.4 Experience transfer between different national contexts

A primary challenge in comparative urban studies lies in navigating the tension between contextual specificity and the desire for generalizable knowledge. The question of whether experience from one national context can be meaningfully applied in another often meets with skepticism. This chapter, however, argues that this barrier can be overcome by distinguishing between different types of experience. This

research's reflection suggests that transferability is not a binary condition but a spectrum, dependent on which conceptual level the analysis is conducted, and how broad the systems in which these experiences are rooted—concrete experience of a whole case may not be entirely transferable to another case, but components and related abstract concepts of a case are usually transferable (Chorus, 2012, p 19). This chapter recaps the following types of experience with their varying transferability across contexts and cases:

- Regarding national contexts: National-context-associated factors are generally hard to change from the station design perspective. Internal operational factors—like security checks and ticketing-seating rules—are rooted in institutional systems; External factors—like travel patterns—are even harder to change as they are rooted in wider mobility systems and socio-cultural norms (subsection 3.3.1); therefore, the associated experience is hard to transfer. Conceptual knowledge associated with events, spare spaces, and bottlenecks (subsection 3.3.2) remains highly generalizable, as events happen to both Chinese and Dutch cases, manifesting in different forms, e.g., as national holidays or football matches.
- Regarding spatial configurations (subsection 3.3.3 and subsection 3.3.4): experience with spatial elements and qualities is easier to transfer. In comparison, experience with spatial layouts—especially layouts associated with flow organization which even involves operational contexts—is harder to transfer. Experience of district-level aspects, such as stations' connections with neighboring city districts, is more transferable than experience of building-level aspects.

3.4.5 Correlation between flexible use and station-city integration

When examining the complex interrelationship in Figure 3.23, a critical insight emerged regarding the role of **stations' connections with neighboring city districts**—these connections are a primary physical manifestation of **station-city integration** and a key enabler of the flexible use. This insight consolidates the functional and conceptual correlation between the two topics—flexible use and station-city integration—flexible use is functional integration of stations and cities, hence being a new value enriching the meaning of station-city integration (Chapter 1, section 1.1 and subsection 1.5.1).

3.4.6 Research contributions and limitations

This research makes two primary contributions to the knowledge body. First, it provides a detailed explanation of how factors affect the overcrowding-underutilization phenomena, in a complex relationships network (Figure 3.23), which serves as a starting point for developing further solutions. By revealing the substantial layouts,

elements, and qualities involved in spatial configurations, it confirms spatial design as an important means of intervention. Second, this research elucidates how national contexts affect stations, differentiating external factors and internal operational factors, which supports the transfer of station design knowledge across different countries.

Methodologically, while both the use of in-depth case studies and prospective scenario analysis are established qualitative approaches in transport and urban research (Hickman et al., 2012; Abou Jaoude et al., 2022; Lu et al., 2023), combining and applying them to the specific question of spare space and the overcrowding–underutilization phenomenon has remained limited. In this research, the scenario-based exploration proved particularly valuable for revealing not only historical patterns in the four selected stations but also their likely performance under future potential conditions. This study's limitation lies in its small scope of four cases, potentially overlooking greater complexity and more significant findings.

3.5 Conclusions

This chapter establishes the definitive mechanics driving the dual phenomena of overcrowding and underutilization (O&U) across different national contexts and spatial configurations. By evaluating four major railway station cases under varied peak and non-peak scenarios, this research provides a substantial, evidence-based framework that explicitly answers how national contexts affect the overcrowding–underutilization phenomena in railway stations, as well as how spatial configurations affect these phenomena and hence what spatial design's potential is, thereby advancing the discourse on flexible use and station-city integration.

In answering the **first research question**—how national contexts affect the overcrowding–underutilization phenomena, this study demonstrates that macro-systemic settings dictate a station's physical size and internal operational capacity through distinct, context-dependent pathways. Counterintuitively, raw **passenger numbers** alone do not explain the significant size differences between Chinese and Dutch stations. While Beijing West Railway Station handles approximately 150,000 to 320,000 passengers daily under normal conditions and around 400,000 during the Chinese New Year peak, the current Rotterdam Central Station serves about 104,840 passengers daily on normal days and successfully functions with up to 330,000 passengers under simulation. Yet, despite these comparable peak-throughput scales, Beijing West requires a massive floor area of 500,000 m² with 20 tracks, whereas Rotterdam Central operates within a compact floor area of 45,000 m² with 13 tracks.

Instead, **national contexts** affect overcrowding and underutilization through distinct

internal operational factors and external factors that differ fundamentally between the two environments. In the Chinese case, major stations face unique demographic and operational challenges driven by rigid institutional systems, such as strict **airport-style security checks** and **rigid ticketing-seating rules** where tickets are tied to specific trains and assigned seats. This forces passengers to arrive early, resulting in longer waiting times, which is further compounded by a passenger demography characterized by **long-distance, infrequent traveling**, a lack of traveling experience, and **bulky luggage**. These internal operational factors significantly decrease passenger transfer efficiency and create severe pedestrian flow bottlenecks before gates, necessitating the design of massive spare spaces (or redundant spaces) to safely accommodate flows and prevent overcrowding during extreme external events like the Chinese New Year. Because these large spatial allocations are hardcoded for peak conditions, they are structurally forced to function as sterile, underutilized voids during standard operations.

Conversely, the Dutch case presents a completely contrasting operational paradigm designed for short-distance, daily travel where passengers seamlessly check in and out using their OV-chipcard, travel without assigned seats, and face no strict security checks or entrance bottlenecks. Furthermore, the demographic behavior relies heavily on walking and cycling as an active way of transportation, supported by bike parking. While external contextual challenges like sports matches or King's Day still create surges that challenge station performance, the high efficiency of the internal passenger transfer process allows Dutch stations to maintain operational resilience within a significantly smaller floor area, proving that solutions to the overcrowding-underutilization phenomena cannot be universally generalized but must be tailored to these localized institutional settings and socio-cultural norms.

In answering the **second research question**—how spatial configurations affect these phenomena and what spatial design's true potential is, the findings prove that specific spatial layouts, elements, and qualities directly govern a station's resilience against overcrowding and its capacity to systematically reduce off-peak underutilization. Physical configurations influence overcrowding via the geometry of elements potentially forming **bottlenecks** to the pedestrian flow and layouts that fail to distribute critical circulation streams smoothly. This spatial mechanic is demonstrated within the analyzed precinct radius, where the current Rotterdam Central Station utilizes a highly connected, pedestrian-friendly plaza to access adjacent city areas as critical passenger overflow buffers during disruptions, whereas Beijing West Railway Station is physically isolated by arterial roads and a long north facade that traps pedestrian streams away from its nearby sunken plazas due to unnoticeable footbridges and tunnels.

Correspondingly, spatial design holds immense potential to mitigate underutilization during quiet periods by intentionally configuring layouts to support **non-transport uses**, which are categorized into commercial activities, leisure activities, and leisure events. This intervention potential is directly governed by the layout of commercial areas relative to gated zones. Positioning storefronts at the front of the station building in Shanghai Railway Station and outside gated boundaries at Rotterdam Central makes them fully accessible and visible to non-passengers, while the massive subterranean commercial zones of Beijing West suffer from poor accessibility and are completely

masked from the plaza by facility-like atrium roofs.

Furthermore, initiating self-motivated leisure activities and hosting large-scale leisure events depends heavily on maintaining high **spatial qualities**, human scale, and a peripheral constellation of mobility sites. Burying car parking underground and relocating bus or tram stations to the side areas creates the coherent, large spaces as event venues necessary to enliven the precinct. Prioritizing surface traffic elements and neglecting dedicated bike parking reinforces a purely transit-oriented identity that prevents the environment from being used for lingering.

A further critical manifestation of spatial design's potential lies in managing the fundamental layout aspects associated with flow organization, specifically the choice between **unidirectional and bidirectional circulation** patterns. Unidirectional layouts, prevalent in Chinese stations, completely separate ingress and egress paths to handle higher maximum flow volumes and eliminate head-on pedestrian conflicts, yet they increase spatial dispersion and risk leaving certain areas underused. Bidirectional layouts, prevalent in Dutch stations, consolidate passengers along shared paths to optimize space utilization during standard hours, but introduce complex shared-space friction points that challenge operational safety during sudden directional peak surges.

Ultimately, layout aspects like stations' **connections with neighboring city districts** serve as the primary physical mechanism affecting both overcrowding and underutilization across all scenarios. Strong street-level connections establish a dual-purpose resilience; they empower a station to effectively absorb extreme transit disruptions into the surrounding fabric, while simultaneously allowing neighboring residents to naturally filter into the precinct for non-transport uses during standard operations. This confirms that static, fixed layouts possess an unexploited potential for flexible use. While the physical geometry remains unchanged, a highly integrated spatial configuration allows a transit hub to transition seamlessly between transport accommodation and active urban life, establishing spatial design as a powerful intervention means for successful station-city integration.

Design Principles

This part, comprising **Chapters 4** and **5**, addresses the knowledge gaps identified in Part I by substantiating the spatial relevance of flexible use into concrete spatial design principles.

Chapter 4 develops a set of design principles for designing stations that enable flexible use. These principles cover elements and layouts of stations at building and district levels.

Chapter 5 tests and validates these principles. Through research-by-design, it translates the principles into concrete spatial proposals for a virtual case study (Station Xtreme), and it evaluates their performance using the assessment framework developed in Chapter 6.

The content of **Chapter 5** has also been published in: Enshan, C., van der Spek, S., Tian, A., Triggianese, M., & van der Hoeven, F. (2025). Evaluate design principles for flexible use of railway station areas: Through research-by-design and agent-based simulation. *Journal of Building Engineering*, 112, 113775.

4 Design principles

Iteratively learned from cases and literature through analytical visualization

ABSTRACT Spatial design has the potential to enable flexible use aimed at reducing overcrowding and underutilization in railway station areas, with design principles serving as essential guides for practice. However, this potential has not yet been realized, as no widely accepted or systematically articulated set of design principles currently supports such flexible use in railway station areas. Addressing this gap in knowledge, this chapter **questions**: What are the design principles for railway station areas that support flexible use aimed at reducing overcrowding and underutilization? It employs a multiple-step **methodological** framework, examining cases and the literature papers through analytical visualization to iteratively develop design principles. The heuristics for design principles are accumulated through the analysis of scenarios, issues, spatial and managerial dimensions, spatial qualities, and expert comments. This chapter **resulted** in the identification of 27 design principles, from which six design qualities emerged: event visibility, reconfiguration, connection, dispersed, human-centered, and flexible use.

KEYWORDS Overcrowding, underutilization, urban design, pattern language

4.1 Introduction

This thesis aims to advance flexible use as a strategy for reducing overcrowding and underutilization, and promoting station–city integration (section 1.5). Spatial design is effective in realizing flexible use (subsection 1.2.4, subsection 3.3.3, subsection 3.3.4), providing an extra means of interventions besides other means like management and planning (Ross 2000; see also subsection 4.2.2, temporal dimension; and subsection 1.3.4). From the spatial design perspective, Chapter 2 revealed gaps in integrating knowledge of crowd dynamics with public space use, as well as in applying spatial layouts as design solutions. Accordingly, this chapter seeks design principles that both integrate existing insights and provide new knowledge on spatial layouts (Figure 4.1).

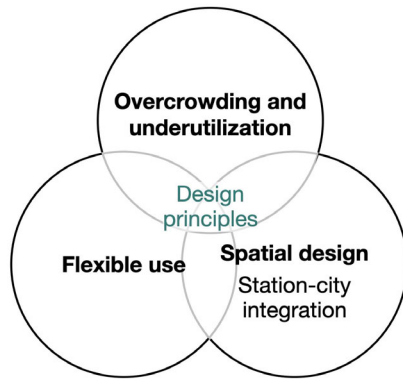


FIG. 4.1 Design principles supporting flexible use aimed at reducing overcrowding and underutilization in station areas. (Source: Author)

Design principles are commonly used in the fields of urban and architectural design, with meanings that vary in different research or design projects, from vague to more specific (Liu, 2020; Van Der Hoeven and Juchnevic, 2016). A classical concept called ‘patterns’ proposed by Alexander (1979, 1977), can serve as a structured definition of design principles:

“Each pattern is a three-part rule, which expresses a relation between a certain context, a problem, and a solution” (Alexander, 1979, p. 247).

“Each pattern depends both on the smaller patterns it contains, and on the larger patterns within which it is contained” (Alexander, 1979, p. 312).

Regarding railway stations, a few manuals of design principles have been developed. For example, the company Network Rail in the UK has developed design principles for stations (Networkrail, 2024) and station areas (Networkrail, 2023). The company ‘Spoorbeeld’ (the Dutch word for ‘Railway Image’) in the Netherlands has developed design principles for different aspects of stations, including urban design of station

areas ([Sporbeeld, n.d.](#)). These kinds of guidance were established with diverse objectives to improve station qualities. However, despite these efforts, design principles that specifically address the problem of overcrowding and underutilization, through flexible use, are still lacking. Regarding this knowledge gap, the following main **research question** is presented:

What are the design principles for railway station areas that support flexible use (aimed at reducing overcrowding and underutilization, and promoting station-city integration)?

Developing such design principles involves the following opportunities and challenges: First, there are multiple data sources for developing design principles, including the literature and case studies of stations that provide insights into existing practices (e.g., [Peters and Tolkoﬀ 2016](#)), as well as scenario analyses that offer insights into future possibilities ([Chapter 3](#)). Second, railway stations are complex projects that involve spatial-temporal and management aspects; therefore, systematic approaches for station analysis should be able to integrate these aspects. Third, many existing design principles lack an external validation process during their development. Regarding these opportunities and challenges, in this chapter, a subsequent minor research question is presented:

How can design principles of complex projects, like railway stations, be developed in a systematic way that enables synthesizing, probing, and validating knowledge?

Addressing these questions, the study applies a multi-step analytical framework to multiple cases to develop design principles for railway station areas. The findings contribute to both the substantive body of design knowledge and the methodological approaches for deriving such principles. The remainder of this chapter is structured as follows: [section 4.2](#) describes the methodology, [section 4.3](#) reports the results, [section 4.4](#) discusses extra insights and reflections, and [section 4.5](#) draws conclusions.

4.2 Methodology

This chapter employs a multi-step methodological framework to systematically develop the design principles, which involves establishing design objectives and design dimensions, collecting data from cases and literature, processing the data iteratively through analytical visualization, formulating initial findings, and reflecting on the findings through expert interviews ([Figure 4.2](#)).

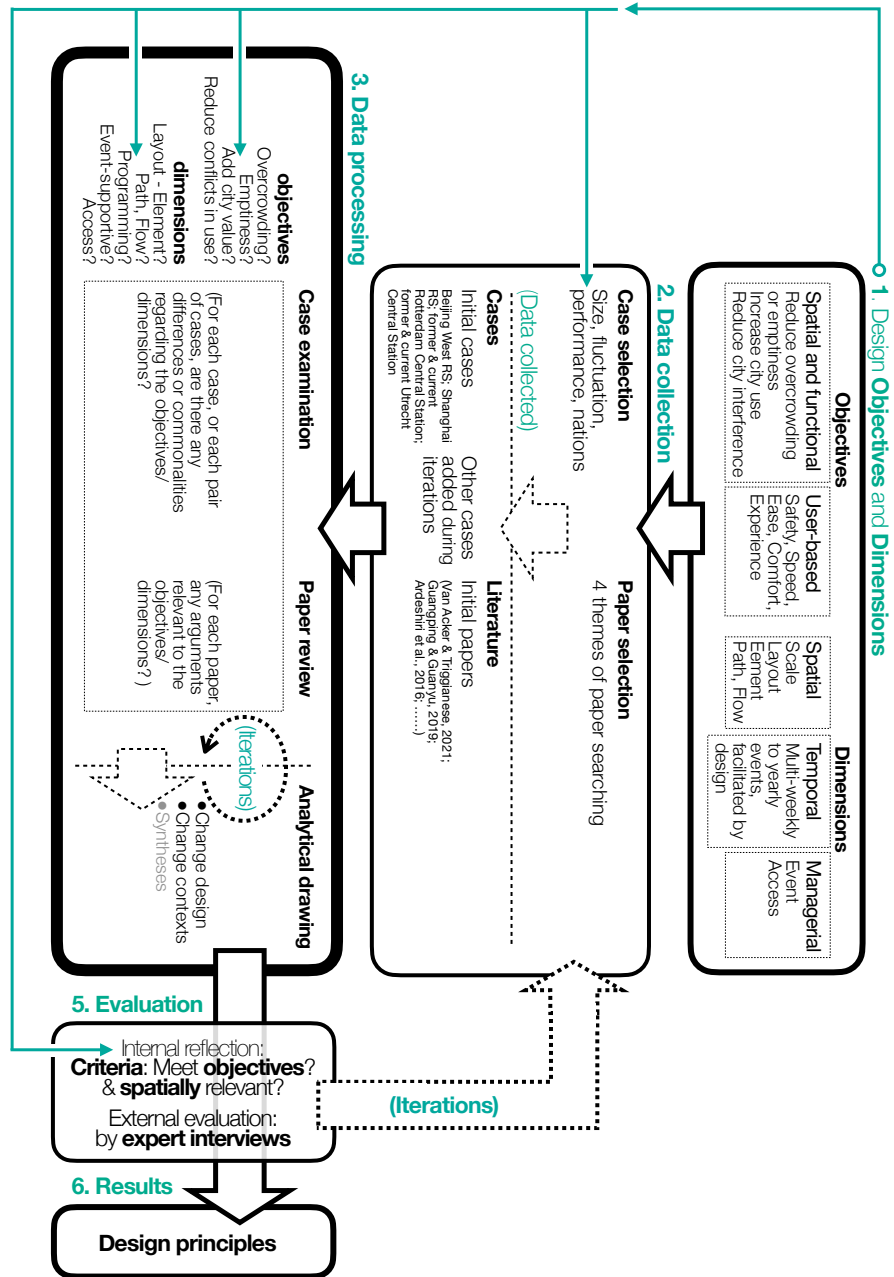


FIG. 4.2 The methodological framework of developing design principles. (Source: Author)

Figure 4.3 provides an example of how such principles are iteratively developed with the accumulated heuristics. The chain of reasoning unfolds as follows: It begins with an ideal scenario in which people engage in leisure activities on station plazas to prevent underutilization (Link 0)→ This leads to the recognition that railway tracks form barriers to accessing these plazas (L1)→ Passages across station buildings are identified as a way to overcome these barriers and facilitate pedestrian flow → Consideration is given to which higher-level spatial factors affect the effectiveness of such passages (L2)→ The positioning of the passages is examined (Links 3' and 3)→ From the two principles developed, the quality or strategy of connection emerges → This leads to the question of what other design principles can be developed, by transforming and applying connection at a larger spatial scale (L4)→ The concept of city axes is introduced (L5)→ An expert comments that city axes can also help stakeholders understand the structure of urban design schemes. Iterations occur throughout this process, as illustrated by the transitions between Links 3 and 4, where ideas move from design principles to emerging qualities and back again. The following subsections describe key components of the methodological framework.

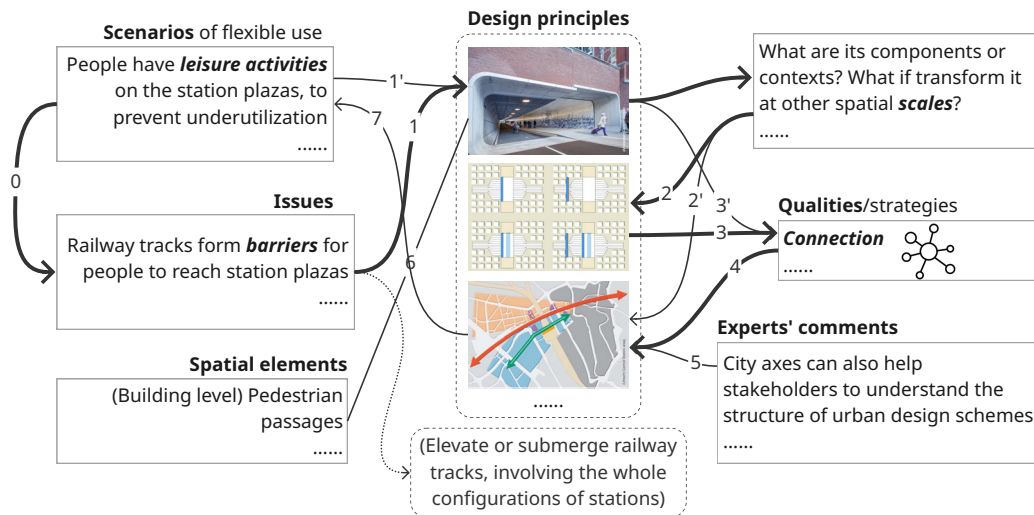


FIG. 4.3 An example of how design principles are iteratively developed.
(Source: Author. See also the full results in Figure 4.5)

4.2.1 Objectives and scenarios to support

4.2.1.1 Design objectives or assessment criteria

As described in [Chapter 1, subsection 1.7.3](#), this research established multiple assessment criteria for positive solutions, including: (1) reducing overcrowding and underutilization, (2) adding socio-economic values to the station or the city, and (3) improving user experience. These criteria serve as design objectives that the design principles are intended to support.

4.2.1.2 Scenarios and assumptions of flexible use

As described in [Chapter 3, subsection 3.2.2](#), this research constructs two scenarios with corresponding assumptions on flexible use, which the design principles should support:

- [Scenario 1-a] During event times when large volumes of passengers come and are delayed before bottlenecks, or [Scenario 1-b] during railway disruption times when many passengers are stranded,
[Assumption 1] stations that support flexible use should be able to effectively use adjacent city areas, as spare space, to enlarge their capacity of accommodating passengers.
- [Scenario 2] During non-peak times when stations are underutilized,
[Assumption 2] stations that support flexible use should support non-transport activities or events. This assumption is further specified into three sub-assumptions:
 - [Assumption 2-a] Stations' commercial areas should be used by leisure users (i.e., non-passengers) beyond passengers to avoid underutilization.
 - [Assumption 2-b] Spaces should have spatial qualities that initiate self-motivated leisure activities (or 'optional activities' as noted by [Gehl 1987](#))—e.g., wandering in the station areas, enjoying outdoor dining—to avoid being underutilized.
 - [Assumption 2-c] It should be possible to organize leisure events (e.g., open markets, air music concerts, dancing) in underutilized spaces to enliven the spaces.

4.2.2 The spatial, temporal, and managerial dimensions of stations

In this thesis, stations are examined in terms of their spatial, temporal, and managerial dimensions. As described below, within these dimensions, the contents of analysis and ways of analysis are further clarified.

4.2.2.1 Spatial dimension

In this thesis, the spatial dimension is foundational for defining the scope of what content to analyze and at what scalar levels.

This thesis focuses on **station areas** with a defined **spatial scale** ranging from district to building levels and within a range of around 250m. District level and building levels are typical scale levels for urban and architectural design interventions. This 250m as a station area range is determined considering the typical ranges of people walking and perceiving, as explained in [Chapter 1, subsection 1.6.6](#).

This thesis analyzes stations' **spatial configurations** ([section 3.1](#)), which is defined as follows: the relational arrangements of spatial elements and their connections, encompassing both the physical **spatial layout**—the tangible arrangement of **spatial elements** like platforms, circulation areas, ticket sales and retail space, and station forecourt ([Edwards 1997](#), pp. 50–83; See also the detailed listing of spatial elements in [subsubsection 1.6.4.1](#))—and physical-associated aspects, such as connectivity, flow potential, and the affordances that spaces provide for movement and interaction ([Van Der Spek, 2001](#)). Rather than describing isolated spatial components, configurations capture the structural relationships between them, shaping how spaces are perceived, navigated, and used.

Non-physical (or semi-physical) contents that are affected by spatial configurations, including pedestrian flow, experience, and station functions, are also examined, from the following perspectives ([Figure 4.4](#)):

- Approach stations as infrastructures that facilitate pedestrian flow transferring from origins to destinations ([Figure 3.7, Figure 3.8](#)) and conducting flow analysis;
- Examine specific paths of users to gain experiential/perceptual understandings of space ([Arne, 2022](#));
- Considering station-city integration, analyze the station areas ([subsection 1.6.6](#)) as things that belong to either the station or the neighboring city.

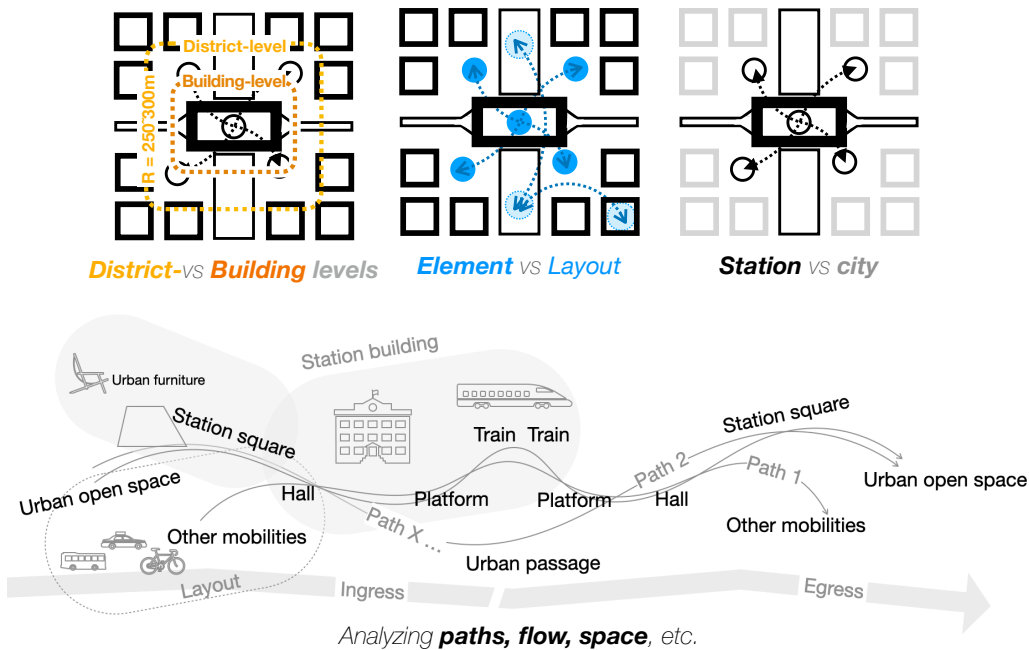


FIG. 4.4 Analyze stations' spatial dimension. (Source: Author)

4.2.2.2 Temporal dimension

In this thesis, the temporal dimension is foundational for defining the scope and enabling the analysis of events, spatial design, and space use. Events can happen with different **frequencies**, or can be observed at different **temporal scales**. Railway station areas are affected by a spectrum of events across different temporal scales, ranging from rare pandemics, Olympic games, yearly festivals (Mccarthy, 2018), multi-weekly railway disruptions (Rijndendetreinen, n.d.), weekly markets, and daily commuting. This thesis focuses on events that occur with a frequency between multi-weekly and yearly, because these types of events in stations are less studied (see more explanations in subsection 1.6.1 and subsection 1.6.2).

4.2.2.3 Managerial dimension

In this thesis, the **managerial dimension** is also considered because management is closely related to flexible use. The following management interventions are considered alongside spatial design interventions: (1) organizing events in station areas during

non-peak times, and (2) regulating access to station elements such as gated areas, specific pedestrian paths ([subsection 1.6.4](#)).

4.2.3 Data sources and data processing

4.2.3.1 Station cases and literature as the data sources

This chapter uses real-world cases and literature as data sources to discover design principles that already exist in practice. The cases used in this chapter include six initial station cases, multiple extended station cases, and non-station cases. The six initial station cases include Beijing West Railway Station (RS), Shanghai RS, the former and the current Rotterdam Central RSs, and the former and the current Utrecht RSs. (See the detailed description of case selection in [Chapter 1, subsection 1.6.5](#)).

Extended station and non-station cases are used in the following situations: (1) When additional station cases help further illustrate the discovered solutions, (2) When extra cases extend the generalizability of the design principles. The non-station cases include airports, shopping malls, and stadiums because they, like stations, are also large infrastructures that deal with massive numbers of users.

12 papers provide heuristics for analytic drawing (See [Supplementary Materials](#)). These papers were selected during the literature review of the PhD project ([Chapter 2](#)). They contain content closely related to building- and district-level design, yet not specified for railway station area design regarding flexible use. These cases and the literature are observed and read, followed by analytical visualizations.

4.2.3.2 Analytical visualization for data processing

Drawing is a powerful medium for designers to acquire knowledge and understanding, as well as generate and develop design ([Unwin, 2007](#)). Designers typically employ a certain level of abstraction in drawings to capture the essence instead of exhaustive details of reality ([Edwards, 2008](#)). Abstraction enables the findings and design outcomes to be more generalizable to new contexts. This chapter conducted analytical visualizations in a structured way. It examined each case regarding its relevance to design objectives and design dimensions, compared relevant pairs of cases to see evident commonalities or differences, and then drew the findings as design principles (See [Supplementary Materials](#)) After an initial design principle has been drawn, this chapter further changes the principle itself and its contexts to examine the impact. The changes include transferring the principle between different types of buildings or

spaces; transferring the principle between different spatial scales; testing it with different shapes, sizes, positions, directions, and so on ([Department of Architecture Design Fundamentals, Tongji University, 1991](#)). These changes allow for the development of new design principles that do not exist in practice yet (i.e., not in real-world cases or the literature). After the changes and examination, the initial design principles were extended into a broad set of principles containing variations of the initial ones.

4.2.4 Reflect the design principles

The design principles are evaluated in two ways: through expert interviews and through research-by-design. Four experts, including two designers in the practice, a station manager, and a professor ([Table 4.1](#)), were interviewed, providing comments on the design principles based on their broader interests and considerations. In [section 4.3](#), this chapter incorporates experts’ relevant comments into the descriptions of principles.

TABLE 4.1 Occupation background of the interviewees

Interviewee	Occupation
Interviewee 1	Professor of Urban Design at a university; Chief architect at a design firm
Interviewee 2	Architect at a design firm that specializes in railway station projects
Interviewee 3	Urban designer at a design firm that engages in railway station projects
Interviewee 4	Station manager at NS Stations

Methodologically, this chapter is also supported by other chapters: [Chapter 3](#) builds five scenarios of flexible use and identifies relevant spatial elements and issues, which serve as heuristics for developing design principles in this chapter; [Chapter 5](#) further tests the design principles through research-by-design and agent-based simulation.

4.3 Results

In this chapter, more than twenty design principles were discovered or developed ([Figure 4.5](#)). Both the literature and station cases provide substantial heuristics for the final result. Different design principles have their varying strengths and limitations ([Appendix B](#)). It is evident that more potential design principles can be found in future research following the same methodology.

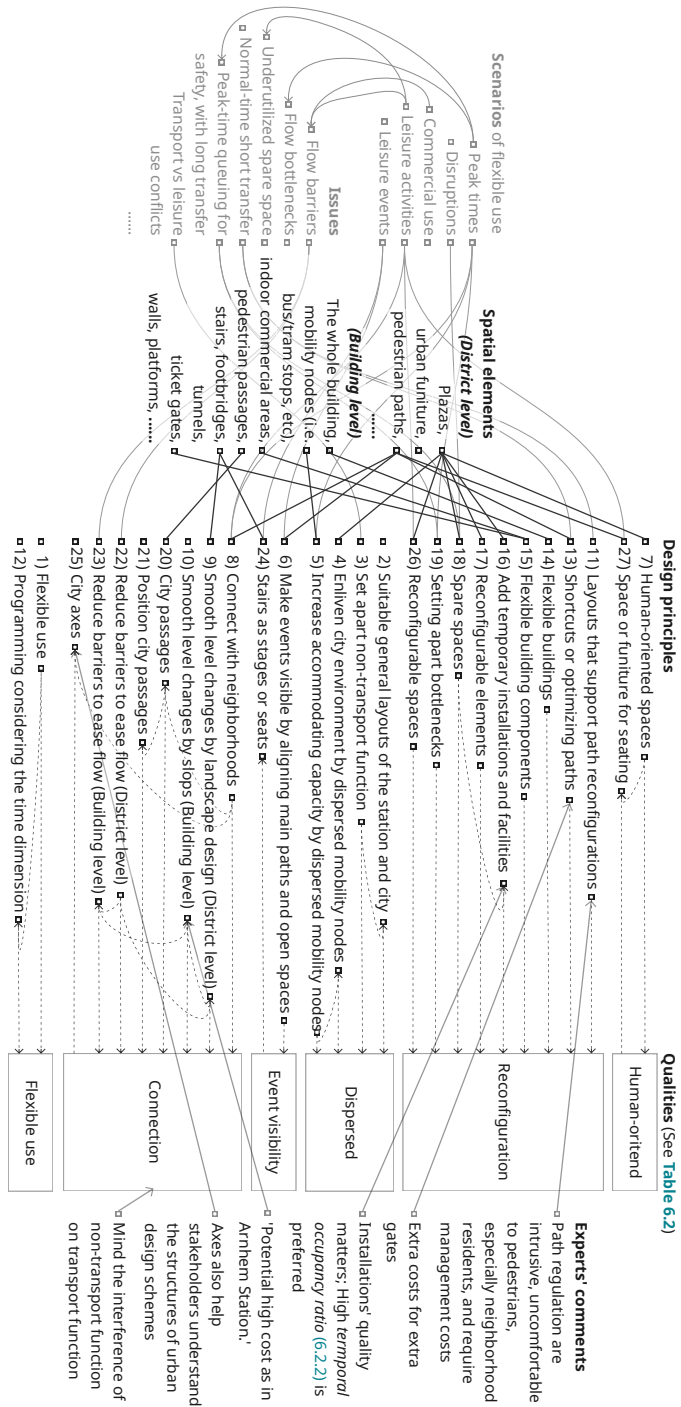


FIG. 4.5 The design principles iteratively developed with accumulated heuristics. (Source: Author)

In the final 27 developed design principles, six qualities emerged: human-oriented, event visibility, connection, reconfiguration, dispersed, and flexible use (Figure 4.5 and Table 4.2). For the simplicity of this final report, the 27 (minor) design principles are aggregated into six major principles, based on these qualities. Table 4.2 provides a brief overview of qualities, the major design principles, and the key heuristics they are based on. Each quality adds a certain value to the stations or solves issues of the stations.

TABLE 4.2 Design principles for flexible use of station areas with supporting heuristics

Qualities to achieve	Major design principles (DPs)	Main heuristic basis
1. Event visibility	Ensuring event visibility by aligning paths and spaces.	Events on the plaza of the current Rotterdam Central Railway Station (RS) easily attract pedestrian attention, enlivening the environment, while any events in Beijing West RS's sunken south plaza remain unseen from ground level.
2. Reconfiguration	Incorporating temporary elements and reconfiguration-supportive layouts.	In Figure 4.16, Layout B (inspired by pedestrian controls in airports and stations) supports efficient non-peak time transfers and safe long-distance peak-time transfers, while Layout A (referencing Allianz Arena, where the metro station is far away from the arena) does not.
3. Connection	Establishing high-quality connections at different scales.	In Utrecht Central RS and Rotterdam Central RS, there are high-quality city axes and pedestrian passages, enabling easy pedestrian movement to enliven the environment. In contrast, Beijing West RS has inconvenient footbridges and tunnels, and pedestrians only use them out of necessity.
4. Dispersed	Adopting dispersed layouts for high capacity or vibrancy.	While facing similar contextual challenges of holiday peaks, Shanghai RS is typically less crowded than Beijing West. Shanghai RS has eight bus stations dispersed around it, while Beijing West RS has two major bus stations concentrated.
5. Human-oriented	Prioritizing core spaces for humans instead of vehicles.	The current Rotterdam Central RS has a human-oriented plaza supportive of leisure events, while the former plaza was dominated by vehicles, trams, and a metro station, leaving no space for such events.
6. Flexible use	Enabling flexible use through programming.	In Guangzhou, China, during the Chinese New Year, when railway stations are under pressure from surging high volumes of passengers, stadiums in the city were planned for backup use of stations in case of emergencies.

The following sub-sections present the design principles with more details, in the form of: context - problems/potentials - solutions - examples - limitations. In section 4.1, this chapter already described the general context—station areas aiming for flexible use and station-city integration, and general problems—overcrowding and underutilization. In the following sub-sections, when describing specific components of principles, their corresponding specific contexts will be mentioned.

4.3.1 Ensuring event visibility

4.3.1.1 Make events visible by aligning main paths and open spaces

To reduce underutilization, leisure events such as open-air concerts, markets, and roadshows (Smith et al., 2021), can be organized to create a vibrant station environment; But If the events happen in 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 will not be able to attract people easily. Therefore, open spaces hosting events should be well aligned with leisure pathways to enhance visibility and attract attendees. Obstacles blocking views should be removed. Figure 4.6 illustrates two comparable scenarios: Events on the plaza of the current Rotterdam Central Railway Station (RS) easily attract pedestrian attention, enlivening the environment, while any events in Beijing West RS's sunken plazas remain unseen from ground-level plazas.

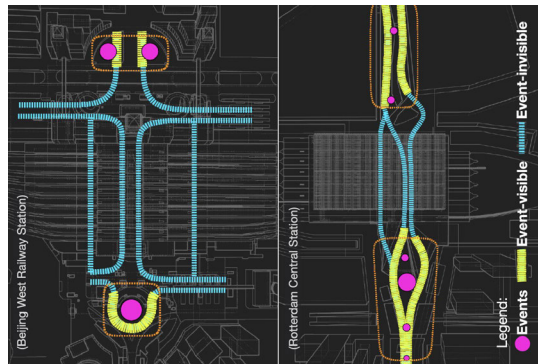


FIG. 4.6 Event visibility regarding path-space alignment. (Source: Author)

4.3.1.2 Leverage 'see-and-be-seen' by using stairs as stages or seats

Events' visibility can be enhanced by using stairs as stages or seats. Grand stairs are generally not recommended for station areas as they hinder pedestrian flow, potentially causing pedestrians to stumble. However, in some situations, station areas still have grand stairs due to topography or floor changes, like the grand stair in the west of Utrecht Central Station, or the grand stairs of the Cologne Cathedral in front of the Cologne Central Station. In this context, the grand stairs can be designed as potential performance stages or audience seats, taking advantage of the level change to leverage the 'see-and-be-seen' relationship (Gehl, 1987) between audiences and performers. Using grand stairs as stages or seats has been practiced in various real-world **cases**. For instance, the grand stairs at the west side of Utrecht Central

Station have been used as seats during open-air exhibitions (Figure 4.7), the grand stair in the hall of Antwerpen Central Station has been used as performance stage for music festivals, and the grand stairs in front of Cologne Central Station has used as a stage for demonstrations.



FIG. 4.7 Stairs for seating during events (Source: architectenweb.nl)

4.3.2 Incorporating *temporary* elements and *reconfiguration*-supportive layouts

To support different uses at different times, stations can provide users with the following options: temporary installations and facilities to fill the empty underutilized spaces for leisure use during non-peak times; reconfigurable walking paths during peak and non-peak times; and layouts that support reconfigurations at both district and building levels.

4.3.2.1 Temporary elements

During non-peak times, if a station's underutilized spaces are huge and boring, then temporary elements—installations and facilities—can be added (Figure 4.8 and Figure 4.9). Installations stimulate events, reduce the size of huge empty spaces to make them more human-scale, and add positive complexity to the scenes. Common temporary elements for urban public spaces include urban furniture, potted plants, art installations, stalls, and so on (Ivers, 2018). Installations can be interactive, like Ferris wheels, or just visually interesting, like big inflatable art installations (Ivers, 2018). Certain installations, like chairs, can even be reconfigured by users (Figure 4.8). For large indoor spaces, adding temporary pop-up stores is an option. While temporary elements may be installed either frequently (e.g., weekly) or infrequently (e.g.,

seasonally), the temporal occupancy ratio ([subsection 4.2.2](#))—i.e., the proportion of time the space is actively used—remains critical. A high ratio is preferred, which means minimizing the duration of pre-event preparation and post-event dismantling that render the space unavailable.



FIG. 4.8 Temporary and configurable urban furniture (Source: Ivers 2018)



FIG. 4.9 Reconfigurable space with installations. (Source: Shutterstock.com)

According to an expert during the interviews, one pitfall of adding temporary elements is that, if the installations and facilities are not attractive by themselves, they deteriorate the space quality, according to an expert during the interview. For instance, in the Antwerpen Central Station case, when the Ferris wheel is installed ([Figure 4.10](#)), the corresponding facilities, such as ticket-selling points and fenced pavilions, potentially make the square messy. On the street level, pedestrians' views are much blocked by these facilities, rendering the beautiful facade of the station less visible to pedestrians.



FIG. 4.10 The Ferris wheel as a temporary installation. (Source: Flickr.com)

4.3.2.2 Spare spaces preventing overcrowding

During peak time, if a station has surges of passengers, it is necessary to have spare spaces for accommodating them, or, equivalently, setting apart bottlenecks. As illustrated in Figure 4.11-left and Figure 4.12-left, the origins and destinations are separated by spare spaces, reducing the congregation of pedestrians, as compared to the situations illustrated in Figure 4.11-right and Figure 4.12-right. spare spaces make pedestrians walk longer, and since different people walk at their different desired individual speeds, the peaks of pedestrians at the origins will be smoothed when they arrive at their destinations (Figure 4.13, based on an interviewed expert's comment).

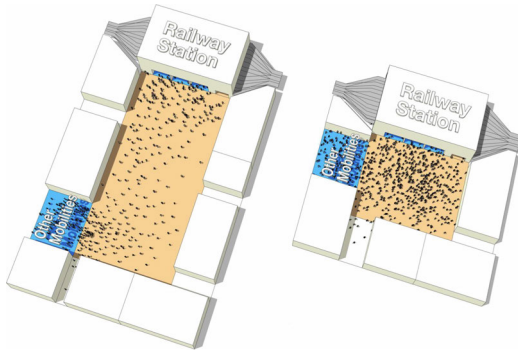


FIG. 4.11 Spare spaces (at the district level). (Source: Author)

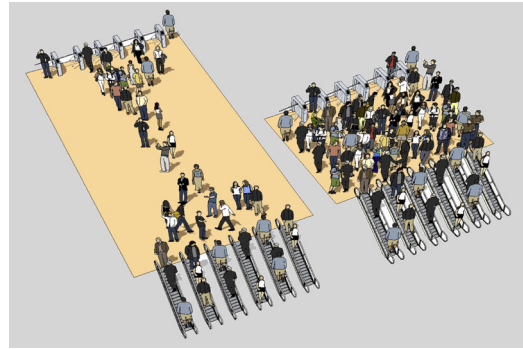


FIG. 4.12 Setting apart bottlenecks (at the building level). (Source: Author. Inspired by Hoogendoorn and Daamen 2004)

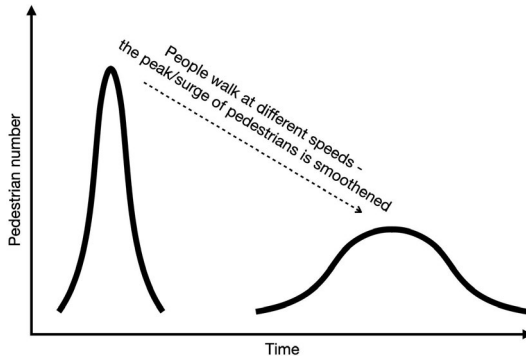


FIG. 4.13 Longer walking distance smoothens the flow peak (Source: Author)

4.3.2.3 Path reconfiguration for safe and efficient transfers

Despite spare spaces being helpful in preventing overcrowding during peak times, they add to a longer transfer distance, causing a burden for passengers during non-peak

times. In this context, path reconfiguration is an alternative. As illustrated in [Figure 4.14](#), in a more ideal setting, during peak times like national holidays, pedestrians walk in a fenced zigzag path, forming an orderly queue, preventing random congregation or stampedes; during non-peak times, the path is reconfigured into a direct form, thanks to the fences removed. In addition, during non-peak time, the spare spaces can be used by city users for leisure activities and events. The reconfiguration of pedestrian paths can not only be applied to outdoor spaces but also to indoor spaces ([Figure 4.15](#))—station building can be designed with path shortcuts, enabling efficient direct transfers between different mobility nodes during non-peak times, while retaining the lengthy paths for peak-time use.

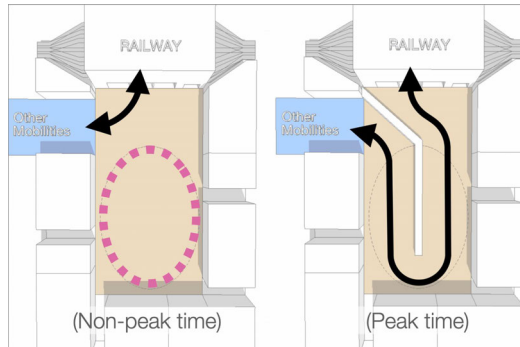


FIG. 4.14 Path reconfigurations (with seasonal frequency—reconfigure during national holiday times). (Source: Author)

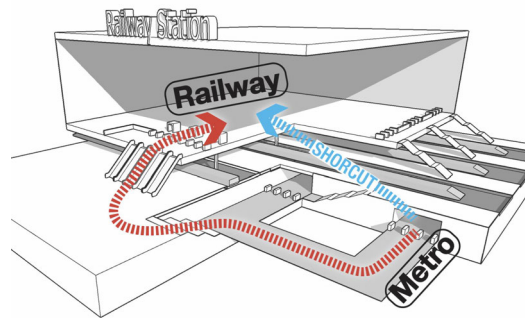


FIG. 4.15 Shortcuts of paths. (Source: Author)

4.3.2.4 Layouts that support path reconfiguration

Reconfigurable paths are supported by corresponding spatial layouts. Typically, physical spatial layouts are static and not reconfigurable by themselves, but certain kinds of layouts serve as the prerequisite for the reconfiguration of paths. For instance, in Layout B in [Figure 4.16](#), the mobility nodes are located close to spare spaces, enabling the transfer paths to be reconfigurable: During non-peak times, passengers walk from one mobility site to another in a short distance; During peak times, passengers walk along the zigzag path that prevents overcrowding. In comparison, Layout A in [Figure 4.16](#)—left, where mobility nodes are located far away from each other, does not support reconfigurable paths: Passengers have to walk a long distance from one mobility site to another even during non-peak time.

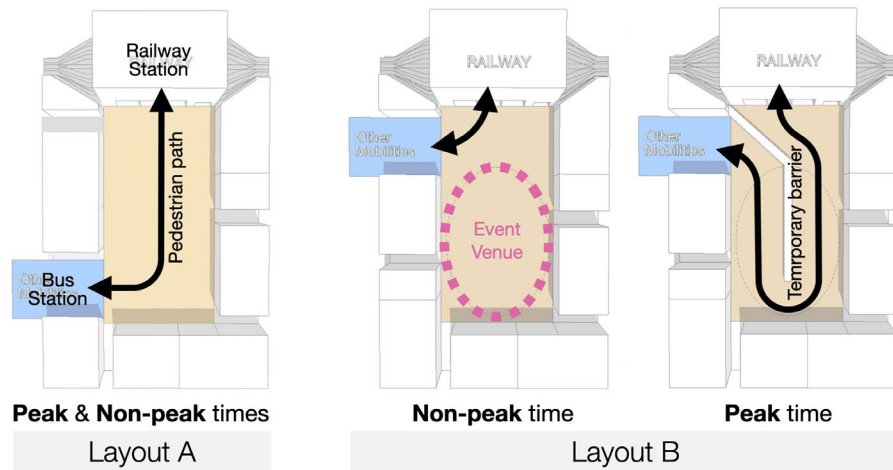


FIG. 4.16 Layouts (of mobility nodes) affect path reconfigurations. (Source: Author)

Using fences or ribbons to form the zigzag path may appear to be an intrusive intervention for some users. Alternating to fences or ribbons, more user-friendly spatial elements can be used, such as urban furniture, water bodies, fountains, potted plants, art installations, and stalls (Figure 4.17). These elements usually create a pleasant environment for staying, compensating for the longer waiting time.

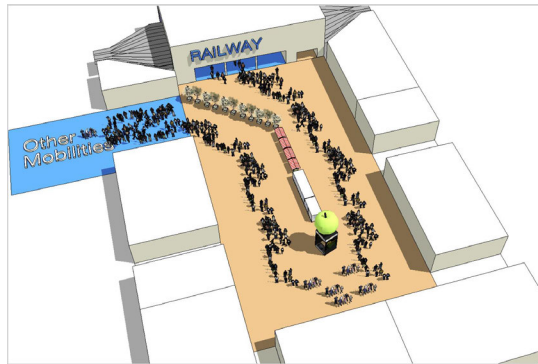


FIG. 4.17 Path regulation using non-intrusive, human-friendly elements. (Source: Author)

Reconfigurable paths balance peak and non-peak time uses; however, during the interview, experts expressed related concerns. For instance, path reconfigurability requires managerial costs. Creating extra shortcuts beyond normal paths in the station buildings requires more construction investment, especially considering that extra electronic systems are needed. It also adds more complexity for the system and for the users. Moreover, zigzag paths, if their necessity is not understood by pedestrians, will easily raise complaints.

4.3.2.5 Kinetic architecture and temporary use buildings

Beyond urban elements and paths, buildings themselves can be reconfigurable and temporary to support flexible uses. A type of so-called ‘kinetic buildings’—buildings with movable components driven by engines—is being explored in the architecture field (Dąbrowska-Żółtak et al., 2021; Engadget, 2019; Megahed, 2017; Parametric Architecture, 2024). Real-world cases, such as The Shed building, Manhattan, New York (Figure 4.18), demonstrate the concept, yet built examples remain rare due to high construction costs and maintenance. Similarly, temporary structures and buildings designed for re-assembly (Miguel, 2024) offer flexible solutions (Figure 4.19). In station examples, Shanghai South Railway Station and Beijing West Station, there are spare checking machines in the gate areas to be used during peak times. In addition, unique station examples, like Rotterdam Stadion Station, are used only during event periods.

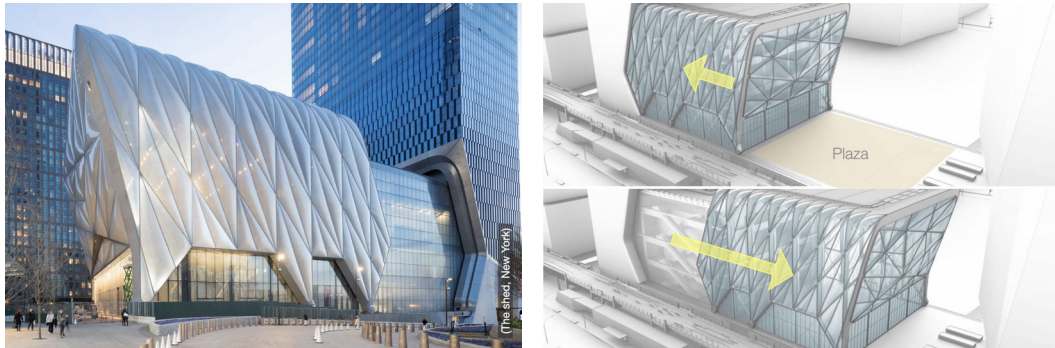


FIG. 4.18 A changeable building—The Shed. (Source: [Architecturaldigest.com](https://www.architecturaldigest.com))

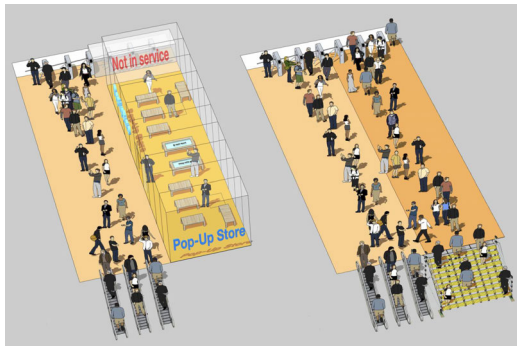


FIG. 4.19 Changeable elements of buildings. (Source: Author)

4.3.3 Establishing high-quality *connections* at different scales

To flexibly use spaces for transport and non-transport activities at different times, people should be able to move freely, requiring stations and surrounding city areas to be well-connected. The connections between the station and city can be established at different spatial scales in diverse forms, including city axes, path networks in the districts, passages across railways and station buildings, and smooth landscapes.

4.3.3.1 City axes

City axes (Figure 4.20) delineate the main urban structure, 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 station area (re)development projects like the Amsterdam Bijlmer ArenA station area, the Rotterdam Central station area, Utrecht Central station area (Figure 4.21), and the Delft station area.



FIG. 4.20 Two city axes were planned during the redevelopment of the Utrecht Central station area. (Source: [Structuurplan, Stationsgebied Utrecht](#), December 2006)



FIG. 4.21 District-level axes connecting stations with neighborhoods. (Source: Author)

4.3.3.2 District-level path networks

The station and its city neighborhoods should be well-connected by district-level path networks (Figure 4.22 and Figure 4.23). Several common barriers and bottlenecks can hinder their performance, including: stairs; lengthy, narrow, and boring paths; tunnels

and skywalks/footbridges, which require effort to climb walking areas that are interfered with by intensive vehicle traffic; paths with sudden changes in the width, causing greater bottleneck effects (Rzezonka et al., 2021); and strict security checking points or ticket gates.

To maximize accessibility and comfort, during the design process, such barriers and bottlenecks should be avoided, and corresponding design strategies can be taken. For example, ground-level paths can be prioritized to minimize level changes and preserve the street-level walking experience, while pedestrian routes can be separated from traffic either through horizontal alignment or by submerging or elevating roadways. In addition, paths should be shaped with well-considered geometries that allow for smooth transitions in width, ensuring comfort and continuity for users.



FIG. 4.22 Reduce barriers to ease flow (at the district level). (Background image source—Meipian.cn; annotated by author)

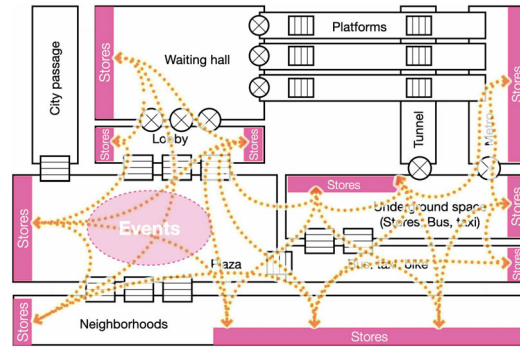


FIG. 4.23 Reduce barriers to ease flow (at the building level). (Source: Author)

4.3.3.3 Cross-railway passages and their positioning

Railway tracks are commonly seen in station areas, cutting city areas apart. In this context, to enable easy pedestrian movement, cross-railway passages are needed. At the district level, these passages across railway tracks should be positioned according to the stations' usage as well as the city neighborhoods' conditions (Figure 4.25). 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 (Figure 4.24).

The more passages, the more choices for pedestrians to pass through; however, it takes financial costs to build passages. Moreover, for large railway stations at the building level, it is usually difficult to vertically arrange the passages with many other fundamental elements, such as railway platforms, the ground, and stations' internal passages.



FIG. 4.24 The city passages (at the building level). (Source: [Amsterdam-viptours.com](https://amsterdam-viptours.com))

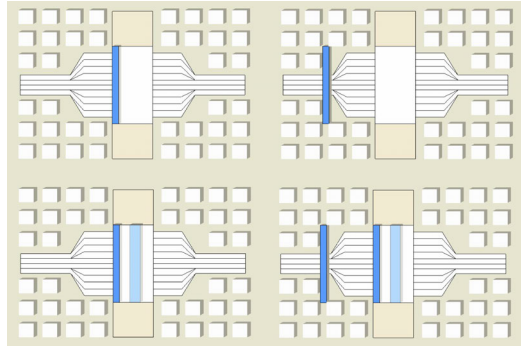


FIG. 4.25 Position city passages (at the district level). (Source: Author)

4.3.3.4 Smooth level changes through landscape design

Level changes are common in station areas due to many station buildings being multi-floor, or having topographic variations in the surrounding landscape. Stairs are a common solution for managing level changes; however, they present limitations—such as hindering pedestrian flow and posing a risk of falls. For larger level changes, escalators serve as an alternative. For small level changes, an alternative to stairs is to create smooth transitions through landscape design. Smooth landscape design is applicable at both the district and building levels (Figure 4.26 and Figure 4.27). At the building level, it occasionally provides a fresh spatial experience, as demonstrated in the Arnhem Central Station case. One drawback of implementing landscape design to smooth level changes is that it often involves high construction costs; thus, escalators may serve as a more economical alternative, especially for significant level differences. Additionally, such landscape solutions risk causing wayfinding confusion for users unfamiliar with these spatial configurations.



FIG. 4.26 Smooth level changes by landscape design (at the district level). (Source: [ThePaper.cn](https://thepaper.cn))



FIG. 4.27 Smooth level changes by slopes (at the building level). (Source: [UNStudio.com](https://unstudio.com))

4.3.4 Adopting *dispersed* layouts for transport capacity or urban vibrancy

4.3.4.1 Increase accommodating capacity by dispersed layouts of mobility nodes

Railway stations typically include many mobility nodes, like metro stations and entrances, bus stations or stops, tram stops, and parking lots. A dispersed layout of multiple mobility nodes, compared to a concentrated layout, helps to prevent the sudden congregation of pedestrians during peak times and accommodates more stranded passengers, reducing the risk of stampedes. In real-world cases like Shanghai Railway Station, as many as eight bus stations are evenly dispersed around the train station (Figure 4.28). When organizing events in cities, according to an expert during the interview, it is common practice to use multiple event sites dispersed across a large city area, preventing people from sudden congregation during particular situations, for example, when it is raining.

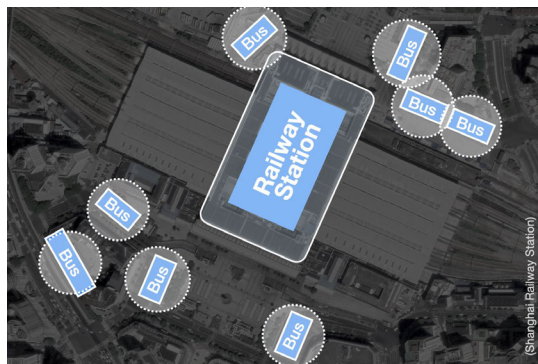


FIG. 4.28 Increase transport capacity by dispersed mobility nodes (at the building level). (Source: Author)

4.3.4.2 Enliven city environment by dispersed layouts of mobility nodes

If areas around a station are underutilized during non-peak times, adopting dispersed layouts can encourage pedestrians to walk longer distances, thus enlivening the area (Figure 4.29). In Japan, many stations have such layouts because different railway companies historically developed their own facilities close to one another. A well-known case is Tokyo's Shibuya Station, which features numerous entry and exit points connected to various mobility networks, such as the metro, bus, and pedestrian walkways. This arrangement encourages people to move through the area for diverse purposes—commuting, leisure, or shopping—thereby keeping the environment lively

even during off-peak hours.

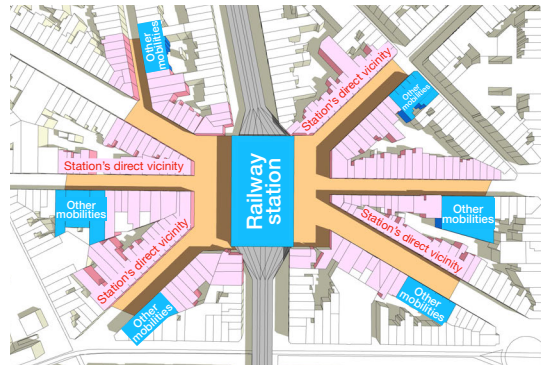


FIG. 4.29 Enliven city environment by dispersed mobility nodes (at the district level). (Source: Author)

Despite their advantages, dispersed layouts may result in harder wayfinding for pedestrians (Jay, n.d.). Therefore, it is necessary to keep a balance between being dispersed and concentrated when designing the layout of mobility nodes.

While the dispersed layouts discussed above emphasize mobility nodes, the broader relationship between stations and their surrounding urban fabric can also be understood through station–city layout typologies. Qi and Lu (2019) distinguished spaces as belonging either to the station or to the city, and categorized their spatial layout into six types: separated, connected, adjacent, inserted, mixed, and stacked (Figure 4.30). Their study of multiple stations across diverse contexts shows that a single station often embodies several layout types in varying proportions. Building on these findings, the design of station–city layouts should be carefully adapted to the specific station context.

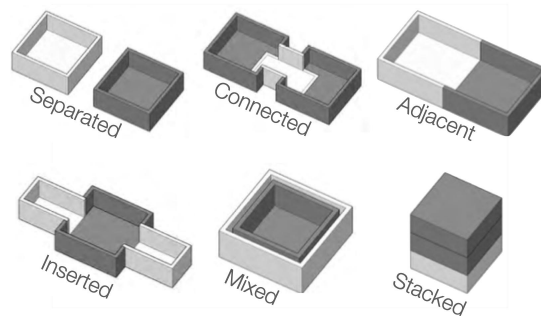


FIG. 4.30 Different general layouts of the station and city. (Source: Qi and Lu 2019)

One example highlighting the importance of station–city layout is the case of Utrecht Central Station. The former Utrecht Central Station building is mixed with the shopping mall building on the east, causing confusion and raising complaints as passengers can

not distinguish the two buildings. The design of the current Utrecht Central Station resolves this issue by adding a beautiful east plaza, separating the two buildings (Figure 4.31). This layout creates an urban environment around the station yet avoids confusion.

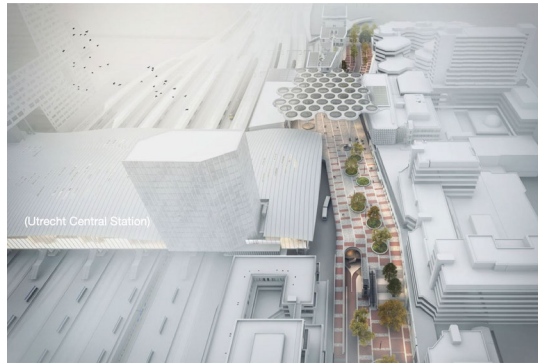


FIG. 4.31 The east plaza at Utrecht Stations separates the station building from the shopping mall. (Source: Santenco.nl)

4.3.5 Prioritizing core spaces for *humans* rather than vehicles

4.3.5.1 Human-centered spaces

Human experience is often overshadowed by a focus on transportation efficiency during the design of railway stations; however, aiming for flexible use to reduce underutilization, railway station areas must be human-centered so that they attract leisure users during non-peak times. The core accessible spaces in railway station areas should be supportive of leisure activities or even large events. Figure 4.32-left illustrates a basic diagram with a few essential features of a human-centered station space regarding the layout: The space is coherent at a core place in the station areas or in the station buildings, free from traffic elements or intensive pass-by transport flow, so that people would like to stay there. In contrast, the vehicle-oriented space in Figure 4.32-right does not have these features. The current and the former Rotterdam Central stations manifest this contrast clearly. The current Rotterdam Central Station (Figure 4.33-a) has a pleasant plaza which allows people to gather for festivals. This is achieved thanks to the current human-centered layout of mobility nodes—the car parking, bus stops, tram stops, and bike parking are all relocated aside or underground, leaving the core area free for people. In contrast, the former station plaza was full of traffic elements, making it impossible to hold leisure events (Figure 4.33-b). It is also helpful to provide seating in station areas for both passengers and leisure users, making stations not only efficient for transfer but also comfortable for lingering and staying.

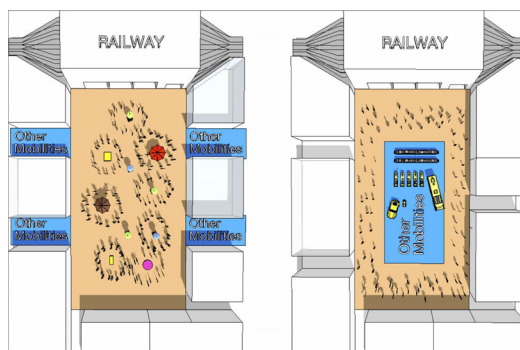


FIG. 4.32 Human-oriented spaces vs traffic-oriented spaces.
(Source: Author)

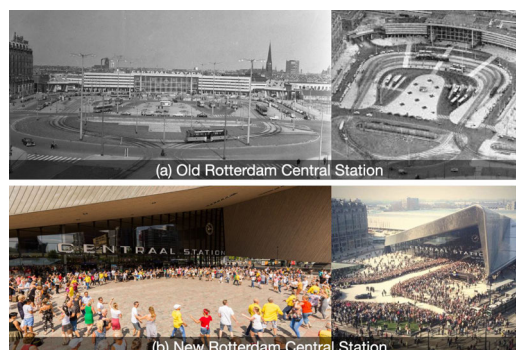


FIG. 4.33 The old and the new Rotterdam Central stations.
(Source: Upper-left - [Wikimedia.org](#); Upper-right - [Internaathetposthuis.nl](#); Lower-left - [Indebuurt.nl](#); Lower-right - [MVSA Architects](#))

4.3.5.2 High spatial qualities

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

4.3.5.3 Human scale

As explained in subsection 1.2.3, modern railway stations are prone to over-sizing. Therefore, designing railway station space at a human scale is essential to prevent them from becoming sterile, underutilized voids. To judge whether a station square is appropriately proportioned, there are classic spatial theories that govern physical dimensions and human perception. E.g., following Sitte (1889, pp. 39–44, The size and shape of plaza), a pleasant plaza functions as an 'outdoor room' where a comfortable sense of enclosure is preserved, suggesting that the horizontal distance between buildings should ideally not exceed twice the height of the principal building façade ($D/H \leq 2$). Beyond this enclosure relationship, Ashihara (1970, pp. 42–50, Scale) suggests that human spatial perception in exterior environments operates on a 1/10 scale module compared to interiors. This scales down comfortable, active outdoor spaces to an intimate boundary of approximately 20 to 25 meters, which represents the

natural limit for human visual recognition and vocal interaction. Scholars also notice an edge effect in space use—that the edges of the forest, beaches, groups of trees, or clearings were the preferred zones for staying, while the open plains or beaches were not used until the edge zones were fully occupied Gehl (1987). Therefore, creating active edges along spaces is also important.

When large spaces like station plazas must be designed larger to accommodate statutory peak-capacity passenger flows, it is architecturally necessary to subdivide these vast spaces into smaller human-scale squares. Rather than creating a single, amorphous concrete expanse, designers can implement 'soft' boundaries—such as stepped level shifts, tree canopies, low retaining walls, and flexible urban furniture. During non-peak hours, these sub-divisions create inviting, human-scaled sub-spaces that encourage dwell time and civic vitality, with active edges surrounding the boundaries of these sub-areas. During peak periods or major events, the soft nature of these boundaries allows the partitioned sections to seamlessly coalesce, preserving the spatial elasticity required for high-capacity transit flows and pleasant flexible temporal use (Figure 4.34).

If a station plaza must remain exceptionally large and cannot be easily subdivided, transforming the hardscape into green lawns is an alternative. Rather than laying out a vast, heat-absorbing expanse of concrete, using lawns allows the space to function as a restorative urban park during daily off-peak times while remaining flat and open enough to safely absorb surging pedestrian flows during transport peak times. This approach is common used in stadium design, and is exemplified by a rare station example of Jiaxing Railway Station, themed a 'train station in the forest' (Gooood n.d., Figure 4.35).



FIG. 4.34 King's Cross Station Square (7500m²). (Source: kemp architectural lighting.com)

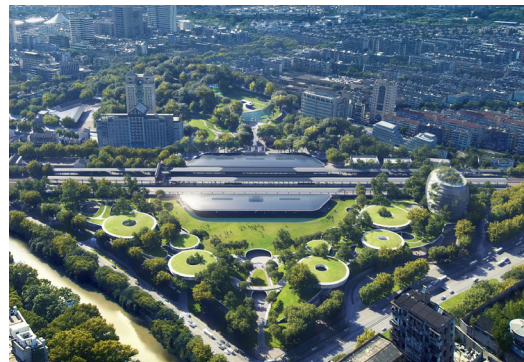


FIG. 4.35 'Train station in the forest'—Jiaxing station. (Source: Gooood, n.d.)

4.3.6 Enabling *flexible use* through programming

4.3.6.1 Planning stations with city infrastructures

To promote flexible use, city infrastructures can be programmed to work with railway stations, whether located nearby or located farther away. For example, green parks and pedestrian-friendly streets, if located next to stations, can be temporarily adapted to accommodate waiting passengers during railway peak times or to support evacuation during emergencies. Large infrastructures such as sports stadiums and music venues, which typically are not used on a daily basis, can be shared for stations' peak time transport use, even when they are not adjacent ([Figure 4.36](#)). In the real-world case of Guangzhou, China, during the Chinese New Year, when railway stations are under pressure from surging high volumes of passengers, stadiums in the city were planned for backup use of stations in case of emergencies ([Xinhua News Agency, 2016](#)).

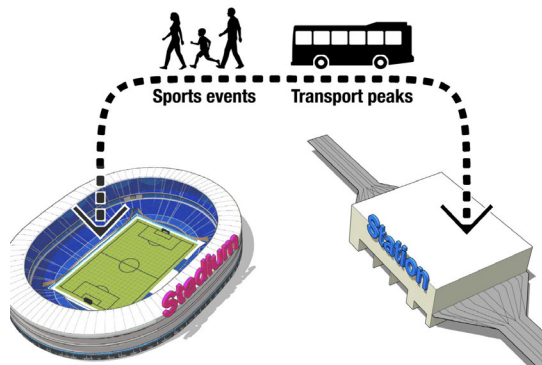


FIG. 4.36 Programming considering the temporal dimension (for flexible use). (Source: Author)

4.3.6.2 Dual uses of transport spaces

To promote flexible use, transport spaces for vehicle traffic can be programmed for temporary non-transport leisure activities ([Bendiks and Degros, 2020](#)), as exemplified by the seasonal practice of 'Paris Plages (Paris Beaches)'—every summer, a proportion of roads in Paris, normally used for vehicle traffic passing by, is temporarily transformed into beaches for diverse leisure activities ([De La Pradelle and Lallement 2004](#); [Figure 4.37](#)). Similarly, stations' transport spaces, when equipped with temporary installations or reconfiguration-supportive layouts ([subsection 4.3.2](#)), can also be programmed for leisure uses.



FIG. 4.37 'Paris Beaches'—Roads in Paris seasonally transformed into beaches in the summer. (Source: stadsstranden.nl)

4.4 Discussion

4.4.1 Non-design interventions

During this chapter's research process, a series of non-design, purely management interventions were mentioned by experts and by the author's colleagues. Although they are not the focus of this thesis, these non-design interventions meaningfully supplement the broader discussion of flexible use of stations. This chapter reports them as follows:

To avoid overcrowding and stampedes, there are management interventions, including: (1) Reschedule holidays for the public, letting different groups of people have the same holidays at different times; (2) Manage regional-level transportation. E.g., the coordination of scheduling trains between multiple railway stations in Amsterdam when there are sports events near Amsterdam Bijlmer ArenA station, spreading the capacity of stations to prevent overcrowding; (3) Shutdown stations; (4) Manage user expectations, notifying passengers that during peak time, there will be longer transfer times than usual; (5) Manage passenger access to the station building based on departure times. For example, only passengers with trains departing within the next two hours are allowed to enter, preventing the building from becoming overcrowded with early arrivals.

Notably, the above interventions from (1) to (5) involve decreasing temporal and spatial scales; typically, the smaller the temporal and spatial scales involved, the easier it will be to implement the interventions. Interventions (1) and (5) spread the travel demand across certain time periods; in comparison, intervention (2) spreads the travel capacity across certain stations (or spaces); Both strategies help mitigate the pressure

of large volumes of travelers coming to a station at a peak time.

4.4.2 Research contributions

This chapter has two contributions to the design knowledge body. First, contently, it provides design principles that practically facilitate designers in addressing the overcrowding-underutilization issue of stations. These principles also enrich the content of relevant academic discussions, such as urban open space, responsive landscape with a ‘loose-fit’ feature (Thompson, 2002), and traffic space as public space (Bendiks and Degros, 2020). Second, at the methodological level, this chapter provides a multi-step methodological framework that is generalizable for developing similar design principles in future research. This framework complements existing approaches (Alexander, 1977; Van Der Hoeven and Juchnevic, 2016), thereby expanding the methodological means for generating design principles. Compared to Christopher Alexander’s approach—developed over eight years of practice and evaluated largely through intuitive judgment (Alexander, 1977)—the proposed framework is more feasible within shorter research time frames due to its reliance on multiple data sources, and it produces more objective outcomes through systematic expert reflection.

4.4.3 Limitations and future research directions

This chapter exhibits two limitations. First, although the developed principles were reviewed by experts, they may still contains unforeseen limitations. Second, during interviews with field experts, it is noted that the design principles primarily address the spatial form of station buildings and their surround urban districts, while other crucial aspects—such as programming, user types, spatial qualities, nature-based solutions, and cost-benefit analysis of solutions—remain largely unexplored. Recognizing these limitations, future research should investigate these overlooked aspects.

4.5 Conclusion

This chapter addressed two research questions. In [section 4.1](#), two questions were presented: what are the design principles for railway station areas that support flexible use (aimed at reducing overcrowding and underutilization, and promoting station-city integration)? how can design principles of complex projects, like railway stations, be developed in a systematic way that enables synthesizing, probing, and validating knowledge? The first question is addressed by the resulting design principles: prioritizing core spaces for humans rather than vehicles, ensuring event visibility by aligning paths and spaces, establishing high-quality connections at different scales, incorporating temporary elements and reconfiguration-supportive layouts, adopting dispersed layouts for transport capacity or urban vibrancy, and enabling flexible use through program planning. The second question is addressed by the multi-step methodological framework for developing design principles, which contains identifying design objectives and assessment criteria, clarifying the spatial and managerial dimensions, learning iteratively from cases and literature through analytical visualization, and reflecting through expert interviews and case implementations.

Supplementary Materials

The detailed descriptions of the design principle development—[Appendix B](#).

5 Evaluating design principles

Through research-by-design and agent-based simulation

ABSTRACT Design principles are widely used in the design field, yet some remain visionary rather than grounded in real-world applications. Six visionary design principles were developed in [Chapter 4](#) for the flexible use of stations aimed at reducing overcrowding and underutilization. Assessing their effectiveness is therefore essential before implementation. This chapter aims to address the gap in validating these design principles. Recognizing the potential of jointly employing research-by-design and agent-based simulation, this chapter presents a major research **question**: How effective are these design principles, as demonstrated through research-by-design (RbD) and agent-based simulation (ABS)? **Methodologically**, it first applies the design principles to Station Xtreme and generates multiple design proposals, then simulates the generated proposals, followed by assessments and reflections. The **results** suggest that the principles are generally effective, though limitations emerged: for example, quality connections may demand greater investment and space, while dispersed layouts can increase wayfinding difficulty and operational complexity. This chapter contributes to the growing body of design knowledge by validating these flexible-use principles. It also establishes a transferable conceptual framework that integrates RbD and ABS, offering a novel methodological approach for testing other visionary design principles.

KEYWORDS Urban design, architectural design, simulation, validation

5.1 Introduction

Design is inherently a forward-looking discipline, focused on inventing innovative solutions for a better future—often addressing challenges or possibilities that do not yet exist in the real world (Cross, 1982; Nijhuis and Bobbink, 2012). Within this context, design principles are widely used to guide creative decision-making. Some principles are derived from analyses of built projects and are therefore grounded in practice, while others are visionary in nature, proposing directions for future development. These visionary principles function less as proven rules and more as hypotheses—speculative ideas that require validation through application and evaluation.

As described in [Chapter 4](#), six major spatial design principles were developed for the flexible use of stations aimed at reducing overcrowding and underutilization (see also the [project website](#)), including:

- 1) ensuring event visibility,
- 2) incorporating temporary elements and reconfiguration-supportive layouts,
- 3) establishing high-quality connections at different scales,
- 4) adopting dispersed layouts for transport capacity and urban vibrancy,
- 5) prioritizing core spaces for humans rather than vehicles, and
- 6) enabling flexible use through program planning.

These design principles were inspired by or inferred from station and non-station buildings of multiple scales and contexts, and their effectiveness is hypothetical, as not all of them have been implemented in the real world. Regarding validation, ideally, whether design principles are effective should be observed before and after the construction of the projects that use the principles. However, this is practically challenging because large infrastructure projects like railway stations usually take years or even decades to build, and this time range usually falls outside typical research projects' time frames. Alternatively, in [Chapter 4, subsection 4.2.4](#), this research has conducted expert interviews to reflect on the design principles, providing an initial validation. Complementary to expert interviews, this chapter sees two methods—research-by-design and agent-based simulation—as potentially helpful for validating visionary design principles.

Research-by-design (RbD), also called 'research through design' or 'study by design', is a methodological approach where design practice becomes the primary mode of inquiry to generate new knowledge (De Jong and Van Der Voordt, 2002; Klaasen, 2003; Habraken, 2005; Cross, 2011). Unlike traditional research that analyzes designs only after they are completed, RbD integrates research into the design process itself—exploring questions and generating knowledge before designs are built. By using prototyping, making, and iteration as research tools, RbD actively investigates

how different design solutions and their contexts influence one another (De Jong and Van Der Voordt, 2002, p. 21). In this way, design solutions are intrinsically assessed.

Agent-based simulation (ABS) is another valuable approach for spatial design assessment. In the spatial design practice, the spaces being designed are mostly for humans to use; ABS, using agents mimicking humans, takes the end-users into core consideration in design. Simulation, by computationally quantifying the measurement, adds more objectivity to assessment, complementing other traditional design evaluation approaches such as research-by-design, which heavily rely on personal judgment (See also subsection 6.1.3).

5.1.1 Research objectives and conceptual framework

Building on the visionary design principles and validation potentials outlined above, this chapter sets two objectives: (1) to address the gap in validating design principles for flexible use (which address overcrowding and underutilization in stations), and (2) to explore the potential of combining research-by-design with agent-based simulation in the assessment of design principles. To achieve these objectives, an initial challenge arises: design principles can not be modeled through agent-based simulation, as design principles are not systems themselves. To address this, the study designed an indirect approach—applying the design principles to a design project to transform them into design proposals, then simulating the design proposals, and finally, by observing the performance of the design proposals, it is feasible to see the effectiveness of the corresponding design principles. With this methodological adaptation, this chapter proposes a conceptual framework illustrated in Figure 5.1.

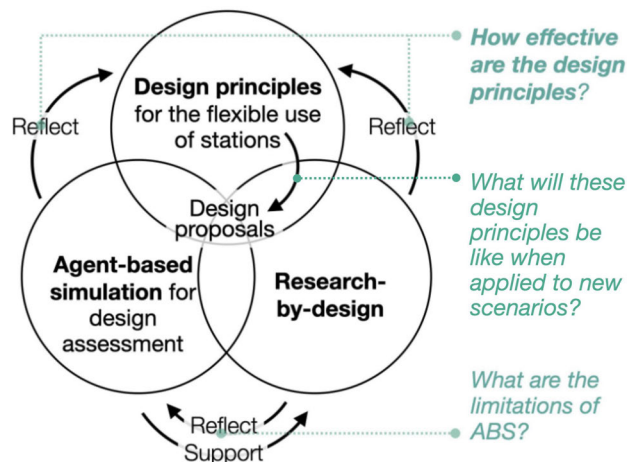


FIG. 5.1 This chapter integrates multiple research topics. (Source: Author)

In this conceptual framework, multiple components work together to integrate and enhance one another. In the process of generating design proposals through research-by-design and the follow-up assessment through agent-based simulation, new understandings emerge, allowing critical reflections on the design principles' effectiveness. By introducing computational quantification, agent-based simulation complements traditional spatial design assessment methods like research-by-design, which rely heavily on expert judgment. In the practice of research-by-design, where design principles' effects are examined, this chapter also provides an opportunity to reflect on the limitations of agent-based simulation ([Figure 5.1](#)). Within the framework, this chapter addresses a major question and two minor questions:

How effective are the design principles of flexible use of stations, as demonstrated through research-by-design and agent-based simulations (ABS)? What will these design principles be like when applied to new cases? What are the limitations of ABS in assessing complex projects like railway stations?

To answer these questions, this chapter conducted research-by-design to apply the design principles, followed by an assessment using agent-based simulation. This chapter provides detailed insights into the design principles in new scenarios for understanding their effectiveness. It also highlights the potential and limitations of agent-based simulation in design assessment. The remainder of this chapter is organized as follows: [section 5.2](#) describes the methodology; [section 5.3](#) presents the assessment results; [section 5.4](#) discusses the relevant research implications, contributions, and limitations; and [section 5.5](#) concludes.

5.2 Study design

This section implements the conceptual framework ([Figure 5.1](#)) with practical details. This chapter first employs the research-by-design approach, applying the design principles to Station Xtreme and generating multiple design proposals. Then, it simulates the generated proposals through agent-based simulation, followed by assessments and reflections. The following subsections explain the context of the station case ([subsection 5.2.1](#)), the features of design proposals ([subsection 5.2.2](#)), the settings of simulations ([subsection 5.2.3](#)), and the logic of assessments ([subsection 5.2.4](#)).

5.2.1 Context of the case

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

This virtual case includes multiple features highly relevant to the whole research's objectives—overcrowding and underutilization, flexible use, and station–city integration (section 1.5). In the case's setting, a stadium is situated near the railway station, with fluctuating numbers of users transferring between the stadium and the station. The peak time number is set referencing Amsterdam Bijlmer ArenA station's passenger number from its nearby stadium, Johan Cruijff ArenA (Aseniya, 2019). This setting challenges the station design, requiring it to be supportive of flexible use aimed at reducing overcrowding and underutilization. The station's spatial layout is set referencing the Amsterdam Sloterdijk Station area, where the station and the nearby city areas are significantly separated by traffic roads, viaducts, and open-air parking lots. This setting challenges the station design, requiring it to promote station–city integration. The origin–destination (OD) matrix of passengers, which highly relies on spatial layout, is set referencing Amsterdam Sloterdijk Station's (Figure 5.2).

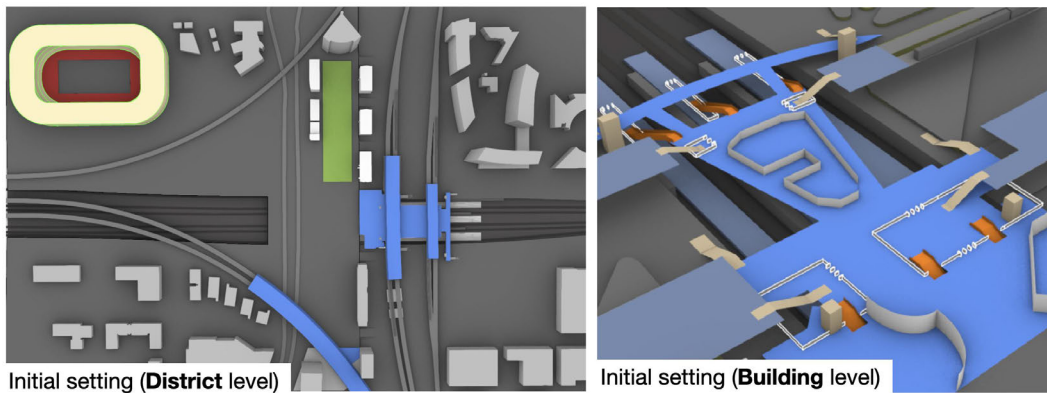


FIG. 5.2 The initial spatial settings of the case at the district and building levels. (Source: Author)

5.2.2 Design proposals

This chapter develops design proposals for the case of Station Xtreme in two stages: first, through a workshop with 20 participants, and then through the author's iterative refinement. The author refined the proposals from the workshop to make each proposal's features more distinct and representative of the design principles.

Four district-level proposals (indexed as DX) with different features were made (Figure 5.3 and Table 5.1). Proposals D1 and D2 have a more dispersed layout with three station buildings. D1 has a landscape with many pedestrian path choices and supports more reconfigurations of them (e.g., opening and closing some paths during different times for controlling pedestrian flows). While Proposal D1 emphasizes the quantity of connections, D2 emphasizes the quality of connections. D1, D2, and D3 are human-centered, with pedestrian-friendly paths and human-scale buildings. In contrast, D4 is a vehicle-oriented proposal, with wide roads and a large vehicle parking area in front of the station's main entrance. The new buildings in D4 are also relatively large and tall, following a 'modernism' style. Regarding these features, this chapter rates the proposals with relative rankings of 'High' or 'Low', or categories of 'Yes' or 'No' (Table 5.1).

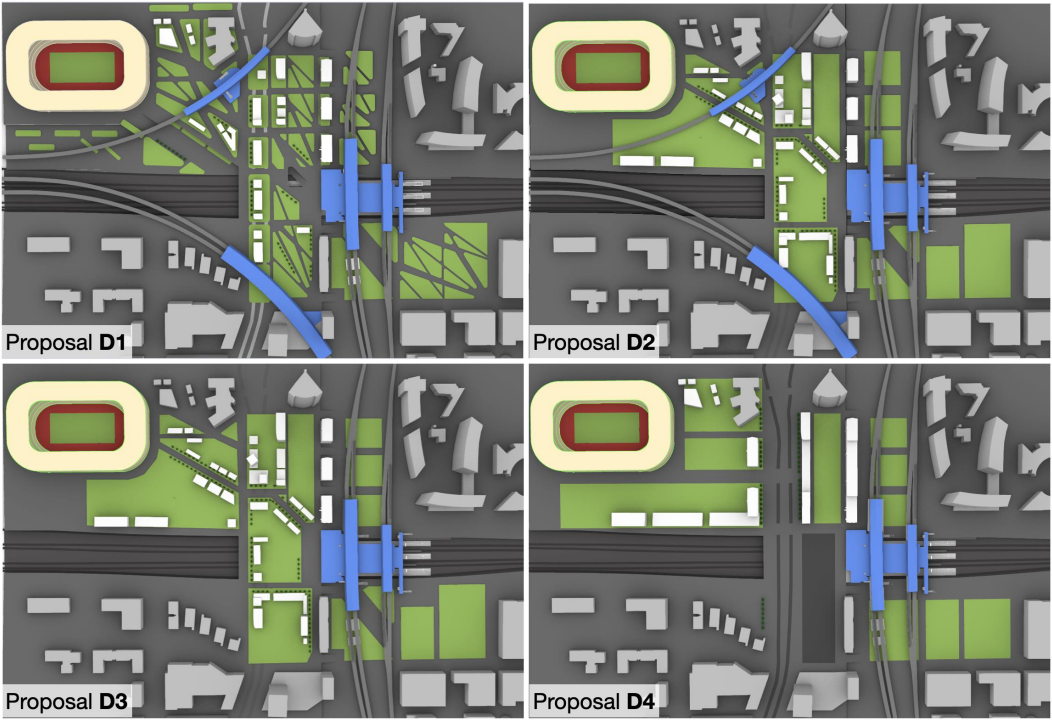


FIG. 5.3 District-level proposals. (Source: Author)

TABLE 5.1 District-level design proposals

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

Three building-level proposals (indexed as BX) with different features were made

(Figure 5.4 and Table 5.2). Proposals B1 and B3 support events to be held in the hall, while B2 has no large space for holding events. B1 has a wide station hall, supporting more routes (which essentially are ‘connections’ from origins to destinations) choices. B1 and B2 are more dispersed regarding their layout of stairs (colored in orange in Figure 5.4), while B3 is more concentrated. Regarding these features, this chapter rates the proposals with relative rankings of ‘High’ or ‘Low’ (Table 5.2).

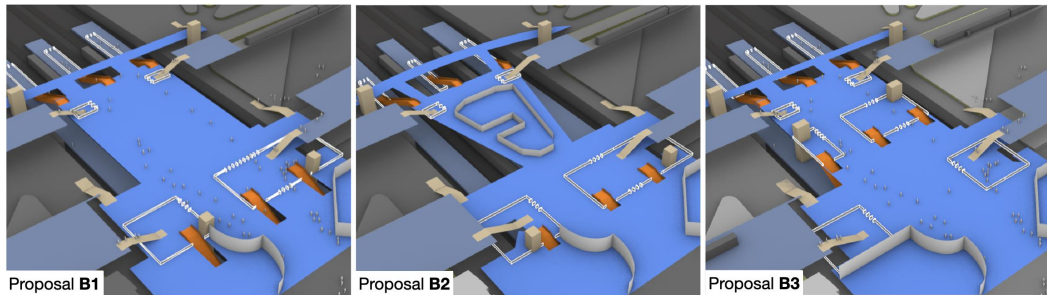


FIG. 5.4 Building-level proposals. (Source: Author)

TABLE 5.2 Building-level design proposals

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

5.2.3 Settings of agent-based simulation for the assessment

This chapter adopts the agent-based simulation framework from Enshan et al. (2025b)’s work. This framework provides systematic evaluation criteria for assessing stations’ performances and the digital tools for simulation. It requires an Origin-Destination (OD) matrix data as a necessary setting, and its optional settings include temporal scenarios associated with flexible uses.

5.2.3.1 The evaluation criteria or station performances

The evaluation criteria for station performance are adopted from Enshan et al. (2025b)’s assessment framework. Initially based on five types of user needs (Hagen and Heilligers, 2015), these criteria are translated into measurable indicators:

- Safety [indicated by agents' crowding density during peak time, the space capacity to accommodate stranded passengers during disruption time, and 'eye-on-the-street' (Jacobs, 1961) during normal time]
- Transfer distance
- Ease of wayfinding [indicated by the agents' degrees of direction change]
- Comfort of facilities [Not applicable in this chapter]
- Visual experience [calculated through a linear regression formula that incorporates multiple factors in agents' views: the proportion of trees, sky, buildings, water, and the number of pedestrians]

5.2.3.2 The digital tools for simulation

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

5.2.3.3 Temporal scenarios associated with flexible uses

This chapter sets three temporal scenarios associated with flexible uses: normal time (weekday non-rush hours), peak times (after a football match when massive stadium spectators come to the station), and disruption time (when the railway has disruptions and trains are delayed). These time scenarios are denoted as [Normal time], [Peak time], and [Disruption time] in this chapter). In different temporal scenarios, different numbers of agents are used (Table ??), and different types of user experiences are examined (Table 5.4).

5.2.3.4 OD matrix

This chapter deduces the OD (Origin-Destination) matrix (Table ??) based on the data published on the NS website (NS, n.d.). This website documents all the stations in the Netherlands with their number of overall passengers, passengers of transfer, and modal split. The number of passengers transferring between the new stadium and the station, during the peak time, is derived by referencing the data from Amsterdam

Bijlmer ArenA Station. The OD matrices also incorporate temporal fluctuations.

TABLE 5.3 The OD matrix simulating the transfers between stations and other places

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

Note: [1] Each value represents a number of agents as a proportion of the total passenger count. The total passenger count is 711/hour (access/egress separated) during the weekday non-rush hours.

[2] In the district-level design proposals, there are three possible stations, with 10, 2, and 1 rail tracks. The ratio of agent numbers for these stations is correspondingly set as 10 : 2 : 1.

[3] The ratio of agent numbers per hour during evening rush time : off-peak time is set as 4.75 : 1.

^a Passengers who switch between platforms.

^b It may seem strange here as the agent number for 'normal time' is higher than 'peak time.' This is because these scenarios are named from the perspective of the railway station instead of the stadium. Normal time is 'normal' for passengers in railway transport, whereas it is kind of 'peak' time for people in the post-match dispersal from the stadium. The flow from the stadium is simulated for a short period of 5 minutes to mimic a post-match dispersal, referencing the data from Amsterdam Bijlmer ArenA station (Aseniya, 2019). Compared to the rushed egress from the stadium, ingress is typically smoother, as spectators arrive gradually over several hours before the match begins.

5.2.3.5 Agent parameters

This research defines the agent characteristics in two ways: First, it adopts MassMotion's default setting of agent behavioral parameters, including individual optimum moving speed, direction preference, and height. These parameters are based on multiple scientific research works (Kinsey et al., 2015). Second, it defines agents' visual perceptual ability based on the work of Enshan et al. (2025b), which builds on a series of technical studies that extract data from human-rated street images.

Of note, in the simulations, the inputs are different design proposals (subsection 5.2.2), and the outputs are design proposals' performances, which are based on evaluation criteria (subsubsection 5.2.3.1). Other things, including agent parameters, the OD matrix, and temporal scenarios (subsection 5.2.3), are settings; Although inputs and outputs are different from proposal to proposal, settings are all the same in simulations.

5.2.4 Make comparisons between design proposals

This chapter compares the design proposals, observing their corresponding performance differences, to investigate the effects of principles on station performances (Table 5.4). The performance examination considers multiple aspects, including spatial scales and scopes, time, people, and experiences. For example, when analyzing transfer distances, these aspects are specified. Different users have different sensitivities to transfer distance in station areas—stadium spectators are less sensitive to distance, while railway travelers are more sensitive to distance. Therefore, when analyzing transfer distance, this paper differentiates the groups of agents that represent these people. Building-level proposals only influence the journeys that happen within the station buildings, while district-level proposals affect the journeys that happen on the district level. Therefore, when analyzing transfer distance, this paper specifies the spatial scope of journeys.

TABLE 5.4 Proposal comparisons

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

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

5.3 Results

This section presents the simulation results. In general, the results show that every proposal has its pros and cons (Figure 5.5). D2 and B1 excel the most in the performances. The following subsections explain each design principle's effects on the related proposals.

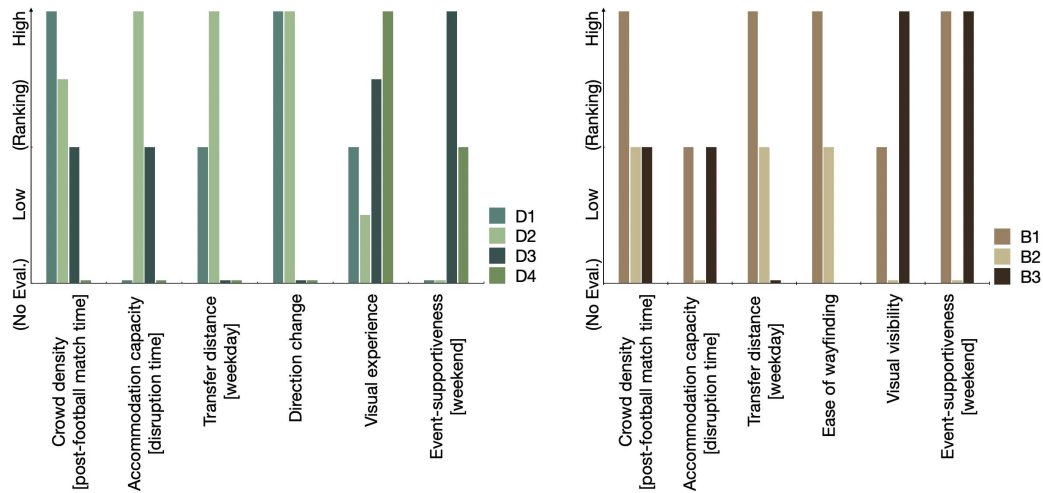


FIG. 5.5 Proposals' performance (Source: Author. The vertical axis denotes each proposal's relative ranking among all related proposals)

5.3.1 The effects of Principle 1 (event visibility)

Figure 5.6 shows the simulation results of proposals B1 and B3 during weekends when an event is going on. In B1, the event is located in the central area, while in B3, the event is located near the main entrance. The event in B3 is visible to 47.47% of agents during their journeys, while the event in B1 is only visible to 21.23% of agents during their journeys. This is because more agents pass by the main entrance area. This shows that when adopting design principle one, the location of events matters. The event location should be considered with respect to pedestrians' routes.

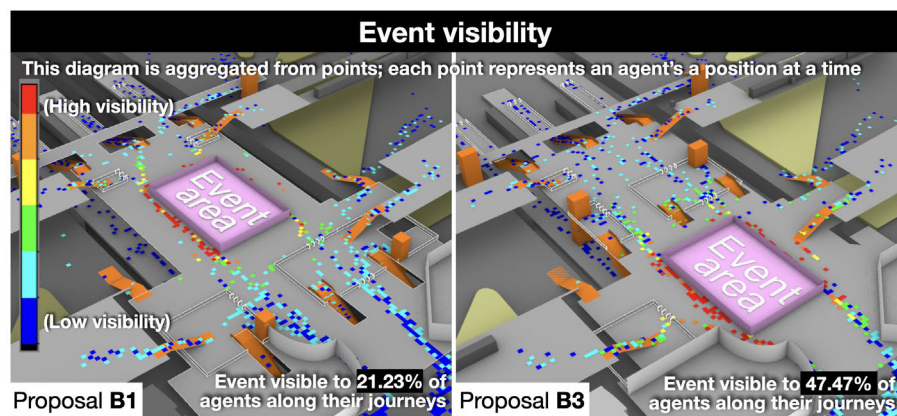


FIG. 5.6 Event visibility in proposal B1 and B3. (Source: Author)

5.3.2 The effects of Principle 2 (reconfiguration-supportive layouts)

During the stadium peak time, in D2, when massive passengers move towards stations, some paths (see paths 9 and 10 in ?? - top) can be closed to avoid overcrowding. In D1, on-site staff can even guide pedestrians to the normally redundant paths (i.e., the path colored in yellow in Figure 5.7, or the path 11 in ?? - bottom) to further reduce the crowd density. D1 enables lower crowd density than D2.

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

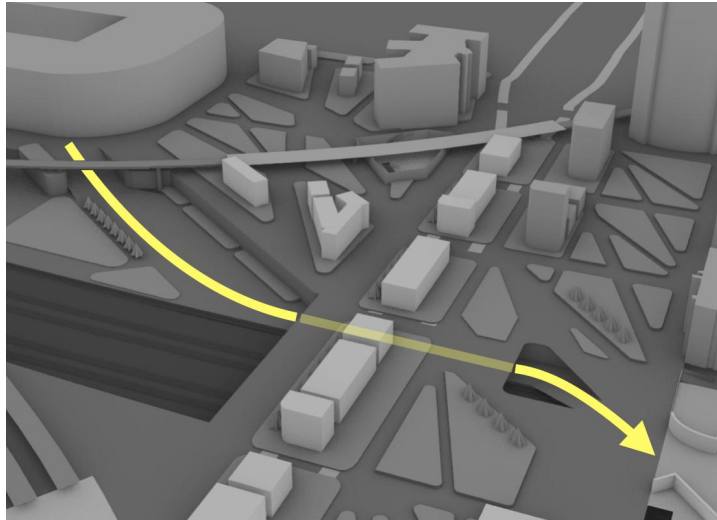


FIG. 5.7 The shortcut path in proposal D1. (Source: Author)

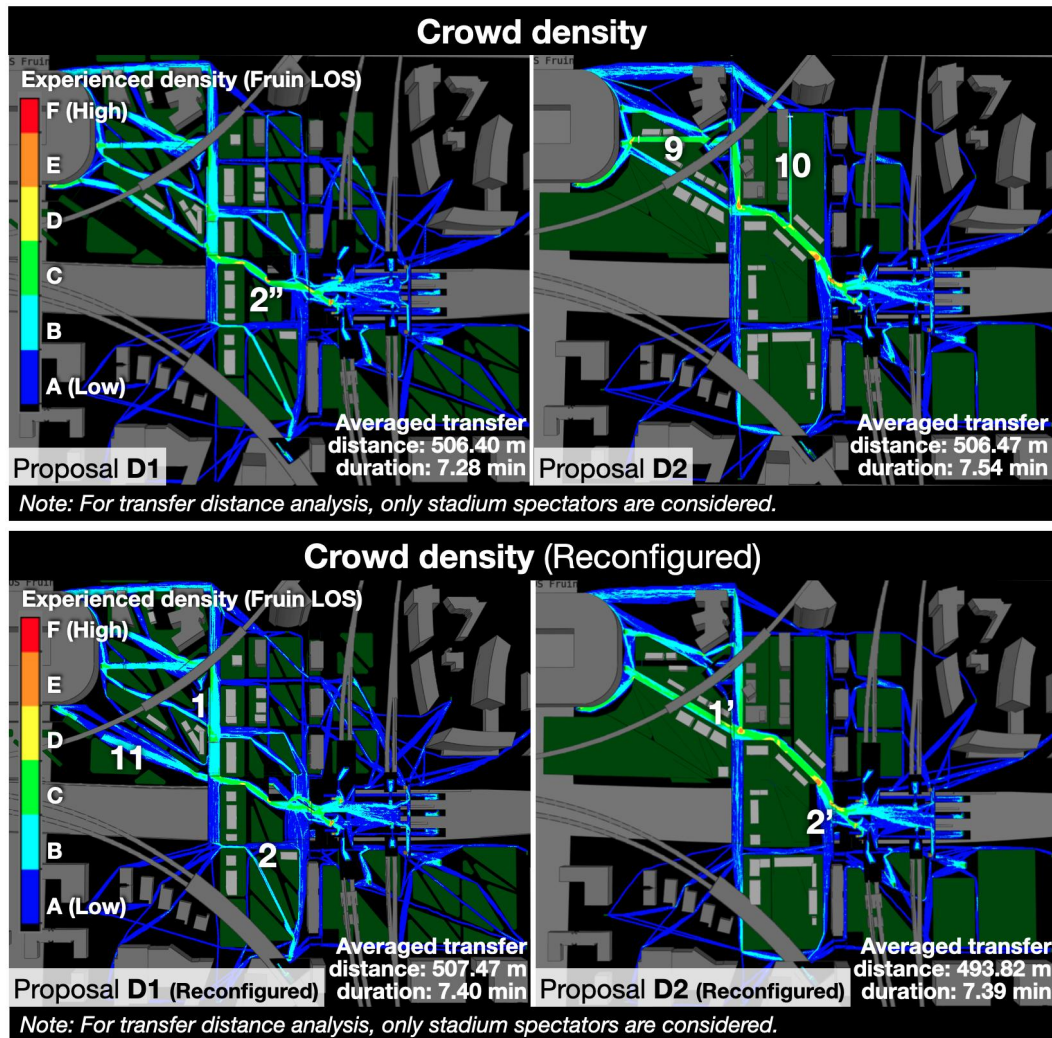


FIG. 5.8 The crowd density in proposals D3 and D4 (Source: Author)

5.3.3 The effects of Principle 3 (quality connections)

Proposal D1 has many walkable paths (connections) and emphasizes the quantity of connections, while D2 has fewer connections and emphasizes the quality of connections. D1 has more connections and supports more configurations, enabling it to have a lower crowd density during peak times (see subsection 5.3.2, ??). With a dense, walkable network, D1 also provides more route choices. Some routes are comparatively shorter in D1 than in D2 (see routes 5 vs 5'). However, the many

connections in D1 come with more costs. As cut by a dense pedestrian street network, D1 has less suitable plots for large-sized buildings (see the new buildings in [Figure 5.9](#) - middle, colored in white), and less green space (see the green areas in [Figure 5.9](#) - middle).

In the simulation, counterintuitively, agents in D1 walk longer distances. This may be due to the algorithm used in the simulations. The simulation is based on the social forces algorithm [Helbing and Molnár \(1995\)](#), which has a force that models attractive effects (e.g., pedestrians stay close to friends, or are attracted by interesting objects). As D1 has more routes, agents may sometimes be 'attracted' to routes that are not necessarily the shortest.

The street visual quality and route direction changes are similar in the two proposals. Only in a few spots, D1 has higher visual quality values (see locations 3, 4, 3', 4' in [Figure 5.9](#) - bottom). In summary, the district-level dense walkable network enables lower crowd density during peak times, makes negligible differences in the direction changes and visual perception of agents, and does not necessarily lower the agents' walking distance.

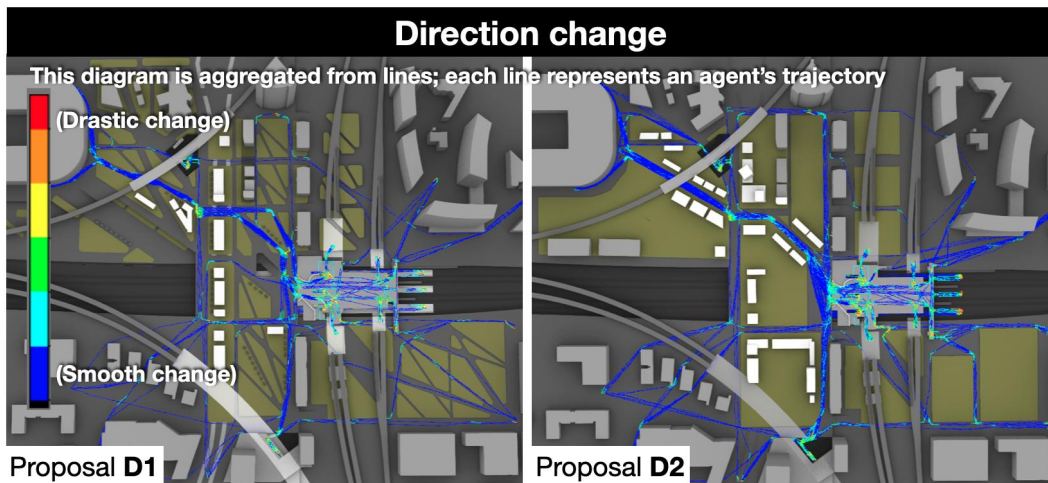


FIG. 5.9 The direction change, transfer distance, and visual quality in proposals D1 and D2. (Source: Author)

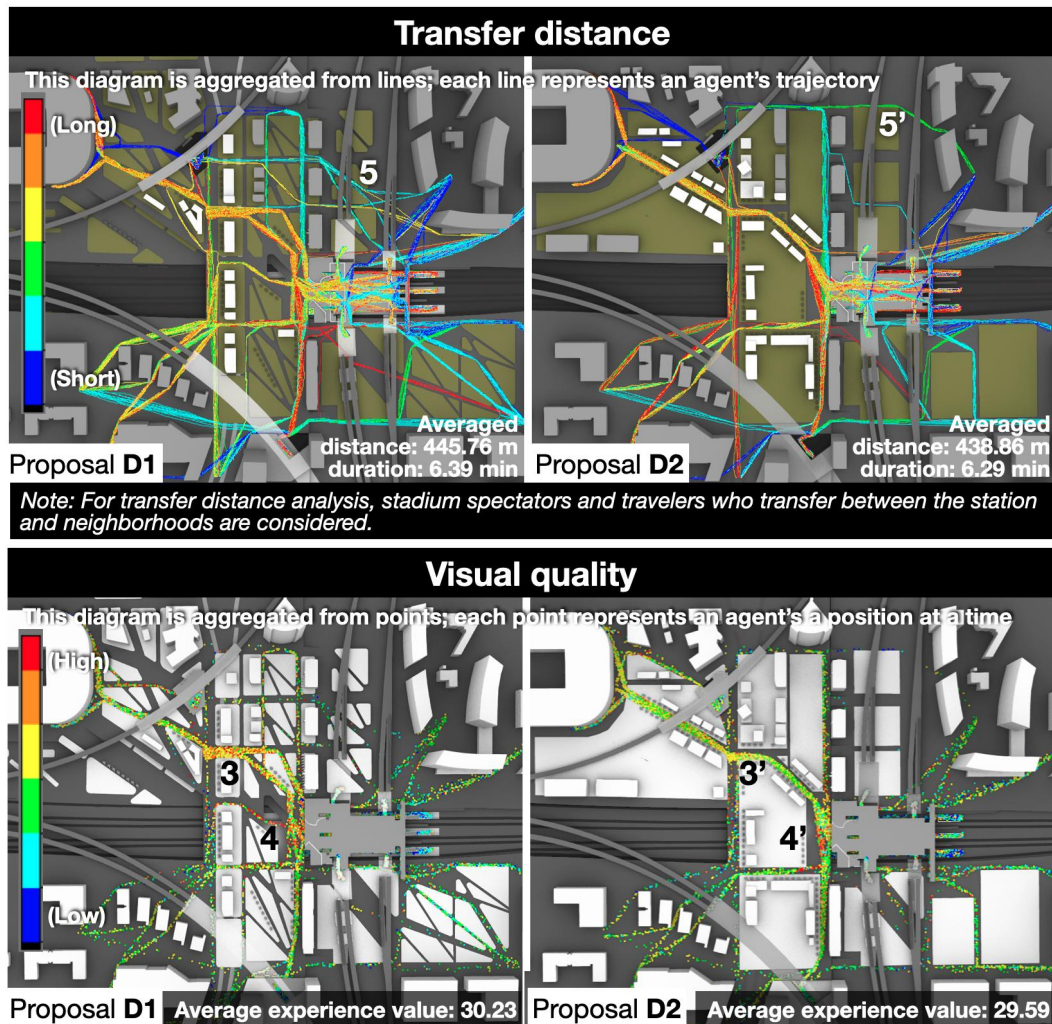


FIG. 5.9 The direction change, transfer distance, and visual quality in proposals D1 and D2 (continued). (Source: Author)

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

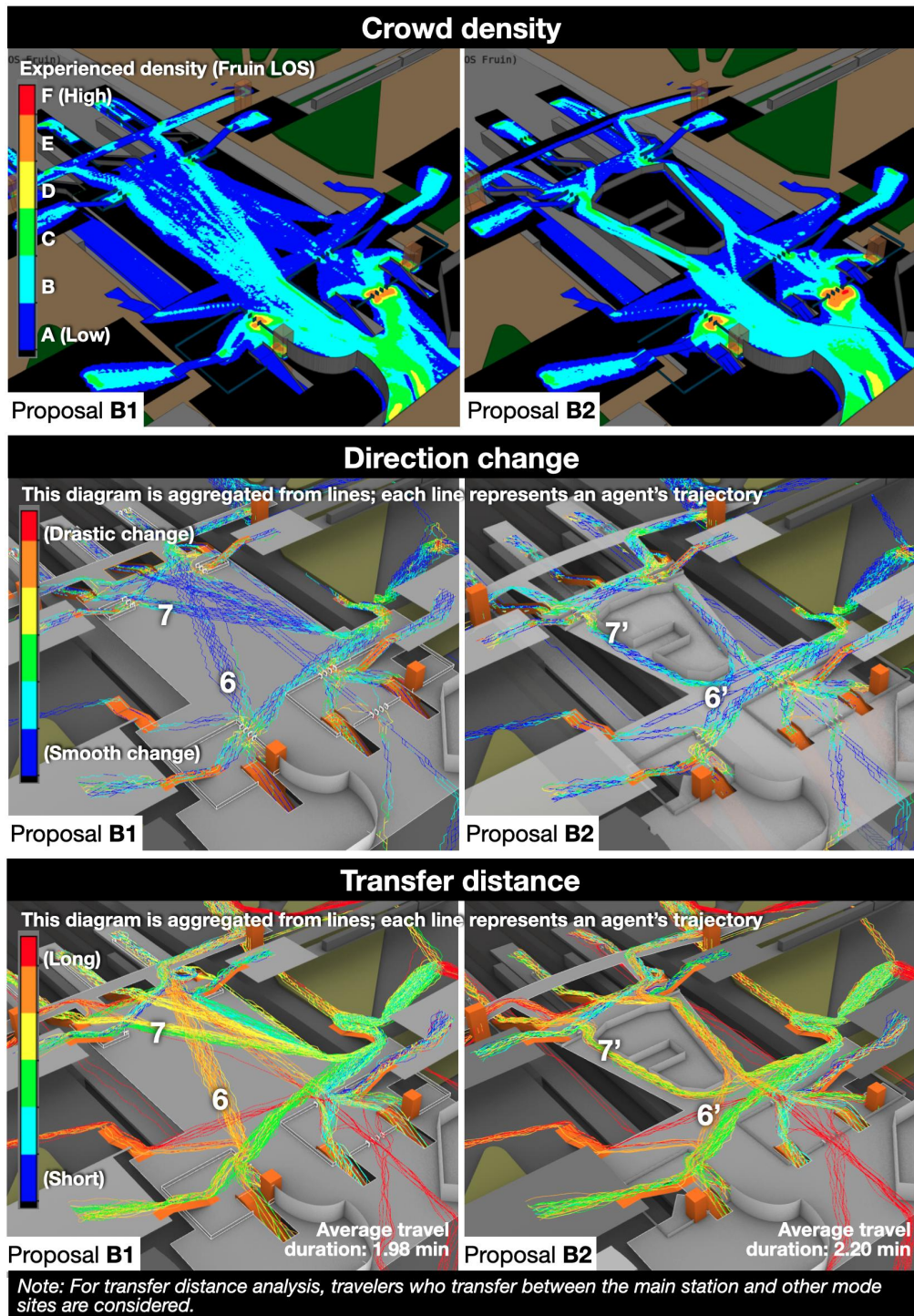


FIG. 5.10 The crowd density, direction change, and transfer distance in proposals B1 and B2. (Source: Author)

5.3.4 The effects of Principle 4 (dispersed layouts)

Regarding the railway station building(s), proposal D2 is designed in a dispersed layout (with three station buildings at three locations), while D3 is designed in a concentrated layout (with only one station building). During peak times, the crowd density in D2 is lower than in D3 at some points (e.g., locations 17 and 17' in Figure 5.11 - top). The density difference is not significant because the passenger volume shared by the two small stations is not significant (the small stations in D2 only add three extra tracks to the main stations' 10 tracks). During disruptions, D2 also has a better accommodating capacity for stranded passengers (see crowding accumulated at locations 15 vs 15' in Figure 5.11 - middle). The averaged visual quality is slightly higher in D2 than in D3 (Figure 5.11 - bottom). This may be due to the higher proportion of agents going through the high-quality main path in D2. Another drawback of the dispersed layout is that it adds to the difficulty of wayfinding. When people have to choose one among three stations, they may mistakenly go on the wrong path.

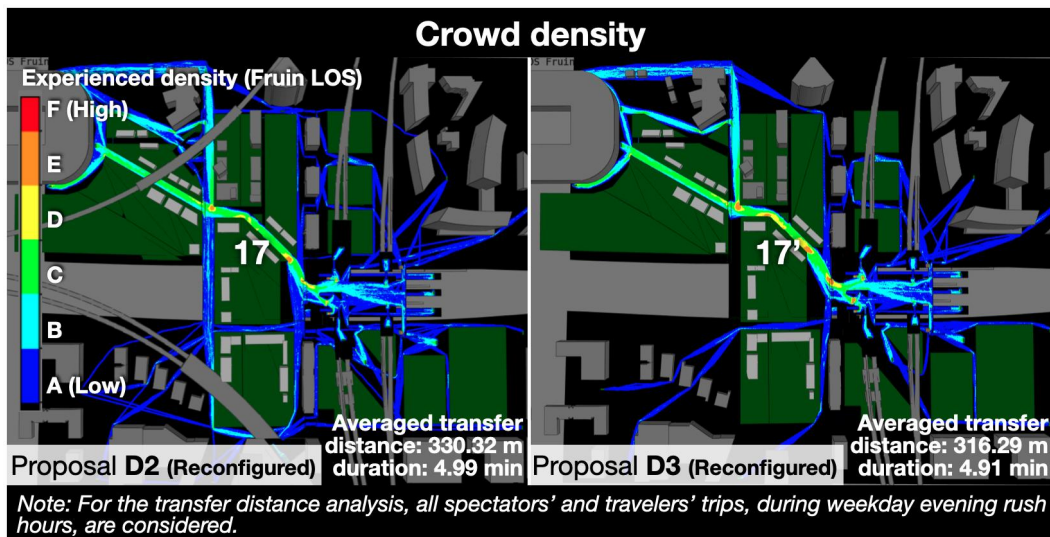


FIG. 5.11 The crowd density (during rush hours and disruption times) and visual quality in proposals D2 and D3. (Source: Author)

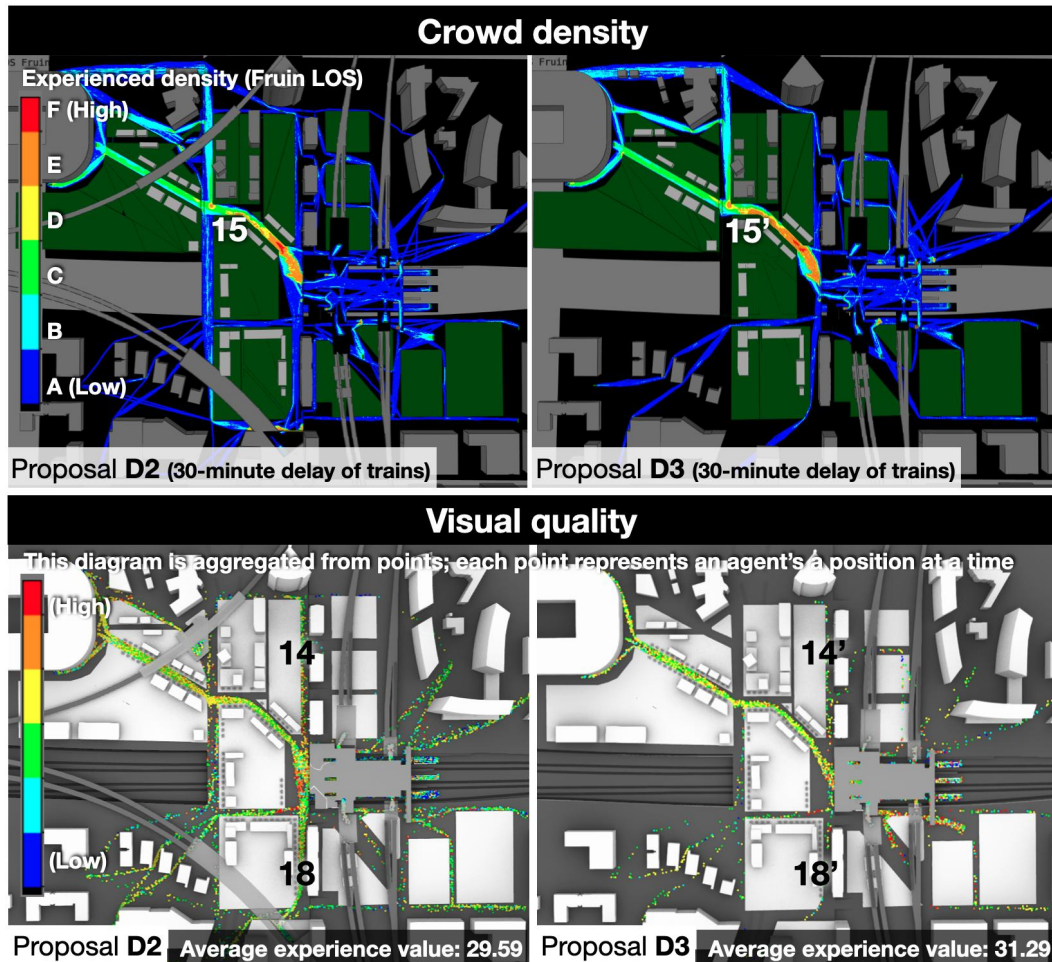


FIG. 5.11 The crowd density (during rush hours and disruption times) and visual quality in proposals D2 and D3 (continued). (Source: Author)

Regarding the stairs and gates, proposal B1 is designed in a dispersed layout, while B3 is designed in a concentrated layout. However, locally, B1 also has an area where three stairs are concentratedly located (area 12 in Figure 5.12 - middle). In general, the crowd density in B3 is higher during peak times (see locations 14' in Figure 5.12 - top). However, the crowd density is not a big issue for B3 during peak time, as the bottlenecks occur at the gates for both proposals B1 and B3.

During disruption times, the stranded agents aggregate in the area where stairs are concentrated (location 13' in proposal B3, location 12 in proposal B1). B1 needs less managerial effort to redistribute the aggregated passengers in area 12. B3 needs more managerial effort to redistribute the more aggregated passengers in area 13'

(Figure 5.12 - middle). In this sense, B1 has a higher capacity to accommodate stranded passengers.

Surprisingly, B3, with a more concentrated layout of stairs, which would intuitively lead to an assumption of shorter transfer distances, actually results in longer average transfer distances (of agents switching between platforms). After further analysis, it is observed that in B1, stairs are more dispersed and evenly positioned, so agents can switch between platforms using the nearby stairs. In B3, some agents need to take longer routes to the stairs further away (see Figure 5.12 - bottom, the routes in yellow dash). This suggests that the initial assumption was based on a limited understanding of layout, considering only the stairs and missing the platforms. When platforms are considered, the initially ‘concentrated’ layout—regarding only stairs—turns out to be actually ‘dispersed.’

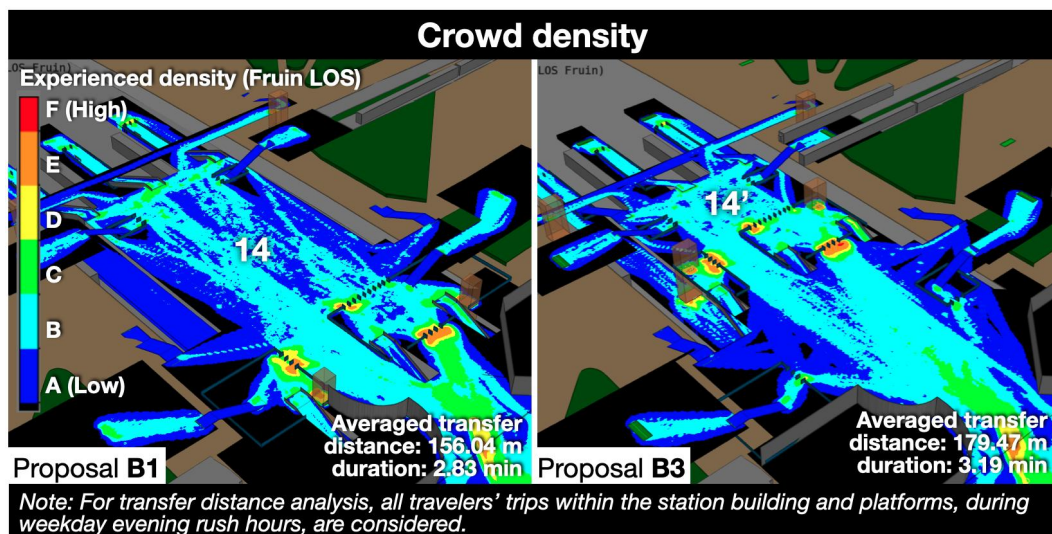


FIG. 5.12 The crowd density, accommodation capacity during disruptions, and transfer distance in proposals B1 and B3. (Source: Author)

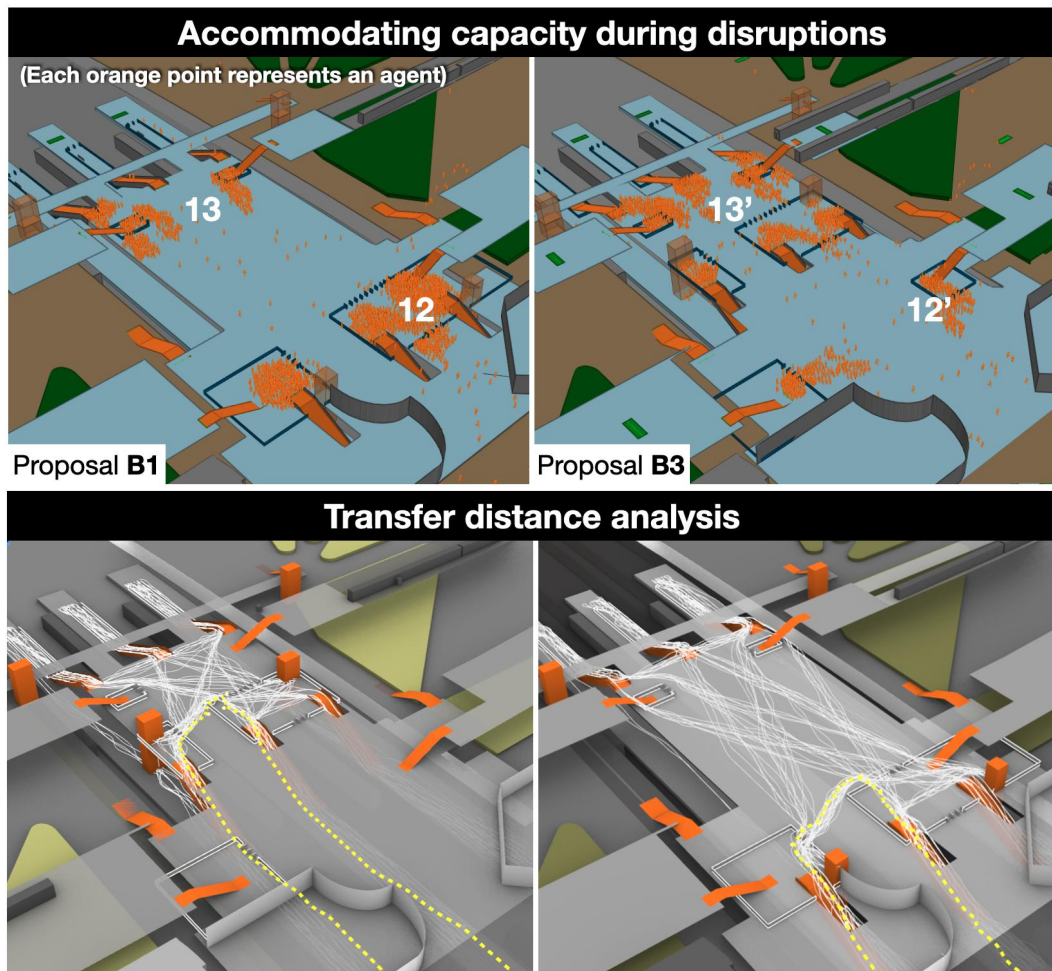


FIG. 5.12 The crowd density, accommodation capacity during disruptions, and transfer distance in proposals B1 and B3 (continued). (Source: Author)

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

5.3.5 The effects of Principle 5 (human-centered spaces)

Proposal D3 is relatively more human-oriented, while D4 is more vehicle-oriented. D3 has human-scale buildings and streets, and it supports large events (to be held in front of the station) to enliven the environment. In contrast, D4 has wide streets and large parking spaces for vehicles; it does not support large events (unless all the transport activities stop, i.e., no buses, trams, and cars come and go to stations, which is not possible). Therefore, during non-peak times, the environment in D4 will be more underutilized and lifeless (Figure 5.13). In summary, the results show that human-centered design creates a more vibrant environment.

Surprisingly, according to the simulation, the average visual quality value is slightly higher in D4 (=31.65) than in D3 (=31.29). This count-intuitive result may be due to the limitations of the current simulation approach. In reality, people generally have negative feelings, fearing being hit by vehicles when they cross the streets; humans also have a perception of the distance of objects (or the depth of space), so a space with buildings far away is less lively than a space with buildings nearby. These patterns are not captured by the current simulation approach. The simulations show a necessity for improving the simulation approach in the future.



FIG. 5.13 Visual quality and potential event sites in proposals D3 and D4. (Source: Author)

5.4 Discussions

5.4.1 Research implications

The research findings offer detailed insights into how each design principle functions within specific contexts and how they are interrelated ([Figure 5.14](#)). According to Alexander, design principles (what he calls patterns) are essentially solutions for problems under certain contexts ([Alexander, 1979](#), p. 314). Meanwhile, in the design practice, the contexts, problems, and solutions are usually not linearly established; rather, they usually iterate and accumulate during design ([Nijhuis and Bobbink, 2012](#)). For designers, creating solutions even helps uncover and define the problems or contexts they address ([De Jong and Van Der Voordt, 2002](#), p. 455). In this research, with the design principles being assessed, their suitable specific contexts become clearer. For example, considering proposals D1 and D2, reconfiguration-supportiveness is a highly relevant station quality in the context where flow bottlenecks exist; without bottlenecks, reconfiguration is not necessary ([Figure 5.14](#)).

With the design principles being assessed, their interrelationships also become clearer. For example, considering proposals D1 and D2, ‘quality connections’ enable ‘reconfiguration-supportiveness’; in Proposals B1 and B3, making stations ‘reconfiguration-supportive’ enables ‘making event visible’ ([Figure 5.14](#)). Negative correlations are also discovered. For example, in proposals D1 and D2, dispersed layouts add to the managerial difficulty of reconfigurations (when different groups of people go to three different station buildings, it is hard to make path reconfigurations satisfying all the groups) and the difficulty of wayfinding ([Figure 5.14](#)).

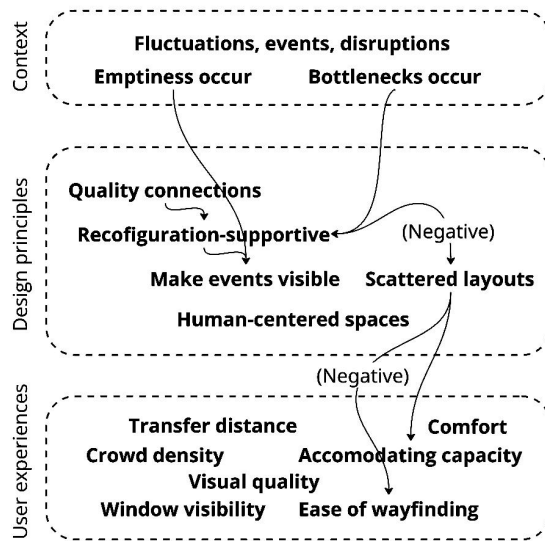


FIG. 5.14 The interrelationship between contexts, principles, and user experiences. (Source: Author)

5.4.2 Research contributions

This chapter contributes to the accumulation of design knowledge. It demonstrates the effectiveness of the design principles for the flexible use of stations, while also revealing the strengths and limitations of each principle. It shows the feasibility of jointly using research-by-design and agent-based simulation (ABS) as an approach for design assessment and offers reflections on ABS's limitations. Notably, this chapter's contribution does not include developing the assessment framework; rather, it builds on the framework previously established by [Enshan et al. \(2025b\)](#).

5.4.3 Research limitations and future directions

The research has its limitations embedded in its station settings. Each case has its own spatial settings, and transferring its experience to other cases requires considerable generalization efforts. More challenging is that stations are the type of buildings with the most diverse variants ([Richards and Mackenzie, 1986](#)). This chapter's case is just one representing its similar counterparts, and there are many other significantly different cases beyond.

This chapter focuses on user experiences as the indicators of station performance; however, in the development and daily operations of railway stations, there are many

other types of performance that other actors—beyond users, including developers, railway companies, governments, NGOs, and local residents—care about. For example, the cost and return to build stations (financial performance), the programming adaptability to future changes, the managerial capacity needed to run stations, and the vehicle transportation efficiency, the reserved spaces for nature (Zemp et al., 2011; Van Den Berg and Pol, 1998; Bertolini and Spit, 1998; Wang, 2022; Boorsma, 2024). Acknowledging these limitations, this chapter outlines work for future research: expand studies on more station settings and performances.

5.5 Conclusions

This chapter addresses one major question. In [section 5.1](#), regarding design principles for the flexible use of station areas, this chapter presents the major question—how effective are the design principles of flexible use of stations, as demonstrated through research-by-design and agent-based simulations (ABS)? The results confirm that the principles are generally effective, each with its own strengths and limitations. For designers and policy-makers, the following executive summary is provided:

- 1) For addressing overcrowding and underutilization in railway stations, design proposals at both district and building levels can promote flexible use by incorporating the following features: event visibility, reconfiguration-supportiveness, quality connections, dispersed layouts, and human-centered spaces.
- 2) However, quality connections may require more investment to build and occupy more usable land; Dispersed layouts may increase wayfinding difficulty and require greater managerial effort for reconfiguration ([Figure 5.14](#)).

The study also answers two minor questions. The first minor question—what will these design principles be like when applied to new cases?—is addressed through the development of multiple design proposals. The second minor question—what are the limitations of ABS in assessing complex projects like railway stations?—is addressed by recognizing that current ABS models have not yet incorporated more human abilities, including subjective feelings of safety, wayfinding capacity, and humans' ability to perceive spatial depth. These limitations of ABS highlight the usefulness of other traditional means for design assessment, such as expert evaluations and designers' analytical drawings.

PART III Assessment Framework

This part, comprising **Chapters 6** and **7**, establishes the quantitative evaluation framework of this dissertation, providing computational tools to evaluate how station design proposals perform across fluctuating temporal scenarios.

Chapter 6 formulates the overarching assessment framework utilizing agent-based simulation to evaluate multi-layered user satisfaction metrics during both peak and off-peak conditions. This framework is demonstrated through the case of Rotterdam Central Station. It is also utilized by **Chapter 5** to assess design principles.

Chapter 7 supplements this framework by introducing a visual assessment model that computationally quantifies visual qualities of environments perceived by pedestrians.

The content of **Chapter 6** has also been published in: Enshan, C., Van de Spek, S., Van der Hoeven, F., & Triggianese, M. (2025). Evaluate user satisfaction for urban design of railway station areas: An assessment framework using agent-based simulation. *Environmental Impact Assessment Review*, 110, 107685.

6 Assessment framework

Using agent-based simulation

ABSTRACT Railway station areas can play a crucial role in promoting sustainable development if integrated with cities and support flexible use 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 chapter addresses the **question**: to what extent ABS can help assess the urban design of station areas? **Methodologically**, this chapter adopts the user pyramid as the theoretical framework, which outlines five types of user needs: safety, speed, ease, comfort, and experience. The chapter 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. The **results** show that 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 250m) with substantial details to inform design decision-making, and it is useful during the design stage when only limited data is available. This chapter 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.

KEYWORDS Mapping, environmental psychology, crowd simulation, vision analysis

6.1 Introduction

Railway stations play a crucial role in promoting sustainable development. Rail transport is more energy-efficient than any other motorized means of transportation 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., 2003; De Jong 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).

6.1.1 Assess urban design toward station-city integration and flexible use

The PhD project that includes this chapter has been conducted to explore the contribution of urban design to station-city integration (Figure 6.1), where a particular station issue is identified—the overcrowding-underutilization phenomena. The use of stations typically fluctuates, especially during events. Events across different temporal scales (Carmona et al., 2003) can cause overcrowding during peak times and underutilization during non-peak times. These events include daily rush-hour commuting, multi-weekly sports events, and yearly holidays. Overcrowding is a safety concern, and underutilization is a waste of space resources, both of which decrease user experience. Therefore, it is beneficial to ease the overcrowding and underutilization in stations, for which **flexible use** is a potential strategy

(subsection 1.2.4). Overcrowding and underutilization 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. **Assessment** of design proposals during the design stage is necessary to ensure design solutions take advantage of the positive impact while avoiding the negative.

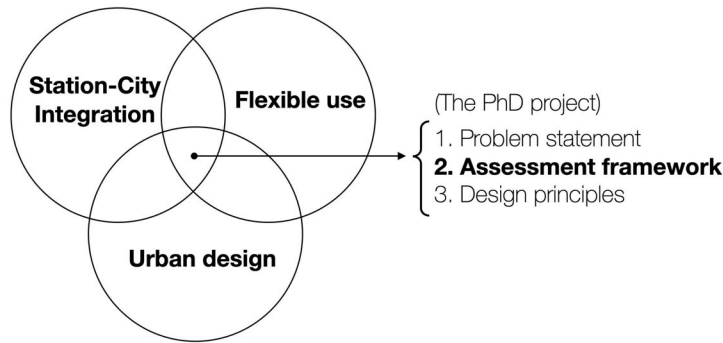


FIG. 6.1 This chapter is part of the PhD project at the intersection of three topics. (Source: Author)

Spatial and human aspects are inseparably considered during urban design. Spatial configuration facilitates users' needs, and **user satisfaction** indicates spatial performance (Figure 6.2). 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.

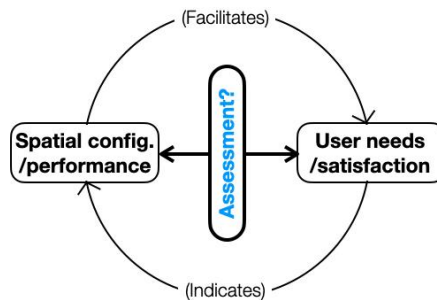


FIG. 6.2 Space and users are interrelated in urban design. (Source: Author)

6.1.2 Existing analytical methods in the urban design field

Various digital methods and tools are available in the field of urban design (Figure 6.3). 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, 1995; Yu et al., 2021; Piga and Morello, 2015). They vary in **modeling strategies**, **content being addressed**, and **data dependencies**.

(Modelling strategies)	(Content)				(Data dependency)			
	Spatial	Human			Require projects' real-world data	Not require projects' real-world data		
		Movement	Visual	Proximity				
Network-based	Spacesyntax				Spacesyntax			
	Accessibility analysis				Accessibility analysis			
	Connectivity analysis				Connectivity analysis			
	Resilience analysis				Resilience analysis			
Space-based		Isovist	Visibility			Computer vision	Eye-tracking	Proximity analysis
		Depth map	Eye-tracking	Computer vision				
Agent-based		Movement simulation	(Vision analysis)					
		Agent-based simulation						
Others			VR				VR	
			Statistical index analysis				Statistical index analysis	

FIG. 6.3 Common methods used in the urban design field. (Source: Author)

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 1m×1m 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 (Figure 6.4).

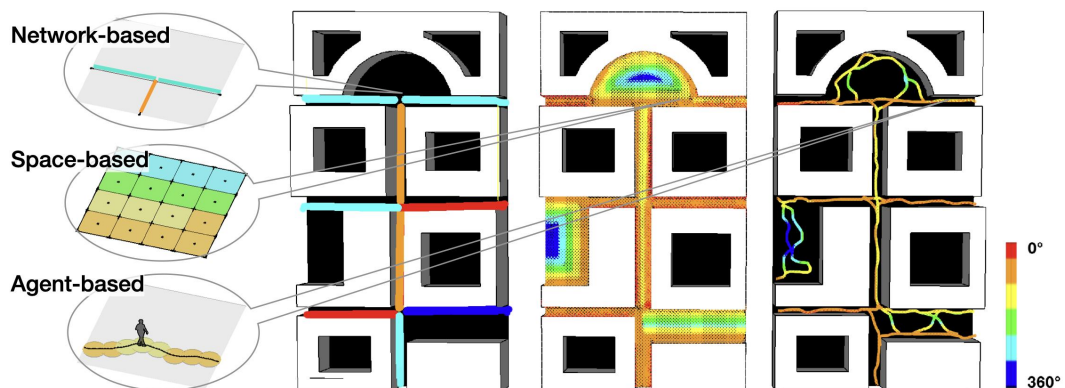


FIG. 6.4 Exemplary evaluation of spatial openness using different approaches. (Source: Author)

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 (Figure 6.5).

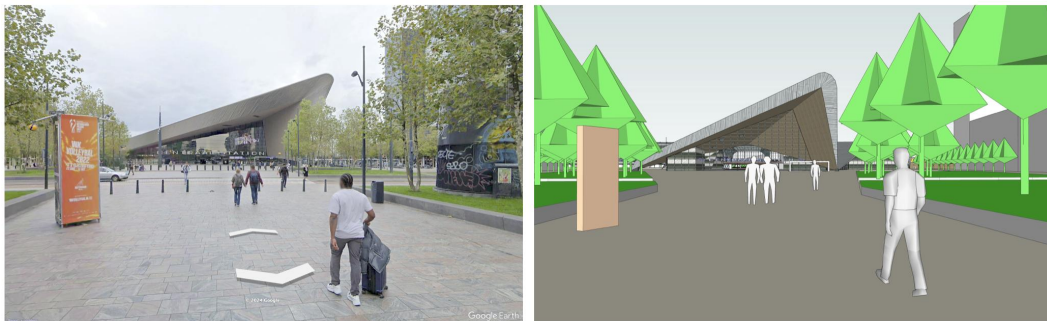


FIG. 6.5 A photo of a real-world scene (Source: Google Maps) vs a 3D representation model of a design (Source: Author)

6.1.3 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 (Figure 6.4). 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 (Figure 6.4). 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.

6.1.4 Research gap and research questions

The above introduces a research gap through a research overview. Assessing urban design alternatives is critical for enabling the flexible use of stations and achieving the positive effects of station-city integration. 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, this chapter sets the research question: **To what extent can agent-based simulation help assess user satisfaction to facilitate the spatial design of station areas (that are integrated with cities and support flexible use)?** 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 chapter constructs the assessment framework by integrating theory, indicators, and digital tools. During this construction, it conducts a multidisciplinary literature review that translates user needs for urban design use, strengthening the scientific knowledge of railway station areas. This chapter also does software development, advancing existing digital tools beyond their existing functionality.

The remainder of this chapter is organized as follows: [section 6.2](#) describes the methods. It defines the station area, user needs, and indicators. [section 6.3](#) and [section 6.4](#) apply these methods in Rotterdam Central Station and analyze the results. [section 6.5](#) discusses the implications of the research findings, and [section 6.6](#) concludes ([Figure 6.6](#)).

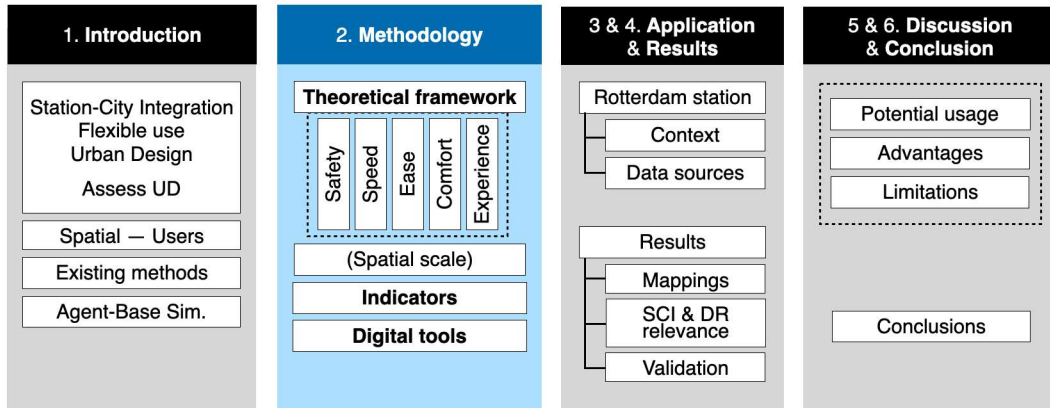


FIG. 6.6 The structure of this chapter. (Source: Author)

6.2 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 (Figure 6.7).

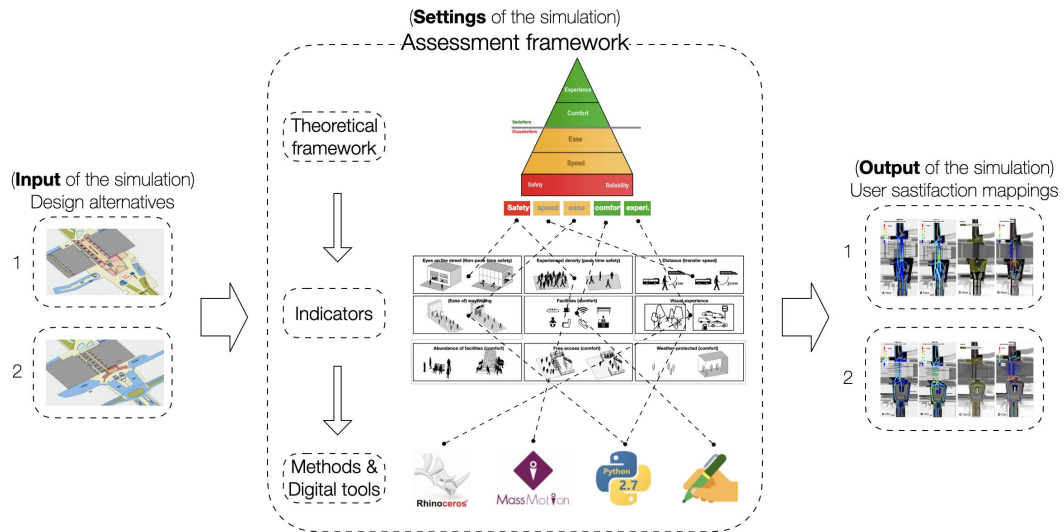


FIG. 6.7 The assessment framework in the assessment process. (Source: Author)

6.2.1 Theoretical framework

Based on a recurring survey of all Dutch rail stations, [Hagen and Heilligers \(2015\)](#) outlined a pyramid of customer needs with five types of user needs of railway passengers: safety, speed, ease, comfort, and experience ([Figure 6.8](#)). 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 [subsection 6.2.2](#) and [subsection 6.2.3](#). Before establishing the spatial link, it is necessary to articulate the spatial scale of the railway station area, as described in the following [subsection 1.6.6](#).

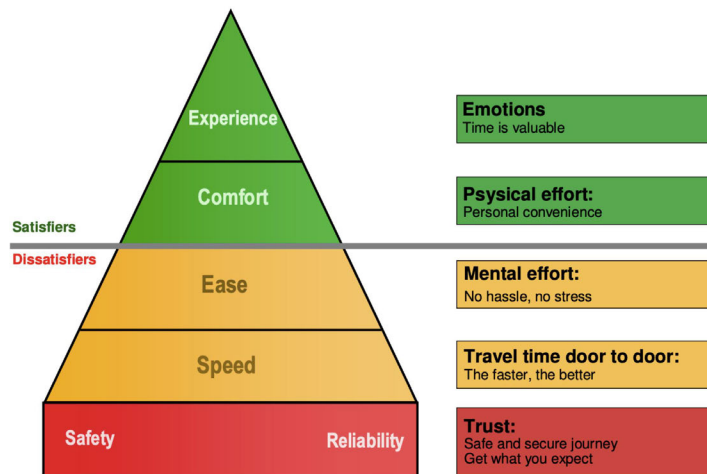


FIG. 6.8 Pyramid of (railway station) customer needs. (Source: [Hagen and Heilligers 2015](#))

6.2.2 Literature review and selection of user satisfaction indicators

This study 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, this chapter links them to spatial-related indicators based on a literature review. Using Web of Science, a topic search (title, abstract, author keywords, and keywords plus) is conducted. The topic words include all 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 with top citations are

examined. Common 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 author's knowledge.

6.2.2.1 Safety

Indicators for safety. Safety in public space has been described as related to many non-spatial, usually equipment and managerial aspects, such as CCTV, sufficient lighting, security signage, 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 study 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 ([Almeida and 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.

6.2.2.2 (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' ([Tfl Programme Management 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.

6.2.2.3 Ease (of wayfinding)

Indicators for ease (of wayfinding). In the initial search using 'ease' as the topic word, no paper shows up. Therefore, this chapter further interprets 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), this chapter interprets 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, 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).

6.2.2.4 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, and 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 study made a limited contribution by calculating comfort statistically using the AHP method (subsubsection 6.2.3.4). This study 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.

6.2.2.5 (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 study 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.

6.2.2.6 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 6.1](#) ([Figure 6.9](#)). These indicators are measured in the simulation ([subsection 6.2.4](#)). The values of user needs are calculated based on these measured indicator values ([subsection 6.2.3](#)).

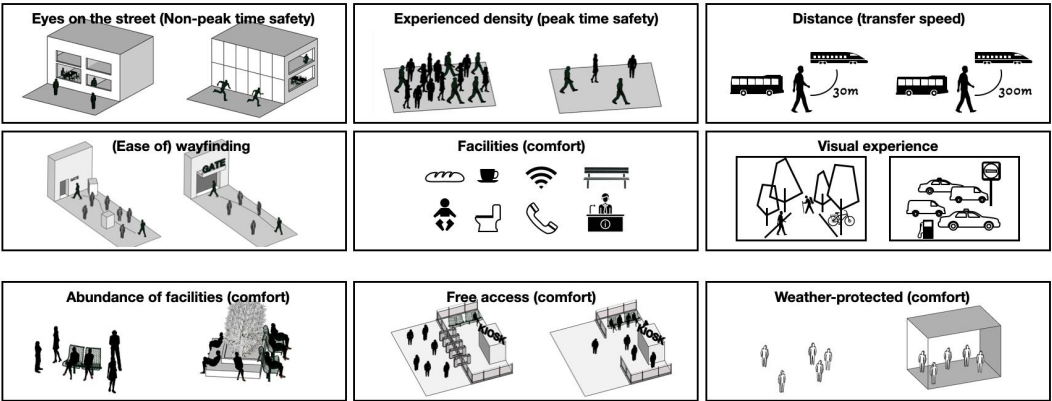


FIG. 6.9 Various indicators of user needs (Source: author)

TABLE 6.1 Indicators selected in this chapter

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	Tfl Programme Management 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

6.2.2.7 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 (Figure 6.10).

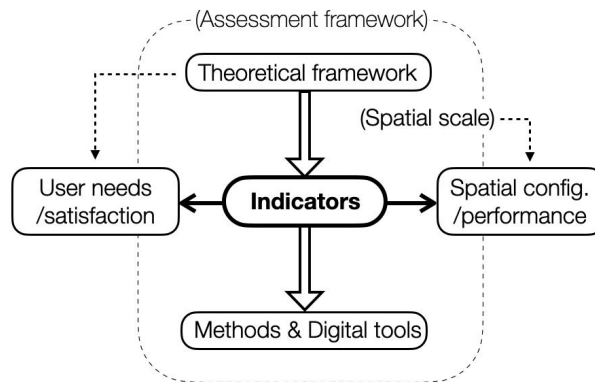


FIG. 6.10 The indicators' critical role within the assess framework. (Source: Author)

6.2.3 Define measurement formulas

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

6.2.3.1 Safety (regarding overcrowding during peak time and ‘eyes upon streets’ during non-peak time)

Eq.(6.1) calculates safety during peak time. Eq.(6.2) calculates safety during non-peak time. d denotes the agent’s experienced density. P_f denotes the proportion of **building facades** in an agent’s vision.

$$V_{safe1} = d \quad (6.1)$$

$$V_{safe2} = P_f \quad (6.2)$$

6.2.3.2 (Transfer) speed

Eq.(6.3) 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.

$$V_{speed} = 1/L \quad (6.3)$$

6.2.3.3 Ease (of wayfinding)

Eq.(6.4) 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 1s in this study. It is the whole time that an agent takes to finish his journey.

$$V_{ease} = \sum_{t=0}^T \Delta\theta \quad (6.4)$$

TABLE 6.2 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 and found and Police offices	0.059
Note: Consistency ratio = 0.053	

6.2.3.4 Comfort (regarding facilities and weather-protected areas)

Eq.(6.5) 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 6.2).

$$V_{comf} = \sum_{i=1}^n f_i \quad (6.5)$$

6.2.3.5 (Visual) experience

Eq.(6.6) 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. Figure 6.11). 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 (Figure 6.5). (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) (Salesse, 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 6.3). 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).

$$V_{expe} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_m x_m + e \quad (6.6)$$

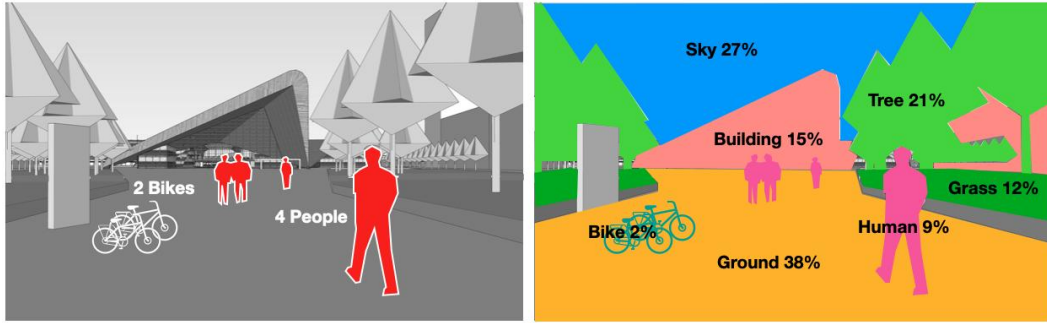


FIG. 6.11 Instance segmentation (the left image) and semantic segmentation (the right image). (Source: Author)

TABLE 6.3 Importance of different facilities regarding comfort

Indicators	Unstd. B	95% CI		Std. Coeff.	P
(Constant)	22.388	Lower	Upper		
Sky	-6.554	20.457	24.320	-0.127	<.001
Building	8.457	-11.685	-1.422	0.257	0.012
Person_No.	0.539	5.135	11.780	0.174	<.001
Water	39.143	0.272	0.807	0.141	<.001
Tree	16.241	62.044		0.145	<.001
Shannon index	4.596	1.421	7.771	0.124	0.005
	2.202	0.656	3.747		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.

6.2.4 Methods and tools

Among the five needs, four can be measured when two types of agent features are simulated - movement and vision (Figure 6.12, left). The other one, comfort, was manually analyzed due to a lack of directly applicable scientific data for quantitative simulation, at the time this research was conducted. MassMotion is used for movement simulation, generating movement trajectories, and relevant information. This chapter writes Python scripts for vision simulation based on the linear regression model. Rhino is used for modeling and rendering. More Python scripts are written for various supporting works, including image segmentation (to get the linear regression model), data analysis, visualization, and so on (Figure 6.12, right).

This paragraph describes the practical software operations in detail, explaining how the indicators (Tables 1, 2, and 3) are applied in the simulation. First, this study builds

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. Second, this study imports the Rhino models into Massmotion, sets the origins and destinations of passengers, sets the OD (Origin-Destination) matrix defining the numbers of passengers, and runs the movement simulation. Then, the flow density, transfer time, and transfer distance can be retrieved. Third, from Massmotion, this study exports the movement trajectories as CSV files, then analyzes these files using Python scripts to get the direction changes of each passenger. Fifth, in Rhino 3D models, through the Rhino built-in Python plugin, with Python scripts, import passengers' (every 5s) positions, set people figures on these positions, set the camera on these positions to mimic passengers' views, and export screenshots (.png images) from the camera positions. Sixth, this study processes 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. Seventh, this study calculates the values of user needs based on all the indicators' values, and uses Python scripts to map the values into different colored points on the passengers' positions in Rhino models.

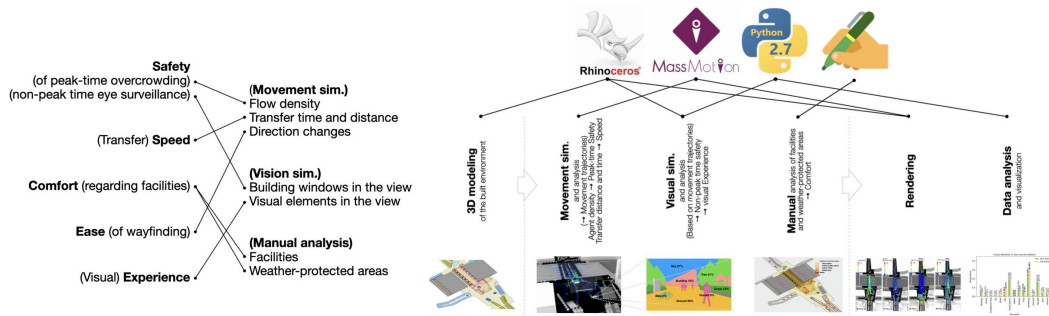


FIG. 6.12 Methods and tools used in this chapter. (Source: Author)

6.3 Case study

To demonstrate the current assessment framework's usage, this chapter 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 author to take field trips to collect data and reflect on the methods and findings.

6.3.1 The context of Rotterdam Central Station

Rotterdam Central Station has been redeveloped, leading to significant changes in user experience. The previous 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 (Figure 6.13, 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 (Figure 6.13, right).



FIG. 6.13 The previous and the current Rotterdam Central Stations.
(Sources: left-large—commons.wikimedia.org; left-small—internaathetposthuis.nl; right-large—tropicaliente.nl; right-small—west8.com)

6.3.2 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 around 250m (subsection 1.6.6), where the more specific analyzed areas cover mobility sites (i.e., bus station, tram station, bike parking sites) and walkable outdoor spaces (Figure 6.14, Figure 6.16, and Figure 6.17; see also subsection 1.6.4.1).

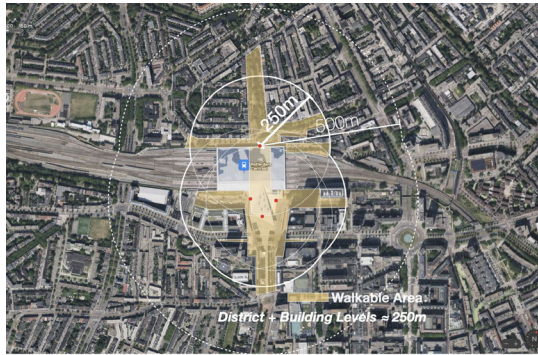


FIG. 6.14 The study area of Rotterdam Central. (Source: Google Maps; annotated by the author)

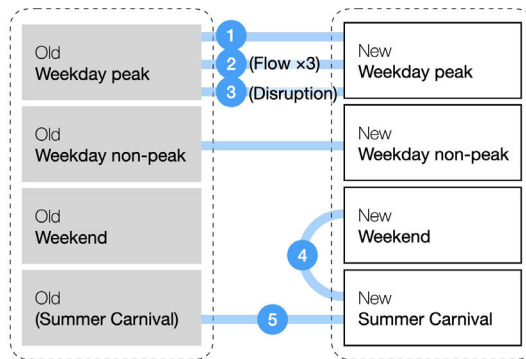


FIG. 6.15 Compare different temporal scenarios. (Source: Author)

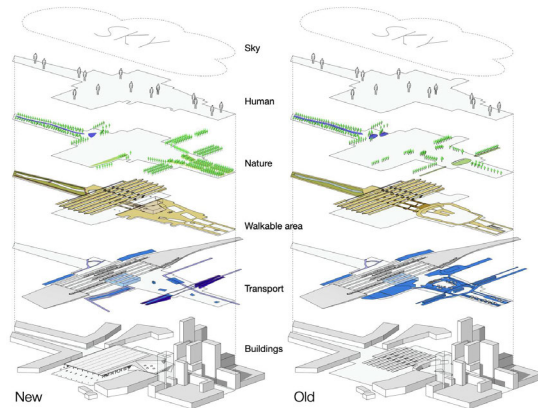


FIG. 6.16 The stations on the district level. (Source: Author)

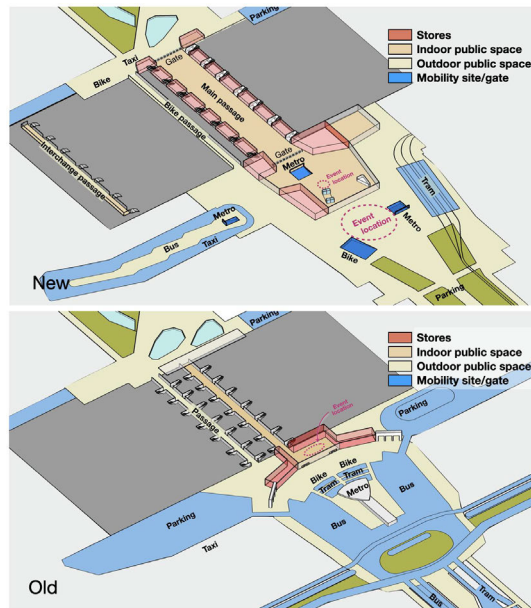


FIG. 6.17 The stations on the building level. (Source: Author)

Regarding the temporal dimension (Carmona et al., 2003), this research sets simulation scenarios for weekday peak, weekday non-peak, weekends, disruption, and summer carnival times. It then compares these scenarios (Figure 6.15).

6.3.3 Data sources

As outlined in Figure 6.7 and Figure 6.28, 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. This study built these models based on satellite images, floor drawings, and historical photos from the internet.

For **movement-related agent parameters**, this study 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 (Tfl Programme Management 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**, this study uses the Origin-Destination matrix with the same mode split (to make the flow the same 'controlled variable') for the previous and the current scenarios. This mode split is based on the author's on-site pedestrian counting and the Dutch railway company's flow data ([NS, n.d.](#)) (see detailed explanation in supplementary materials section S2). For simulating Summer Carnival **events**, the author 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, this study compares them with the real-world user satisfaction changes and interprets 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.

6.4 Application results

6.4.1 Mappings of user satisfaction

The mapping results are shown as follows:

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

[Figure 6.18-A](#). shows the peak time safety perception, represented by the flow density. In the previous station areas, the area in front of the station 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 pedestrian flows. This issue is solved in the current station, where pedestrian flows are more evenly distributed. In the hypothetical scenarios when pedestrian numbers are increased ([Figure 6.18-B](#) and [Figure 6.20](#), locations 1 and 12), the previous station can have severe congestion (level-of-service F) while the current station can still handle the increased pedestrian numbers. Therefore, the current station has a better peak-time safety performance.

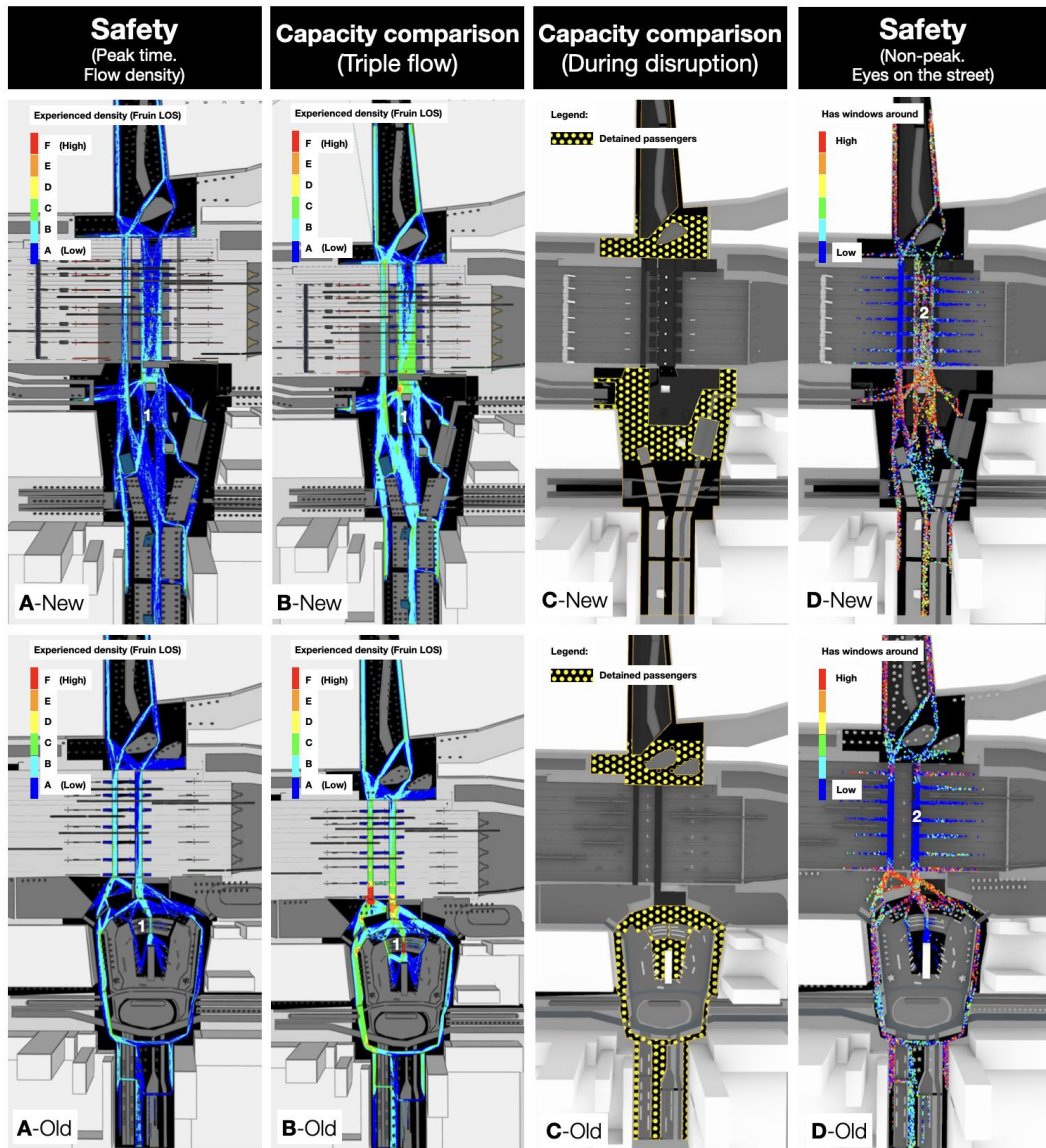


FIG. 6.18 Mapping results: (A) flow density as peak-time safety. (B) capacity comparison with triple times of passenger numbers. (C) capacity comparison during a hypothetical disruption. (D) 'eyes on the street' as non-peak-time safety. (Source: Author)

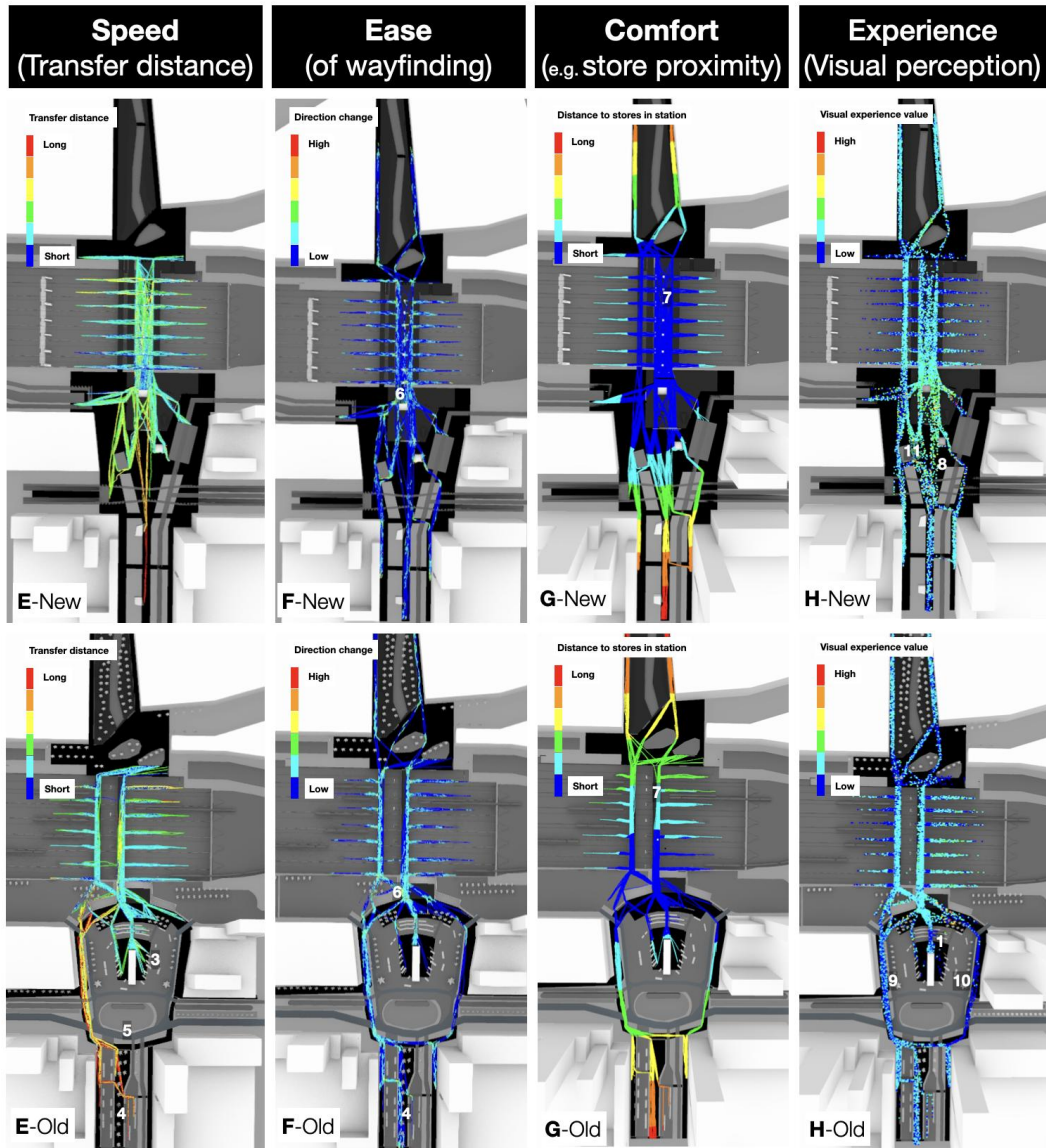


FIG. 6.19 Mapping results: (E) transfer distance. (F) ease of wayfinding. (G) store proximity as comfort. (H) visual experience. (Source: Author)

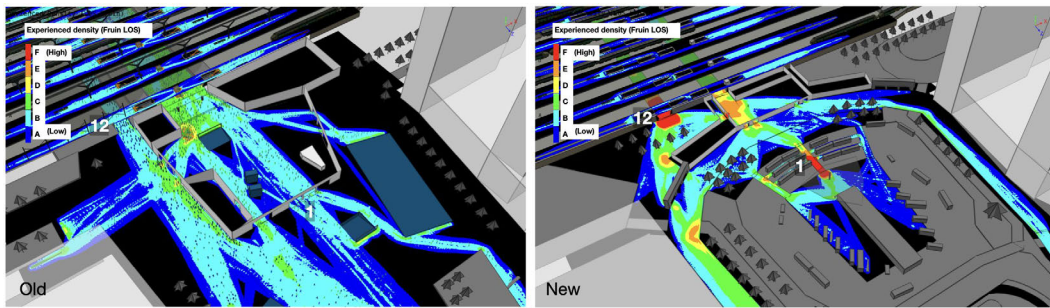


FIG. 6.20 Mapping results: Flow density with three times the agent numbers. (Source: Author)

Figure 6.18-D shows non-peak time safety perception in the station. In the previous station, the main passage across the building under the railway tracks (location 2) receives little eye surveillance. While in the current station, it receives much more eye surveillance thanks to the newly added retail under the track. This means a safer environment during non-peak time, especially at night.

6.4.1.2 (Transfer) speed

Figure 6.19-E and Figure 6.21 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 current scenario are just slightly shorter than those in the previous scenario. In the previous 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 current station, passengers transferring from various modes of transportation have more equitable experiences.

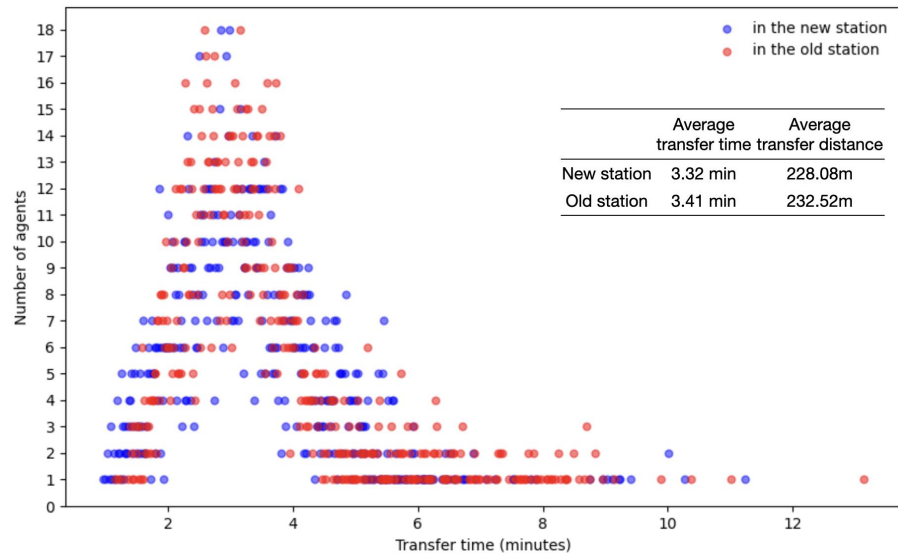


FIG. 6.21 Agents' transfer time and transfer distance. (Source: Author)

6.4.1.3 Ease (of wayfinding)

Figure 6.19-F and Figure 6.22 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 previous 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 current station, passengers have more direct trajectories and would feel much more at ease.

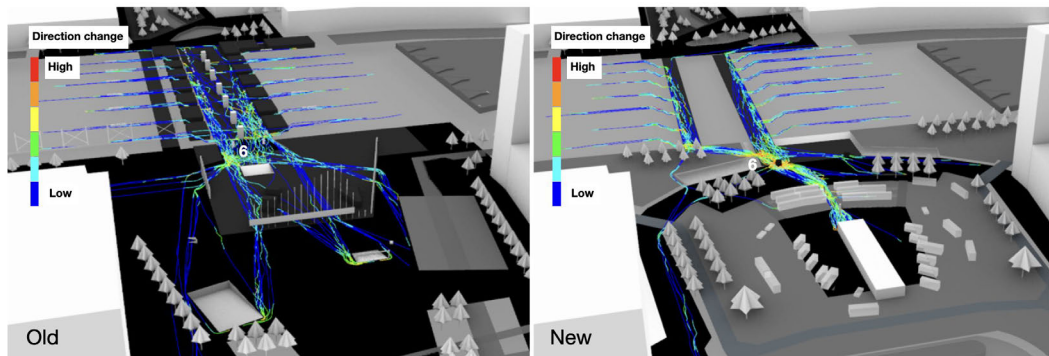


FIG. 6.22 Direction changes in trajectories. (Source: Author)

6.4.1.4 Comfort (regarding facilities and weather-protected areas)

The comfort needs in general are better satisfied in the current station than in the previous station. The previous station has limited retail stores in the station hall, while the current station has plenty of stores located in the hall and in the main passage under the tracks (Figure 6.17), which provide convenient consumption choices for users (e.g., Figure 6.19-G, location 7, where stores are closer to the current station than the old). In the previous station, seats are largely missing. The current 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 (Figure 6.23). The current 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 current station which reduces its comfort use than the old, as the latter was totally free-access (Figure 6.23). Sales of retail located within the gated area have dropped by 25% after the installation of ticket gates (Peters and Tolkoff, 2016, p. 7).

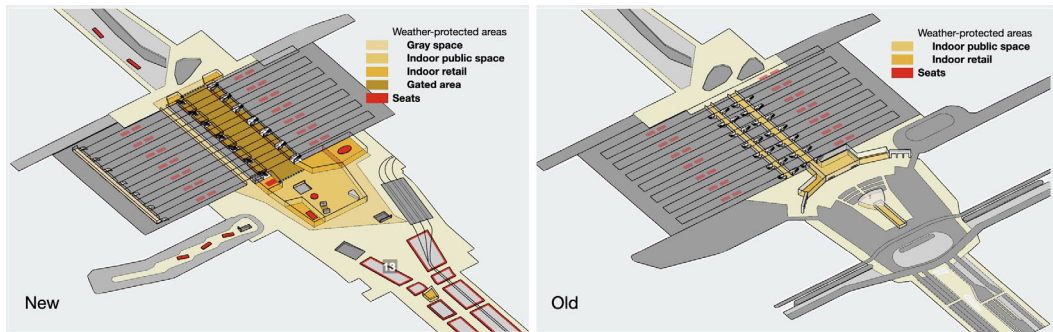


FIG. 6.23 Weather-protected areas and seats. (Source: Author)

6.4.1.5 (Visual) experience

Figure 6.19-H shows visual experience in the station. In the station plaza area, the visual perception is more positive in the current scenario than in the previous scenario. This is because, in the previous scenario, when people stand in the plaza area (location 1), their sight lines towards positive environmental elements (including buildings, trees, and humans) are pretty much blocked by vehicles. In the summed visual perception of all agents (Figure 6.24), a greater proportion of buildings is presented in the view in the previous scenario. This is because the previous paths from the neighborhood were mainly located alongside the building (locations 9 and 10), while in the current station areas, the paths are evenly located in the open spaces (location 11).

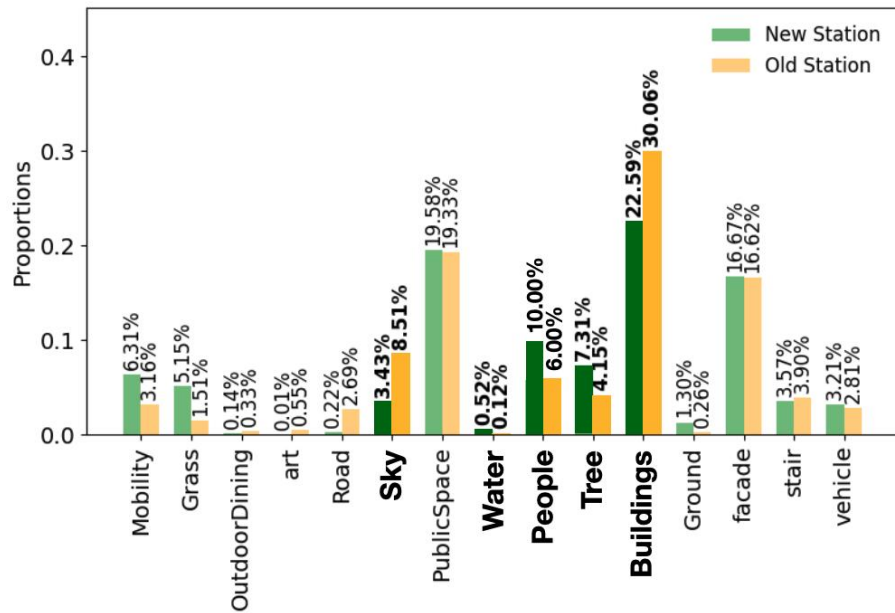


FIG. 6.24 Proportions of different elements in agents' view. (Source: Author)

6.4.1.6 Performance during events and disruptions

The current station is supportive of large events, while the previous station is not. In the current station area, the plaza can be used for big events, and smaller events or installations can be set in the station hall (Figure 6.13 and Figure 6.17). A further simulation shows that adding events in the current station has negligible impacts on the flow density, transfer distance, and transfer time (Figure 6.25). In contrast, in the previous station, no major event can be organized at the plaza as it was occupied by transport facilities (Figure 6.13 and Figure 6.17) unless all the transport function stops to give way to events.

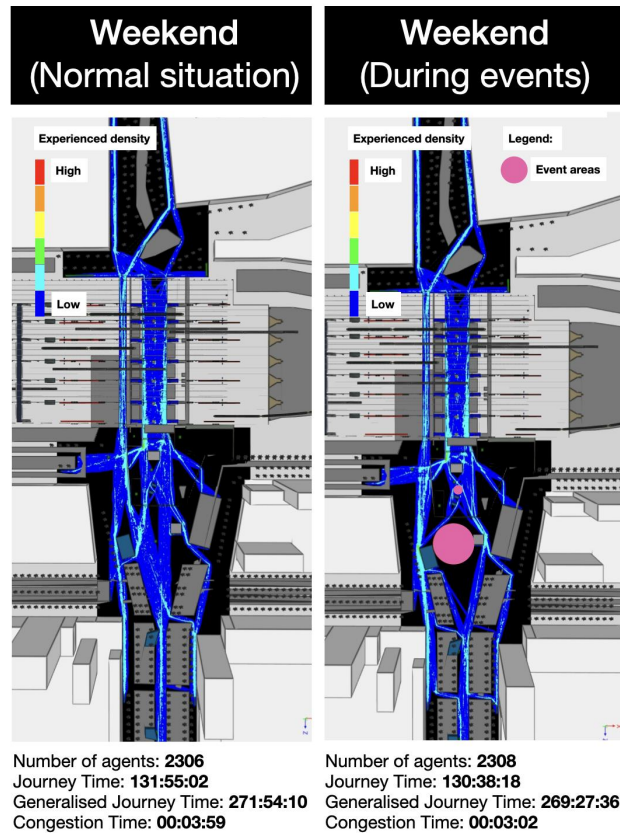


FIG. 6.25 Flow density and agents' transfer time in the current station during normal time and event time. (Source: Author)

The current station is more resilient to disruption than the previous 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 current station is doubled; therefore, it will have a double capacity to accommodate the detained passengers during extreme disruptions (Figure 6.18-C).

6.4.2 Relates to station-city integration and flexible use

Various design interventions, whose impacts are reflected by agents' satisfaction during the above application, are relevant to station-city integration and flexible use.

Some of these design interventions are primarily about the spatial layout, e.g., a better layout of mobility sites with human-centered plaza; and other design interventions are about the elements of stations, e.g., adding stores providing better surveillance (Figure 6.26).

Regarding station-city integration, the previous station area was vehicle-dominant, making the whole adjacent city area unpleasant to visit. The current station has been transformed by interventions that promote high-quality connections, provide the station with city functions and environment, and reduce interference between the station and the city.

Regarding flexible use, these interventions reduce overcrowding, build space that can be potentially used as event venues, and promote quality during non-peak times (Figure 6.26, see also Figure 6.1). These interventions enable the station area to be used during non-peak times, preventing underutilization and an empty, unsafe environment.

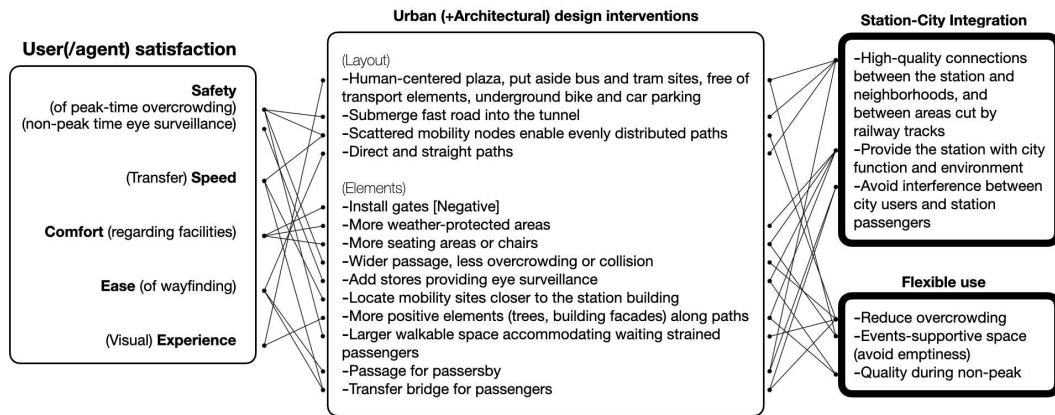


FIG. 6.26 Design interventions and their relevance to station-city integration and flexible use. (Source: Author)

6.4.3 Validation of the assessment framework

In general, as shown in the Rotterdam Central Station (RCS) case, the 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 an adjusted $R^2 = 0.156$, indicating an acceptable accuracy in social science (According to Ozili, 2023, R^2 should be greater than 0.1).

6.5 Discussions

6.5.1 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, 2003). 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 assessment provided by the design consultant service.

The framework also facilitates communication and collaboration with different actors involved in station area developments (Figure 6.27). 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).

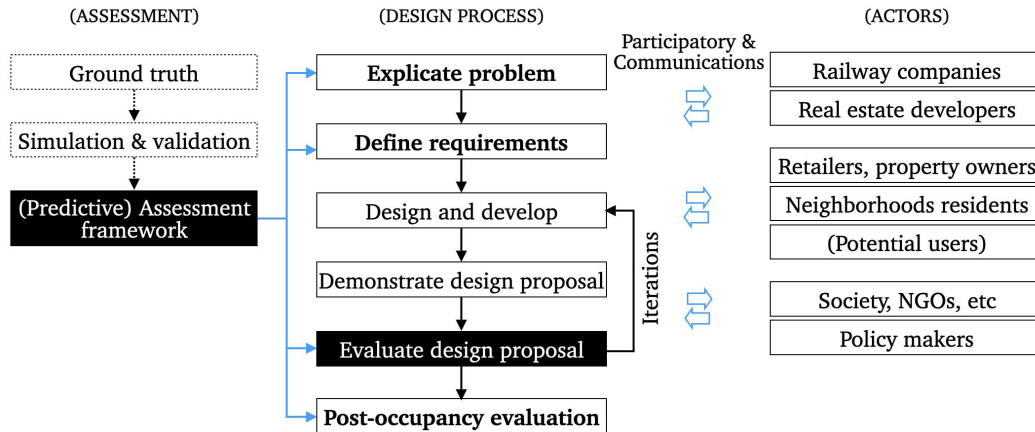
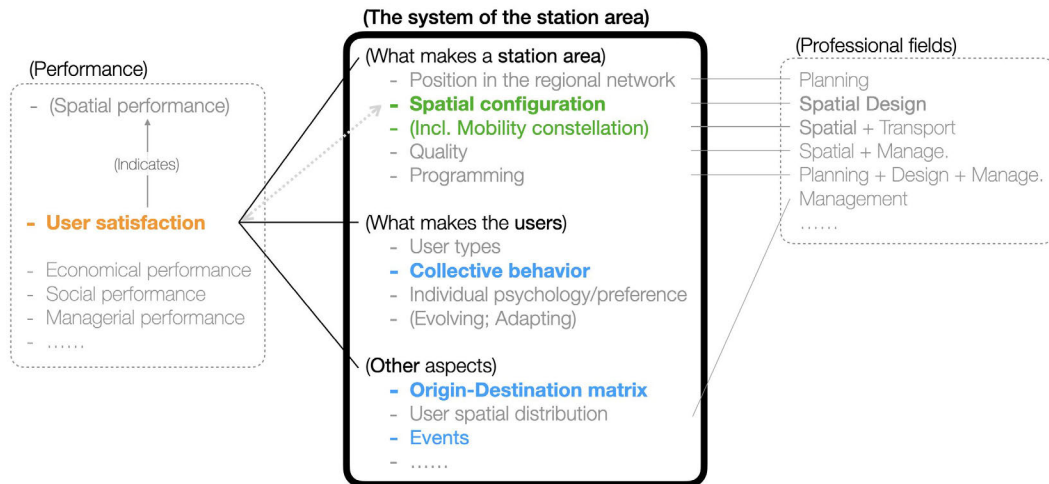


FIG. 6.27 The assessment framework's potential applications in practice. (Source: Author)

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 (Figure 6.28), the more usage it will have in different parts of the whole ecology of practice (Figure 6.27).



Legend in terms of colored text: (Output) (Input) (Settings) (Not simulated factors) (Description)

FIG. 6.28 A limited part of reality is simulated. (Source: Author)

6.5.2 Knowledge contributions

This chapter contributes to the knowledge base of station area design. This chapter's literature review of indicators bridges existing knowledge that is scattered across 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 the PhD project that considers stations' temporal use feature, enriches the meanings of 'flexible use,' 'resilience' ([Shafiei Dastjerdi et al., 2021](#)), 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](#)).

6.5.3 Limitations and future research directions

With a specific (urban design) domain-specific purpose to assess spatial configurations that user satisfaction is indicative of, this chapter only simulates a limited part of the station system ([Figure 6.28](#), 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 ([subsection 1.6.6](#)) 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 [Figure 6.28](#), this chapter outlines a future research direction: to integrate more aspects to expand the assessment framework.

In this research, the stations' performances are judged through comparisons between the current and old stations. A more ideal judgment is to compare the station's performance with standards. However, user 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 in this study is still far from forming such standards. These standards are possible in the future with more scientific evidence or industrial standards, and the assessment framework being applied in more cases (See supplementary materials section S11. Referenceable values regarding user needs).

6.6 Conclusions

This chapter addresses one main research question and two sub-questions: To what extent can agent-based simulation help assess user satisfaction to facilitate the spatial design of station areas (that are integrated with cities and support flexible use)? Is the developed assessment framework effective in telling the user satisfaction caused by different design alternatives? 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 current assessment framework. ABS makes it possible to integrate human perceptual knowledge and spatial quality knowledge. The simulation settings in this chapter include agent parameters, flow, and events, which reflect real-world station systems. This chapter acknowledges 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.

Acknowledgment

Thanks, Minyu Cui, for the on-site pedestrian data collection.

7 Supplementary visual assessment

Evidence extracted from the image segmentation of street views

ABSTRACT The visual quality of the environment influences human perceptions of safety, aesthetics, vibrancy, and more. Assessing visual quality is crucial in design practice, whether for pre-design site analysis or for assessing the performance of design proposals. However, existing computational visual quality analysis models depend heavily on real-world data and cannot evaluate design proposals when projects are not built. This chapter addresses the **question**: How to computationally assess the visual quality of the built environment for design use? **Methodologically**, it employs image segmentation to extract the proportions and numbers of elements in street images, followed by systematic testing of various models and methods to establish relationships between these data and human ratings of the images. A final linear regression model is developed and incorporated into an agent-based simulation to assess visual quality in design proposals during the design stage, as demonstrated in the case of the Amsterdam Zuidas area. The **results** reveal that factors such as the number of pedestrians and the proportions of trees, buildings, and water positively influence perceptions of street 'liveness,' while sky proportion has a negative relationship (likely due to reduced visual diversity). The developed linear regression model offers a practical tool for assessing the visual quality of new scenes in design practice, using only features extractable from typical 3D design representation models.

KEYWORDS Urban analytics, scientific evidence, perception, agent-based simulation, urban design

7.1 Introduction

Visual quality is an important aspect of the built environment. For humans, visual perception contributes to as much as 80% of the whole perception of the environment (Haupt and Huber, 2008). Enhancing the visual perception of space users is an important task of designers' and planners' daily practices. For example, architects are typically enthusiastic about the aesthetics of buildings (Scruton, 2013); urban designers and planners emphasize many visual qualities of the outdoor environment, such as imageability, complexity, enclosure, human scale, transparency, legibility (Ewing et al., 2013). Studies reveal that visual qualities correlate with the intensity of people's activities (Gehl, 1987; Whyte, 2001; De Nadai et al., 2016), because visual features affect people's perception of the environment's safety, comfort, and affect people's willingness to walk (Ewing and Handy, 2009; Paydar et al., 2023). Meanwhile, visual quality is commonly considered highly subjective to people's individual tastes, making it hard to assess objectively and deliver replicable results. Thanks to advancements in computational means, it is possible to conduct more objective and replicable evaluations.

7.1.1 From visibility to visual quality analysis

7.1.1.1 Visibility analysis

The **key computational concepts** for visibility analysis have long been developed in the urban and architectural design fields, where visibility analysis, as a simple analysis of whether things are visible, has been implemented using computational means. The computational measurement of visibility dates back to Benedikt (1979)'s 'isovist' concept, which represents the range that is visible to people at a given point in space. This foundational concept has been extensively developed and applied across multiple scales and contexts, with extensions to three-dimensional analysis enabling comprehensive visibility assessment in complex architectural and urban environments (Turner et al., 2001; Batty, 2001).

The development of visibility graph analysis (VGA) further advanced computational visibility methods by creating graph representations of visibility relationships, enabling the analysis of large-scale spatial networks and their visual properties (Turner et al., 2001; O'sullivan and Turner, 2001). Building upon isovist and VGA, the visibility analysis component of space syntax was built. Space syntax methodology is a major framework for analyzing spatial configuration in built environments. It encompasses visibility analysis as one of its two fundamental analytical pillars—visibility analysis and accessibility analysis. By providing quantitative measures such as visual

connectivity and integration, space syntax allows for the objective assessment of how spatial configuration influences visual experiences, wayfinding, and visual accessibility in urban and architectural settings (Hillier, 1995; Penn et al., 1998).

Various **software** programs have been developed for visibility analysis, such as **Depthmap** (for visibility analysis of space syntax), **Isovist app** (<https://isovists.org>), and the 'view studies' component in **Ladybug** (for environmental analysis). It is also relatively easy to conduct visibility analysis by coding Python scripts and implementing them on modeling platforms such as Rhino and ArcGIS, enabling custom workflows and integration with design processes.

The **data** required for visibility analysis typically consists of 3D geometric models and geometry data, which can be extracted from 3D design representation models such as Rhino, Revit, and ArcGIS. These data are often available from OpenStreetMap data or other sources.

The **applications** of these visibility-based methods span diverse contexts, including urban security analysis (Chen et al., 2021), pedestrian emotion modeling (Xiang et al., 2021), environmental and social sustainability assessments (Zare et al., 2022), wayfinding and navigation studies (Conroy, 2001; Haq, 2003), retail and commercial space analysis (Natapov and Grinshpun, 2020), museum and exhibition design (Dursun, 2007), healthcare facility design (Haq and Luo, 2012), and transportation infrastructure planning (Van Der Hoeven and Van Nes, 2014). The computational approaches to visibility analysis have become integral to evidence-based design practices, enabling designers to quantitatively assess and optimize spatial configurations for desired visual experiences and functional outcomes.

7.1.1.2 Visual quality analysis

Beyond visibility, the nuanced content in people's views can also be assessed (and this method is named as 'visual quality analysis' in this paper) thanks to the development of image processing in the computer vision field in recent years. **Key computational concepts** for visual quality analysis include image segmentation, which involves dividing an image into multiple segments, each representing a distinct object or region of interest (Ronneberger et al., 2015). This segmentation can be used to extract features such as the number of buildings, trees, and other objects in the image, as well as the proportions of these objects. Object detection is another key concept in visual quality analysis. It involves identifying and localizing objects in an image (Redmon et al., 2016; He et al., 2018). This can be used to extract features such as the number of cars, pedestrians, and other objects in the image, as well as the proportions of these objects. Pattern recognition is a key concept in visual quality analysis. It involves identifying and classifying patterns in an image (Simonyan and Zisserman, 2015). This can be used to extract features such as the texture of the image, the color of the image, and the shape of the image.

After extracting features from images using these methods, computational models are developed to establish relationships between these features and human-rated quality scores. These models can take various forms: regression models (linear or non-linear) that predict continuous quality scores (Naik et al., 2014), classification models that categorize images into quality classes, or end-to-end deep learning models that integrate feature extraction and quality prediction (Dubey et al., 2016). In some cases, particularly with deep learning approaches, pattern recognition models (such as convolutional neural networks) can simultaneously extract features and learn the mapping to quality scores in an integrated manner.

Deep learning **algorithms and models**, e.g., Mask R-CNN (He et al., 2018), YOLO (Redmon et al., 2016), U-Net (Ronneberger et al., 2015), VGG (Simonyan and Zisserman, 2015), have been developed to conduct these tasks. Open-source datasets laid the foundation to train these models. (Note: ‘Models’ are trained on datasets using ‘algorithms,’ and models have weights while algorithms do not have; Algorithms and models can have the same names, such as the ‘linear regression’ algorithm and ‘linear regression’ models.) These datasets include CityScape, and Place Pulse. Software libraries and packages such as MMSegmentation, PixelLib, and Scikit-image (Chen et al., 2019; India, 2023; Walt et al., 2014), which integrate such algorithms or models, provide more user-friendly options for doing the visual quality analysis with less coding effort.

Data sources for visual quality analysis in the spatial design and urban planning field have been greatly expanded by the proliferation of street view imagery, particularly from platforms like Google Street View, which has enabled large-scale visual quality assessment across entire cities and regions.

Applications of visual quality analysis in urban planning are extensive. Urban design and planning researchers have leveraged computer vision and machine learning to assess various perceptual qualities from visual data. The assessed visual qualities include perceived safety (Naik et al., 2014), aesthetic quality and beauty (Seresinhe et al., 2015; Zhang et al., 2018), liveliness and vibrancy (Salesses, 2012), environmental quality including greenery, openness, and enclosure (Li et al., 2017; Wang et al., 2021), complexity (Florio et al., 2023), imageability and legibility (Filomena et al., 2019), and socioeconomic characteristics (Gebreu et al., 2017; Jean et al., 2016).

Visual quality metrics have been applied to diverse urban planning applications, including analyzing urban greenery distribution and accessibility, assessing walkability and pedestrian-friendliness, evaluating urban design quality, understanding relationships between visual characteristics and urban functions, and assessing the impacts of urban policies and interventions. Studies have also explored the relationship between visual quality and health outcomes (Li et al., 2022b), property values (Zhang et al., 2018; Gebreu et al., 2017), and social equity (Li et al., 2022b; Long and Ye, 2019), demonstrating the broad relevance of visual assessment for evidence-based urban planning. Studies also commonly combine visual quality with other types of qualities (e.g., human scale urban form, functions mix) to analyze cities, integrating visual quality data with other urban datasets such as census data, land use

information, point of interest (POI) data, mobile phone or GPS data, demographic data, and social-economic data to enable comprehensive urban analytics that inform planning decisions at multiple scales.

The visual quality analytics using computer vision is so extensive that it leads to literature reviews (Ibrahim et al., 2020), or even reviews of reviews (Liu and Sevtsuk, 2024). While these studies demonstrate the breadth of visual quality assessment and its applications, their technical foundations and data requirements vary significantly across different stages of the design process, as discussed in the following section.

TABLE 7.1 Overview of computational visual assessment methods

	Visibility Analysis (Whether visible)	Visual Quality Analysis (What is in view)
Concepts:	Isovist (Benedikt, 1979), VGA (Turner et al., 2001; O'sullivan and Turner, 2001), Space Syntax (Hillier, 1995; Penn et al., 1998)	Image segmentation, Object detection, Pattern recognition
Software/ Models/ Algorithms/ Datasets:	Depthmap, Isovist App, Ladybug, Python (Rhino/ArcGIS)	Models/Algorithms: Deep learning (Mask R-CNN (He et al., 2018), YOLO (Redmon et al., 2016), U-Net (Ronneberger et al., 2015), VGG (Simonyan and Zisserman, 2015)). Software: MMSegmentation (Chen et al., 2019), PixelLib (India, 2023), Scikit-image (Walt et al., 2014). Datasets: CityScape, Place Pulse
Data:	3D geometric models (Rhino, Revit, ArcGIS), OpenStreetMap	Street view imagery (Google Street View)
Applications:	Urban security (Chen et al., 2021), Pedestrian emotion (Xiang et al., 2021), Environmental sustainability (Zare et al., 2022), Wayfinding & navigation (Conroy, 2001; Haq, 2003), Retail & commercial (Natapov and Grinshpun, 2020), Museum & healthcare (Dursun, 2007; Haq and Luo, 2012), Transportation planning (Van Der Hoeven and Van Nes, 2014)	Visual qualities assessed: Safety (Naik et al., 2014), Aesthetic (Seresinhe et al., 2015; Zhang et al., 2018), Liveliness (Salesses, 2012), Greenery (Li et al., 2017; Wang et al., 2021), Complexity (Florio et al., 2023), Imageability (Filomena et al., 2019), Socioeconomic (Gebru et al., 2017; Jean et al., 2016), Enclosure (Li et al., 2017; Wang et al., 2021). Applications: Greenery distribution, Walkability assessment, Design quality evaluation, Policy impact analysis, Health outcomes (Li et al., 2022b), Property values (Zhang et al., 2018; Gebru et al., 2017), Social equity (Li et al., 2022b; Long and Ye, 2019)

7.1.2 Design-related assessment

A critical distinction in computational visual quality assessment lies in the design stage at which assessment occurs, and this distinction is fundamentally driven by data availability. The data available at different stages—detailed street images in built environments versus limited geometric information in 3D design models—determines which assessment methods can be applied. This data dependency creates a fundamental gap: existing methods that rely on street imagery cannot assess design proposals during the design stage, when projects are not yet built, and such images do

not exist. Understanding this data-driven distinction is essential for identifying where existing methods apply and where knowledge gaps remain.

7.1.2.1 Assessing existing scenarios during the pre-design or post-design stages

Visual quality analysis plays different roles at different stages of the design process. In pre-design stages, assessment can help analyze existing site conditions and inform initial design decisions. In post-design stages (after projects are built), assessment can evaluate the performance of completed projects and inform future design improvements. In both pre-design and post-design scenarios, street images of the existing built environment are available, enabling traditional computational assessment methods that rely on detailed street images.

Numerous studies have developed computational models for assessing visual quality in existing built environments, where street-level imagery is readily available ([Dubey et al., 2016](#); [Ogawa et al., 2024](#)). These studies primarily operate at neighborhood to city-wide scales, enabled by the comprehensive coverage of street view imagery from platforms like Google Street View. The technical foundation of these methods relies heavily on extracting detailed visual features from street images, including fine-grained elements such as fences, street furniture, facade textures, and advertisement billboards ([Naik et al., 2014](#); [Tang and Long, 2019](#)), or advanced image features such as color distributions, hue, luminance, edge patterns, and texture characteristics ([Florio et al., 2023](#); [Naik et al., 2014](#)). These detailed street elements and advanced image features are reliably present only in street photos of built projects, enabling comprehensive feature extraction that supports further assessment of visual qualities ([Figure 7.1](#), the left image).

Many studies also integrate street image data with other types of urban data, including building footprints, road networks, land use information, point of interest (POI) data, sensor data of pedestrian flow, mobile phone or GPS data, demographic data, and socioeconomic data to enable comprehensive urban analytics ([Long and Ye, 2019](#); [Li et al., 2022b](#)). This integration allows for multi-scale analysis, from individual street segments to entire neighborhoods and cities, supporting evidence-based planning decisions ([Faludi and Waterhout, 2006](#)). These additional types of data are also only available in existing built projects, and are unavailable in 3D design models used during the design stage ([Figure 7.1](#), the right image).

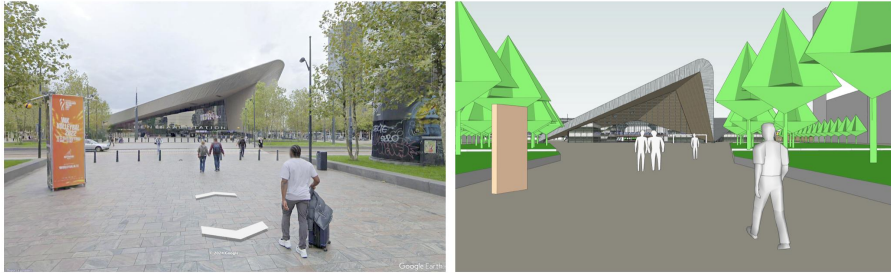


FIG. 7.1 A photo of a real-world scene (Source: Google street view) vs a 3D representation model of a design (Source: Author; modeled in Rhino)

7.1.2.2 Assessing non-existing scenarios in design proposals during the design stage

While extensive research exists on visual quality assessment for existing built environments, studies addressing design-stage assessment for unbuilt proposals are notably scarce. This chapter addresses this gap by developing a model that uses only features extractable from typical 3D design representation models (Figure 7.1, the right image), enabling visual quality analysis for future scenarios (design proposals) before they are constructed (Figure 7.2).

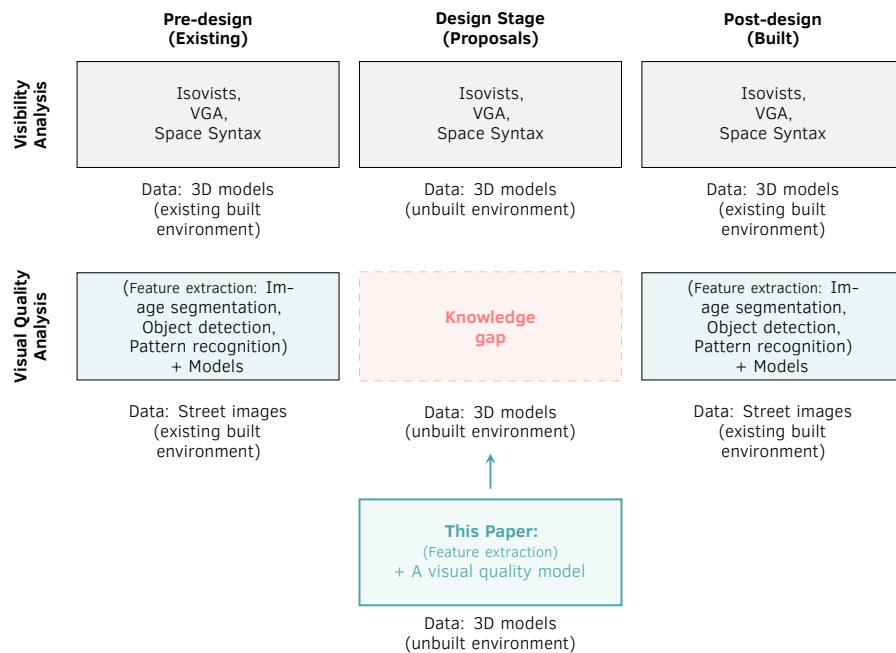


FIG. 7.2 Positioning of this study in the landscape of design-related visual analysis. (Source: Author)

7.1.3 Research question

As such, assessing the visual quality of design proposals during the design stage remains a knowledge gap. The developed models in the aforementioned studies are not applicable for projects during the design stage, when projects are not yet built, and detailed street images or built-environment data are unavailable. This chapter addresses the following **research question**:

How to computationally assess the visual quality of the built environment for design use?

To answer this question, this chapter builds a computational model that assesses visual quality based on limited features that are available in typical 3D design representation models. This chapter also intends to show the potential as well as the limitations of computational means in assessing visual quality during the design stage. The targeted audience of this chapter is designers and urban planners, who are typically not familiar with technical terms and concepts in computer vision and machine learning. Therefore, this chapter explains engineering terms in a way that is accessible to them. The final developed model has a broader general relevance as it can be used in design simulation. After this introduction section, the following sections are outlined as follows: [section 7.2](#) describes the methodology, [section 7.3](#) presents the results, and [section 7.4](#) discusses the research contributions, limitations, and future directions.

7.2 Methodology

This chapter develops a computational model for assessing visual quality during the design stage, when projects are not yet built. A key constraint is that the model must use only features that can be reliably extracted from typical 3D design representation models, as detailed street images and built-environment data are unavailable at this stage. The methodology therefore focuses on: (1) identifying and extracting features available in 3D design models, (2) developing relationships between these features and human perception using systematic model testing, and (3) integrating the model into design workflows through agent-based simulation. This approach addresses the gap identified in the introduction by enabling visual quality analysis when traditional methods cannot be applied due to data limitations.

This chapter follows a structured methodology consisting of multiple components, including manipulating a dataset that has been rated by humans, extracting image features from the dataset, testing various models to model the relationship between

the image features and visual perception, and incorporating the final chosen model into a simulation to do design assessment (Figure 7.3). Many factors influence the modeling accuracy, so many tests are made on each component of the modeling. The full methodology is explained in detail below.

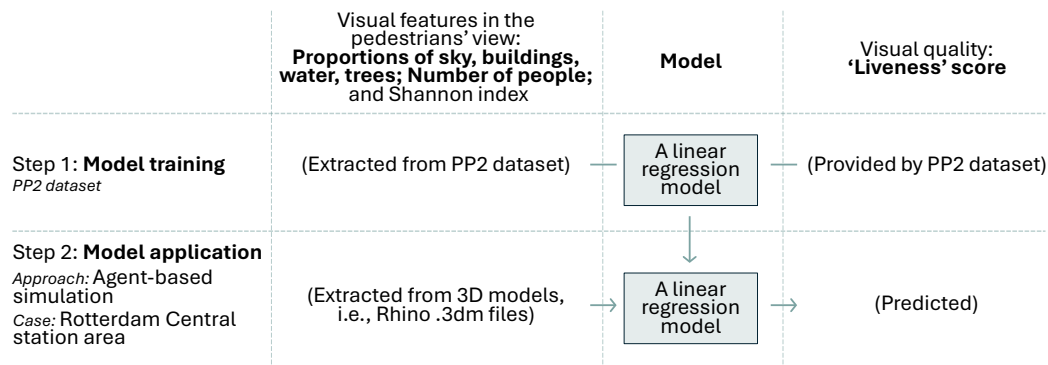


FIG. 7.3 Research methodology of this chapter. (Source: Author)

7.2.1

Extract features that are available in 3D models during the design stage

To enable visual quality analysis during the design stage, this chapter extracts features that are available in typical 3D design representation models. Unlike post-design assessment methods that can analyze detailed street elements (fences, street furniture, facade textures) or advanced image features (color, hue, luminance) from photographs, design-stage assessment must work with limited information. This chapter focuses on two types of features that can be reliably extracted from 3D models: the proportion of uncountable elements in the view (e.g., how many percent of trees) and the quantity/number of countable elements (e.g., how many people) (Figure 7.4). These two features are chosen from many others because they are extractable from typical 3D design representation models of design proposals.



Percentage of elements
(Semantic segmentation)
[Done half-manually using Roboflow]



Number of elements
(Instance segmentation)
[Done automatically using Pixellib]

FIG. 7.4 Extracting two types of image features—the proportion of elements (the left image) and the number of elements (the right image) in the scenes. (Source: Google Street View; processed by author)

7.2.1.1 Proportion-based visual features

The proportion of elements represents the percentage of each visual element (e.g., buildings, sky, trees, water) in the view. These proportions are crucial for design-stage assessment as they can be calculated from 3D model geometry without requiring detailed renderings or photographs.

The proportion of elements is extracted first by machine and then by manual annotation. As the input of the regression model, the images should be segmented as accurately as possible. This chapter first tried to use semantic segmentation models (e.g., the PSPNet models, embedded in the [MMSegmentation](#) library) to automatically extract the different proportions of elements in the images. However, the accuracy of using semantic segmentation models is visually problematic (e.g., [Figure 7.5](#), left image). Also, since the element categories are predefined in the datasets that these models were trained on, it is not possible to investigate new types of elements (e.g., water bodies). This chapter finally decided to use the most accurate method—manually annotating images (through the platform [Roboflow](#), which provides the option to utilize the embedded [Segment Anything](#) algorithm to pre-segment images to save manual efforts) ([Figure 7.5](#), right image).



FIG. 7.5 Comparison of semantic segmentation of images by machine (the left image) and by human (the right image). (Source: Google Street View; processed by the author)

7.2.1.2 Count-based visual features

The number of countable elements (or ‘instances’) in each picture represents discrete objects such as people, vehicles, or bicycles. These counts are important for assessing visual quality as they indicate activity levels and human presence, which are key indicators of ‘liveness’ in urban environments.

The number of elements (or ‘instances’) in each picture is extracted using the instance segmentation model [PointRend ResNet50](#) (which is pre-trained on the [COCO dataset](#) using [Mask R-CNN](#) algorithm) embedded in [PixelLib](#) Python library. The instance segmentation applied is shown to be relatively accurate ([Figure 7.4](#), right image), so it is conducted entirely by the machine in this paper.

7.2.2 Model development

7.2.2.1 Data source and preparation

This chapter uses the Place Pulse 2.0 (PP2) dataset, which comprises images from 56 cities across the world, each evaluated based on six urban attributes: safety, liveliness, boredom, wealth, depression, and beauty. These images are initially rated by humans in a simple manner – pairwise comparison, then the number of clicks is transformed into rating scores of each image using the ‘true’ skill algorithm ([Salesses, 2012](#)). This chapter manipulates the dataset by removing noise and outliers and then comparing model accuracy when using the whole dataset versus using its subsets for modeling.

7.2.2.2 Algorithm selection and testing

This chapter tests different mathematical and computational algorithms to model the relationship between the human-rated ‘liveness’ scores and the image features. The tested algorithms include linear regression, Multilayer Perceptrons (MLPs), and spatial regression. Linear regression is one of the most common and simple mathematical models, assuming linear relationships between independent and dependent variables. The tests of linear regression are conducted in the software program [SPSS](#). SPSS also provides an option—Automatic Linear Modeling, which is similar to linear regression, so this chapter also tests it. Beyond linear algorithms, non-linear algorithms are also tested. This chapter chooses Multilayer Perceptrons (MLPs) (one type of neural network model typically used for classification and regression tasks) as an example of non-linear models to test. When testing the MLPs algorithm, the modeling is approached as both regression and classification tasks [In the classification test using MLPs, this chapter classified the image ‘lively’ scores into 10 categories and trained the model to predict each image’s category] ([Table 7.2](#)). Street images may have spatial auto-correlations ([Cliff and Ord, 1981](#)) that decrease the modeling accuracy. Therefore, spatial regression models, which can resolve auto-correlations, are also tried. The spatial regression is conducted in the software program [GeoDa](#).

TABLE 7.2 Different models for testing

	Linear	Non-linear
(Regression)	linear regression; automatic linear modeling	MLPs; spatial regression
(Classification)	–	MLPs

Note: MLPs (Multilayer Perceptrons) are a type of neural network used for both regression and classification tasks. Spatial regression can be either linear or nonlinear, depending on the model specification.

7.2.2.3 Variable selection for design relevance

The extracted data from image segmentation (i.e., the proportions and quantities of different elements) contains information about many elements, which are potential variables for models; however, not all the elements’ information is essential or meaningful, necessitating variable selection. This chapter carries out variable selection in two steps. First, it utilizes multiple (mathematical or computational) variable selection methods and compares the outcomes. The aim is to determine which combination of variables yields high model accuracy. Considering variable selection methods are also dependent on the algorithms/models chosen, in the research design stage, no specific methods are determined, keeping the choices open. Second, the author makes manual selections to eliminate variables (elements) that have little design relevance.

7.2.3 Incorporating the model into agent-based simulation

To show the usefulness of the linear regression model for design use, this chapter incorporates the model into agent-based simulation and applies the simulation to the case of Rotterdam Central Station. In the simulation, the 3D model of the scene is modeled regarding the proportion and number of elements (Figure 7.6). This modeling process can be seen as a reverse process to the image feature extraction process; Each agent (representing a pedestrian) has a view of the scene, and the scene's visual quality is calculated using the linear regression model. Technically, this simulation is first run in MassMotion, a movement simulation software program, to get the movement trajectories of all the agents; then, it is executed using Python scripts (written by the author) in Rhino to get a mapping of the visual quality.

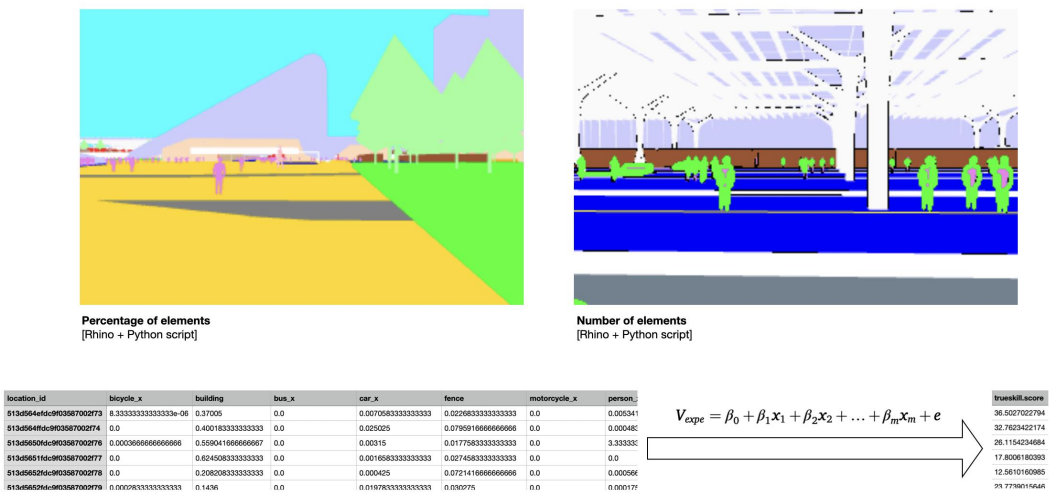


FIG. 7.6 Modeling a design scene regarding the proportion and the number of elements. (Source: Author)

7.3 Results

This section presents the results. Subsection 7.3.1 presents the relationship between humans' perception and view features in a linear regression model. Despite linear regression being the final chosen model in this chapter, it is one among many choices of models, with many factors affecting the accuracy of models (subsection 7.3.2). Subsection 7.3.3 further integrates the linear regression model into an agent-based simulation approach, assessing the visual experience in Rotterdam Central Station and

demonstrating the practical application of this linear regression model in design practice.

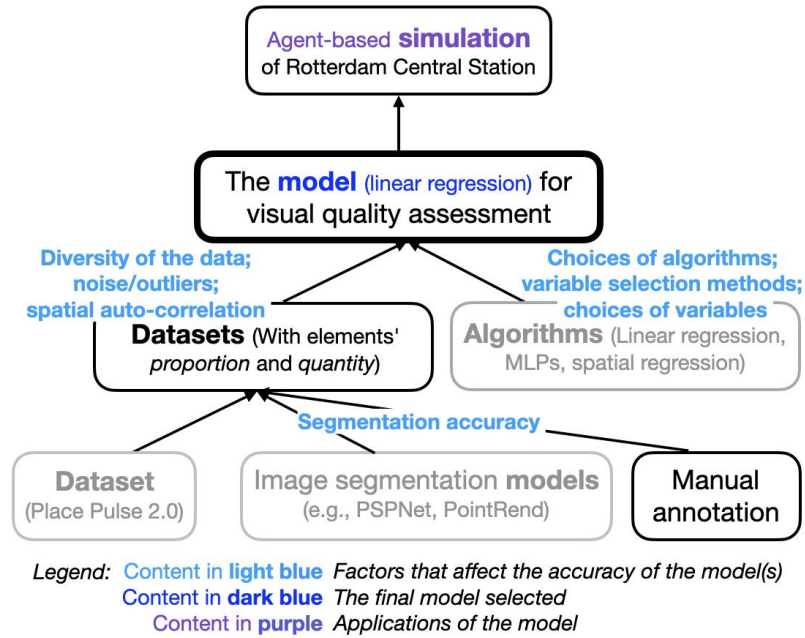


FIG. 7.7 Research results (in colored texts). (Source: Author)

7.3.1 A linear regression model that models the relationship between view elements and 'liveness' perception

Using the linear regression algorithm (Equation 7.1), a linear regression model is developed to model the relationship between human perception of 'lively' and street image features (Equation 7.2). It is the same model that was used in Test 8 in Table 7.4). Table 7.3 displays the varying importance of different visual elements contributing to the 'lively' score. It can be seen from the standardized coefficients that the building proportion in the view contributes the most to the 'lively' quality, followed by the person numbers, tree proportion, and water proportion. Sky, although it is an element that people generally like, surprisingly contributes negatively. This may be because when there is more sky in the scene, there are fewer other elements, hence less visual diversity, leading to a declining perception of 'lively.'

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_m x_m + e \quad (7.1)$$

$$Y_{\text{LivelyScore}} = 22.388 - 6.554 \cdot x_{\text{Sky}} + 8.457 \cdot x_{\text{Building}} + 0.539 \cdot x_{\text{Person_No}} + 39.143 \cdot x_{\text{Water}} + 4.596 \cdot x_{\text{Vegetation}} + 2.202 \cdot x_{\text{ShannonIndex}} + e \quad (7.2)$$

TABLE 7.3 Importance of different facilities regarding liveness

Indicators	Unstd. Coefficients	95% CI		Std. Coefficients	P
		Lower	Upper		
(Constant)	22.388	20.457	24.320		<.001
Sky	-6.554	-11.685	-1.422	-0.127	0.012
Building	8.457	5.135	11.780	0.257	<.001
Person_No.	0.539	0.272	0.807	0.174	<.001
Water	39.143	16.241	62.044	0.141	<.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.

7.3.2 The accuracy of modeling affected by various factors

The final model developed above is built upon a series of works and operations (Figure 7.7); Various factors affect the accuracy of modeling, including factors related to data (e.g., data diversity, data noise and outliers, spatial auto-correlation, and image segmentation accuracy), the choices of different models, the choices of variable selection methods, and the choice of variables. This chapter runs multiple rounds of tests with different factors, with the results listed in Table 7.4 (The final selected model is the one used in Test 8), and more details are explained below.

TABLE 7.4 Tests on different factors affecting model accuracy

Test	Data	Data manipulation	Algorithm	Variable selection method	Variables selected	Accuracy (adjusted R^2)
1	Whole set [without element quantity] (n=92692)	–	Linear regression	[Auto-selection] 'Backward' method	[14 out of 19 variables] ¹ car, vegetation, fence, sky, wall, person, terrain, bicycle, pole, traffic.sign, traffic.light, building, truck, train	0.065
2	Whole set (n=92692)	–	Linear regression	[Auto-selection] 'Backward' method	[39 out of 97 variables] car, car _{No.} , potted.plant, road, bicycle, bicycle _{No.} , pole, vegetation, person _{No.} , sky, wall, fence, fire.hydrant _{No.} , traffic.light _{No.} , ...	0.095
3	Subset Amsterdam (n=506)	–	Linear regression	[Auto-selection] 'Backward' method	[21 out of 97 variables]	0.210
4	Subset Amsterdam (n=490)	Noise and outliers excluded	Linear regression	[Auto-selection] 'Backward' method	[17 out of 97 variables]	0.230

(Continued on next page)

Test	Data	Data manipulation	Algorithm	Variable selection method	Variables selected	Accuracy (adjusted R^2)
5	Subset Amsterdam (n=490)	Noise and outliers excluded; manually annotated	Linear regression	[Auto-selection] 'Backward' method	[26 out of 135 variables] sidewalk, train, parking.meter, building.wall ^{annotated} , traffic.light, kite, road.bricks.red ^{annotated} , water, stop.sign, ...	0.265
6	Subset Amsterdam (n=490)	Noise and outliers excluded; manually annotated	Linear regression	[Manual selection]	[5 out of 135 variables] sky, building ^{annotated} , person _{No.} , water ^{annotated} , vegetation	0.144
7	Subset Amsterdam [include interaction terms] (n=490)	Noise and outliers excluded; manually annotated	Linear regression	[Auto-selection] 'Backward' method	[6 out of 15 variables] ⁴ sky, building ^{annotated} , sky × person _{No.} , sky × water ^{annotated} , building ^{annotated} × vegetation, person _{No.} × water ^{annotated}	0.162
8	Subset Amsterdam (n=490)	Noise and outliers excluded; manually annotated	Linear regression	[Manual selection]	[6 out of 136 variables] ⁵ sky, building ^{annotated} , person _{No.} , water ^{annotated} , vegetation, ShannonIndex	0.156
9	Subset Amsterdam (n=490)	Noise and outliers excluded; manually annotated	Automatic Linear Modeling	[Auto-selection by SPSS]	[10 out of 135 variables] bicycle _{No.} , car _{No.} , person _{No.} , potted.plant _{No.} , fence, rider, sky, vegetation, buliding ^{annotated} , water ^{annotated}	0.278
10	Subset Amsterdam (n=490)	Noise and outliers excluded; manually annotated	Spatial regression ⁶	[Manual selection]	[5 out of 135 variables] sky, building ^{annotated} , person _{No.} , water ^{annotated} , vegetation	0.161
11	Subset Amsterdam (n=490) ⁷	Noise and outliers excluded; manually annotated	MLPs [classification]	[Manual selection]	[5 out of 135 variables] sky, building ^{annotated} , person _{No.} , water ^{annotated} , vegetation	[Not applicable] ⁸
12	Subset Amsterdam (n=490) ⁷	Noise and outliers excluded; manually annotated	MLPs [regression] ⁹	[Manual selection]	[5 out of 135 variables] sky, building ^{annotated} , person _{No.} , water ^{annotated} , vegetation	0.101

13	Subset Amsterdam (n=490) ⁷	Noise and outliers excluded; manually annotated	MLPs [regression] ⁹	[Semi-automatic selection] ¹⁰	[5 out of 135 variables] car, building _{annotated} , bicycle _{No.} , car _{No.} , person _{No.}	0.137
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Note: [1] This data has no element quantity/number information and, therefore, has fewer variables;
[2] The ‘_{annotated}’ subscript represents that the corresponding element is manually annotated;
[3] The ‘_{No.}’ subscript represents that the variable is the quantity/number of the corresponding element.
[4] This data includes five variables (that were selected in test 6) and their ten interaction terms.
[5] This data has the Shannon index added.
[6] The spatial weight matrix was created using Euclidean distance between the geometric centroids of the spatial units. The spatial regression model used is the spatial lag model, which has a higher accuracy than the spatial error model in this case (0.161 vs 0.153).
[7] The NaN values are imputed with zeros.
[8] In this classification task, the data is divided into ten categories. The model achieves an accuracy of 0.173, meaning it correctly classifies 17.3% of the instances. While this is slightly better than random guessing (which would yield 10.0% accuracy for ten categories), the performance is still poor.
[9] Hyperparameters: solver: ‘adam’, learning rate init: 0.001, hidden layer sizes: (100, 50), alpha: 0.0001, activation: ‘relu.’
[10] In this test, the variables are selected by the machine, based on the ANOVA F-test. However, the number of top variables to select is decided manually, as five.

7.3.2.1 Geographical diversity of data samples

The diversity of data samples affects the accuracy of modeling, as shown by the comparison between tests 2 and 3 in [Table 7.4](#). It is a common understanding in data analysis that the more diverse the dataset is, the harder it becomes to identify clear patterns, as the variability in the data increases. This chapter first tried the whole Place Pulse 2.0 dataset (data sample size $n = 92692$, after exclusion of images with missing score values), which contains street view images from 56 cities across the world; then it tried to use a subset of the whole dataset, which contains data of only one city – Amsterdam ($n = 506$). The latter test resulted in significantly higher accuracy ($R^2 = 0.210$) than the former ($R^2 = 0.095$). The difference in accuracy when modeling using the whole dataset and the subset also indicates that geographically, different environments vary significantly. [Therefore, it is important to note that this chapter’s final model has a limited context, and its generalization ability in other cities or geographical areas needs further examination.]

7.3.2.2 Data noise and outliers

Data noise and outliers affect the accuracy of modeling, as shown by the comparison between tests 3 and 4 in [Table 7.4](#). When analyzing the relationship between ‘building proportion’ and the ‘lively’ score, it first seems no statistically reliable relationship exists (with a high p-value, > 0.05). This is counter-intuitive because common sense suggests that a scene with more buildings would appear livelier (e.g., [Figure 7.8, a](#)). Presumptively, a strong, reliable relationship should exist (p-value < 0.05). After

examining the data, the author realized that in the dataset, while most images have buildings as positive elements, there are some images where the buildings look really negative to pedestrians' perception, as they basically are walls with little or no windows and cover a large proportion of the scene (e.g., Figure 7.8, b). After removing these 'outlier' images, the p-value dramatically reduces to a value less than 0.05. Totally unrecognizable image (e.g., Figure 7.8, c), and images of tunnel environments that are significantly different from normal street scenes (e.g., Figure 7.8, d) are removed. After noise removal (data sample size from $n = 506$ to $n = 490$), the accuracy of modeling increased (from $R^2 = 0.210$ to $R^2 = 0.230$). This accuracy difference also indicates that different scene environments will have an impact on the model accuracy. Therefore, the developed model is limited in urban street environments, and the generalization ability needs further examination when applied to other environments, such as indoor spaces and tunnel environments.



FIG. 7.8 The data noise or outliers in the data. (Source: Google Street View; annotated by the author)

7.3.2.3 Spatial autocorrelation of data samples

Spatial autocorrelation of data samples affects the accuracy of modeling, as shown by the comparison between tests 10 and 6 in Table 7.4. Given the same data, when spatial autocorrelation is addressed (by applying the spatial weight matrix), the accuracy value increases (from $R^2 = 0.144$ to $R^2 = 0.161$). Spatial regression takes the assumption that visual quality is associated with spatial autocorrelation, while linear regression takes the assumption that visual quality depends on the image features and is independent of locations. Despite being more accurate in these tests, the spatial regression model is a less usable model than the linear regression model. This is because spatial regression models are dependent on weight matrices, and each weight matrix is unique (linked with the corresponding geographical area), making the associated spatial regression not transferable to other geographical contexts.

7.3.2.4 The accuracy of image segmentation

The accuracy of image segmentation affects the accuracy of modeling, as shown by the comparison between Tests 4 and 5 in Table 7.4. With manually annotated variables,

the model's accuracy increased (from $R^2 = 0.230$ to $R^2 = 0.265$). This chapter's final selected model includes manually annotated variables ([Equation 7.2](#), Test 8 in [Table 7.4](#)). More accurate semantic segmentation of images can be achieved with the fast development of image segmentation in the computer field (e.g., see ([Paperswithcode, n.d.](#))).

7.3.2.5 The choice of algorithms

The choice of (mathematical or machine learning) algorithms affects the accuracy of modeling, as shown by the comparison between tests 5 and 9; and between tests 6, 10, 11, and 12 in [Table 7.4](#). Auto-linear regression in SPSS software has slightly higher accuracy than linear regression ($R^2 = 0.278$ vs $R^2 = 0.265$). Spatial regression has a higher accuracy than linear regression ($R^2 = 0.161$ vs $R^2 = 0.144$). Typically, MLP (Multilayer Perceptron) regression is able to capture more complex relationships than linear regression hence it is more accurate. However, surprisingly, the MLP regression is no better than the linear regression in this chapter's tests ($R^2 = 0.101$ to $R^2 = 0.144$). This may be due to the sample size being small ($n = 490$), while MLP is usually effective on large data. When changing the task from a regression task to a classification task, the MLP's performance is still not impressive (accuracy as 0.17 vs 0.10, see table note [8] in [Table 7.4](#)).

This chapter adopted linear regression as the final algorithm for the training model, considering that the normal linear regression algorithm is clearer for interpretation, and none of the other algorithms yielded dramatically improved accuracy. Linear regression is usually an oversimplification of reality, but statistically, nevertheless, it shows the net effects of independent variables on the dependent variable.

7.3.2.6 The choice of variable selection methods

When using the machine to auto-select variables, different variable selection methods can lead to different final sets of selected variables, resulting in models with different accuracy. For linear regression, in SPSS software, there are 'forward,' 'backward,' and 'stepwise' as variable selection methods. When testing the whole set of data ($n = 92692$), these three methods resulted in similar accuracy. When testing with the subset data of Amsterdam ($n = 490$), the 'backward' method resulted in the highest accuracy ([Table 7.5](#)). For MLP regression, this chapter tested various methods, including KBest F-test, KBest Mutual Info, Lasso, Tree Importance, and PCA. The highest accuracy resulted from the KBest F-test method ([Table 7.5](#)). Since automatic selections by the machine usually include variables that hardly have relevance to spatial design during the design stage, or can not be modeled reliably (e.g., the proportion of parking meters and traffic lights and the number of bicycles in Test 5),

this chapter has to drop them and make manual selections further. After several rounds of tests, a combination of variables that balance the accuracy and design relevance was chosen (Test 6 in [Table 7.4](#)).

TABLE 7.5 Model accuracy affected by variable selection methods

Models	Selection Methods	Accuracy (adjusted R^2)
Linear regression (Based on Test 5 in Table 7.4)	Stepwise	0.220
	Forward	0.220
	Backward	0.265
MLP regression (Based on Test 13 in Table 7.4)	KBest (F-test)	0.201
	KBest (Mutual Info)	- 0.130
	Lasso	0.051
	Tree Importance	- 0.102
	PCA	0.151

7.3.2.7 The choice of variables

Models' accuracy is determined by the variables selected. Typically, more variables enable more accurate models. For example, in comparisons between Tests 1 and 2 in [Table 7.4](#), when the variables of element quantity were added, the model's accuracy improved (from 0.065 to 0.095). Many variables automatically selected by the machine have little relevance to the spatial design or can not be modeled reliably and, hence, are dropped. The manual selection finally includes five variables: sky, building_{annotated}, person_{No.}, water_{annotated}, and vegetation (see Test 6 in [Table 7.4](#)). Beyond these selected variables, two types of artificial variables calculated based on them, interaction terms and the Shannon index, are also tested.

Interaction terms represent the combined effect of two or more independent variables on the dependent variable (e.g., exercise and diet may have combined effects on weight loss). Including interaction terms slightly increases the model accuracy, as shown by the comparison between Tests 7 and 6 in [Table 7.4](#). However, in this chapter, the interaction terms selected by the machine have no evident real-world meaning (e.g., sky $\times$ person_{No.}).

Shannon index has been used as an indicator for measuring diversity in the built environment ([Zhong et al., 2020](#); [Zachary and Dobson, 2021](#)); In urban design research, visual diversity or complexity are qualities commonly mentioned to be important to environmental perception ([Ewing and Handy, 2009](#); [Jacobs, 1961](#)); This chapter achieved a statistically reliable Shannon index (p-value < 0.05), calculated based on the visual proportions of several elements, including buildings, sky, trees, grass, and sidewalks. The model's accuracy increased with this Shannon index being added as an extra variable (See the comparison between Tests 8 and 6).

7.3.2.8 Comparing the accuracy of the models in this chapter with those in other studies

The above tests explained how various factors affect models' accuracy. With manipulations of these factors, other studies in the existing literature have achieved much higher accuracy values, compared with the $R^2 = 0.167$ and the adjusted $R^2 = 0.156$ of the final model in this chapter, reaching R^2 values such as 0.54 (Naik et al., 2014), 0.51 (Nagata et al., 2020), and 0.238 (Liang, 2020). This chapter's approach only includes the proportions and quantities of visual elements (to make it usable for design renderings). In comparison, other studies incorporated more advanced visual features as variables or non-visual variables. In the study by Naik et al. (2014), all variables are features that only exist in photos, and do not exist in typical cartoon-like design renderings. In the study by Nagata et al. (2020), the width of roads and interactive terms are important variables; also, that study includes many statistically unreliable variables (p -value > 0.05). In the study by Liang (2020), variables related to urban form and road networks are included.

7.3.3 Applying the model to the case of Rotterdam Central Station

To showcase the use of the visual quality assessment model, this research incorporated it into agent-based simulations, in which each agent navigates the simulated environment and continuously assesses the scenes it views along its journey. The simulations are applied to the case of Rotterdam Central Station, with a comparison between the previous and the current scenarios.

As shown in the bottom left image in Figure 7.9, the mapping can differentiate the visual qualities in different locations across the area in the same scenario. E.g., comparing location 1 and location 2, the former has a higher quality score than the latter, which corresponds to the real-world user perceptions—at location 1, users see a more lively scene with more people and building facade, while at location 2, users see a less lively scene with fewer people and less building facade.

As shown in the bottom left and right images in Figure 7.9, the mappings can differentiate the visual qualities at the same locations in different scenarios. E.g., comparing location 1 and location 1', the former has a higher quality score than the latter, which corresponds to the real-world user perceptions—at location 1 in the current station, users see a more lively scene with positive elements like people, trees, and building facade, while at location 1' in the previous station, the views are mostly blocked by vehicles. These mappings demonstrate the effectiveness of the visual quality assessment model and illustrate the potential of computational assessment of visual quality in design practice.

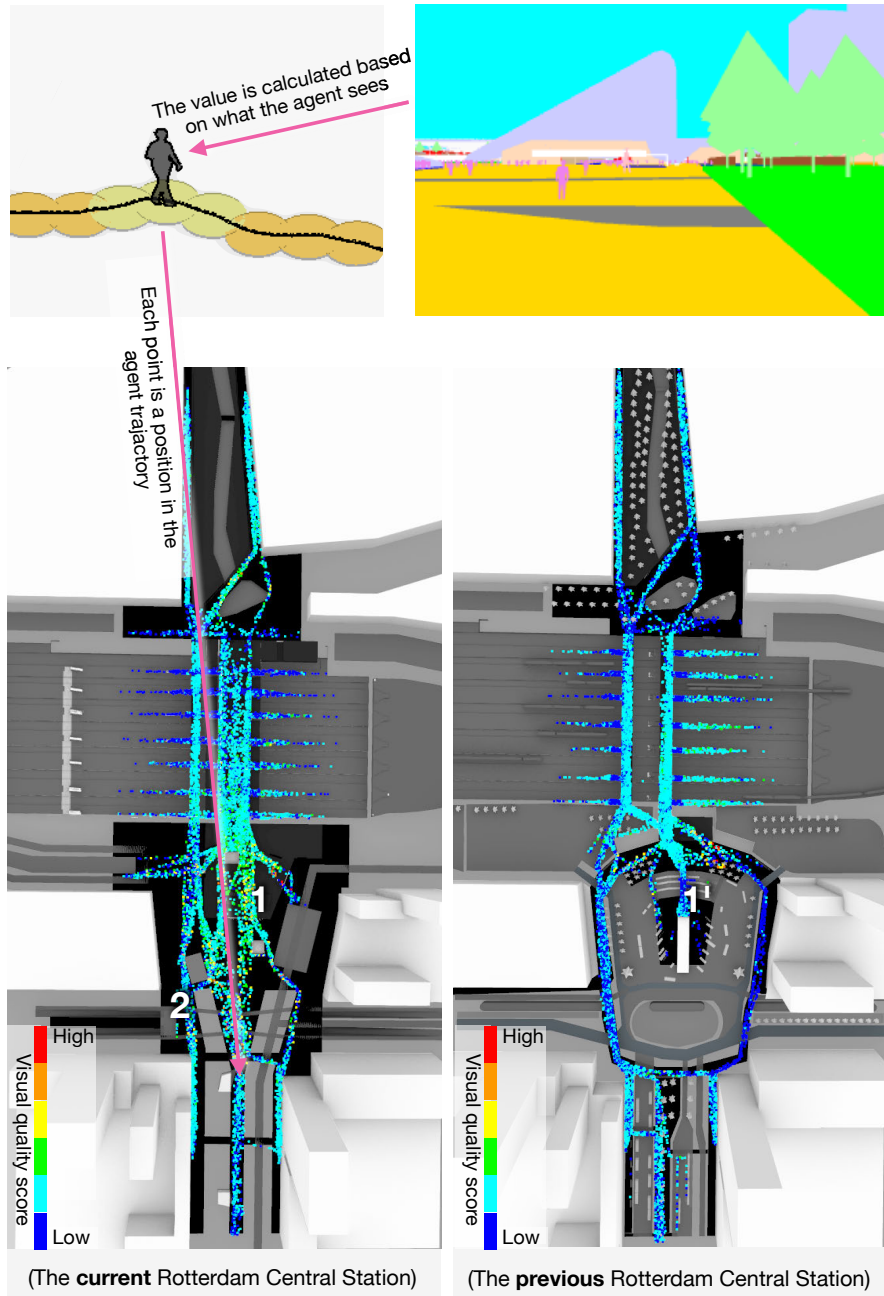


FIG. 7.9 Mapping the visual quality in the current and the previous Rotterdam Central Station areas. (Source: Author)

Notably, in the above showcase, significant technical challenges were encountered in conducting the simulation. First, this chapter optimized computational accuracy and the speed of image processing. E.g., while exporting .jpg pictures results in huge errors in the calculation of element proportion in the view, exporting as .png format resolves this issue. The processing of all agent views by Python scripts using a pixel-by-pixel approach takes hours, while using [PIL \(Python Image Library\)](#) only takes a few minutes. Second, this chapter addressed the differences between different digital tools. E.g., while an agent position is recorded with coordinates as X, Y, Z in MassMotion (the movement simulation software), the same position is denoted as X, -Z, Y in Rhino (in 3D spatial modeling software). Lastly, in this agent-based simulation, the visual quality mapping relies on movement trajectories, which are generated based on the origin-destination (OD) matrix using movement algorithms. This approach potentially introduces bias into the visual mapping.

7.4 Discussions

7.4.1 Research contributions

This chapter contributes to the knowledge body in the following ways: First, by building a linear regression model that calculates visual quality ('lively') based on the environment's elements, it extends the quantitative understanding of visual quality. Second, this chapter shows the possibility, as well as outlines the limitations and future directions of visual quality assessment through computational means.

7.4.2 Limitations of assessing visual quality using computational means

This chapter exhibits the limitations of computational assessment of visual quality. As shown by the research results, models are typically built on many primary works and correspondingly affected by various associated factors. On the one hand, the final linear regression model in this chapter is trained on data with limited variability in terms of geography (Amsterdam) and environmental type (outdoor street environment). On the other hand, other research suggests different environments can result in significant variations of perception ([Lou et al., 2024](#)). Therefore, the model should be limitedly used for new cases with similar characteristics. Training a model requires huge efforts, and yet the model's generalizability and accuracy are often

limited. This highlights the necessity of traditional means of visual quality assessment – designers’ (who are experts with aesthetics to a certain degree) manual judgments.

7.4.3 Future research directions

There are several future research directions toward more generalizable and accurate models (Figure 7.10). Future research can verify the training data’ variations, by including new data of more types of geography, environments (outdoor), or buildings (indoor); These new data can either be collected in similar ways to what this chapter did—extracting image features from datasets like Place Pulse 2.0, or be collected from VR experiments—where digital virtual environments provide directly-extractable image features. Of note, in this chapter, manual labeling/annotation was used to ensure the segmentation accuracy and to investigate elements that are not included in segmentation models’ variable categories. However, manual labeling, as a laborious task, is challenging to apply to large datasets. Thus, image segmentation by machine is still promising and requires more accurate segmentation models trained on more properly labeled datasets, using future new algorithms.

This research builds a model for assessing visual qualities based on features that are reliably available in 3D models during the design stage. With the emergence of generative AI tools capable of creating photorealistic images, advanced image features (e.g., color, hue, luminance, edges, patterns) are becoming increasingly accessible during the design stage. As a result, future research could develop models based on these advanced features. However, the challenge lies in the reliability of these features to represent reality, as images of future scenarios are still not photos of the existing world. Photorealistic images generated during the design stage—whether by AI or traditional architectural rendering—often vary in quality and can be easily altered.

Future research can also conduct city-level mapping using the developed model, and compare the effectiveness of mappings using this model versus using existing other models (Figure 7.10). If the developed model has a similar effectiveness, then it provides a new way of city-level visual quality assessment that does not rely on street images but on 3D models. This would be meaningful for areas that have no street images but have rough 3D spatial information.

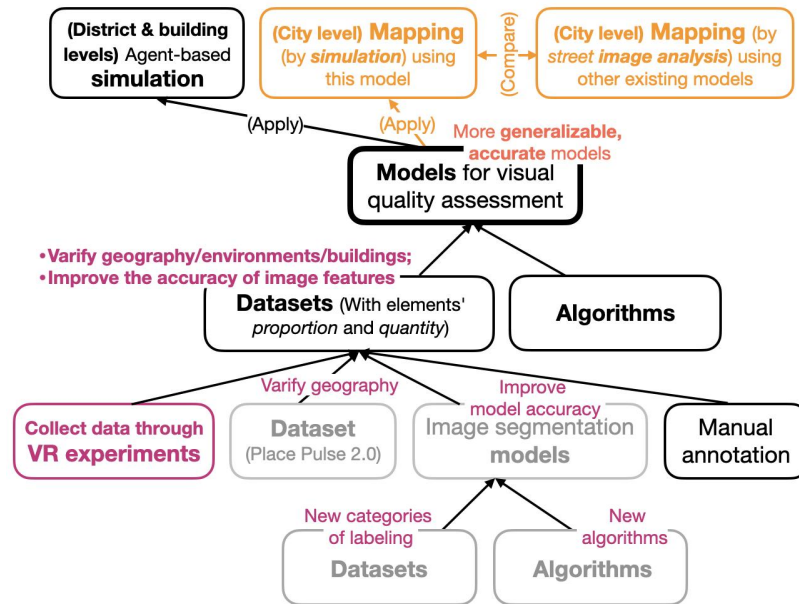


FIG. 7.10 Future research directions (in colored texts). (Source: Author)

7.5 Conclusions

In the introduction section of this chapter, a research question is proposed: how to computationally assess the visual quality of the built environment for design use? This question is answered by this chapter's final linear regression model. This model is developed based on extensive tests on a series of relevant factors. The usage of this model is further demonstrated through an agent-based simulation of the Rotterdam Central Station area.

8 Conclusions

The thesis has investigated the overcrowding-underutilization (O&U) phenomena in railway station areas and provided design solutions and tools. Overcrowding raises concerns about safety, and underutilization is a waste of a valuable resource, necessitating knowledge to reduce them. Meanwhile, knowledge gaps were identified in literature reviews ([Chapter 1, section 1.3](#), and [Chapter 2](#)): (1) the understanding of the spatial relevance of the overcrowding-underutilization (O&U) phenomena and flexible use; and (2) the assessment framework as well as design principles that enable flexible use of stations.

This research **aims** to provide designers and other stakeholders with the tools and insights to better understand, assess, and design railway station areas in a way that they can support flexible use (aimed at reducing overcrowding and underutilization) and promote station-city integration.

This thesis addresses three research questions (see the following [section 8.1](#)) in three PARTs. First, it starts with an examination of spatial relevance, studying cases to understand the causes of the O&U issues, reflecting on the relevance of spatial configurations, and discussing the potential of spatial designs ([Part III](#), Chapters 2 and 3). Second, it develops design principles for the flexible use of stations and tests the design principles through research-by-design ([Part II](#), Chapters 4 and 5). Third, it develops an assessment framework for evaluating whether design proposals support flexible use. These studies respectively resulted in a published paper or a manuscript. This concluding chapter synthesizes the conclusions, reflects on the findings, and provides recommendations ([Part III](#), Chapters 6 and 7).

8.1 Answers to research questions

8.1.1 Research question 1 (PART I, Chapters 2-3)

What is the *spatial relevance* of the overcrowding and underutilization in the station area?

The overcrowding-underutilization phenomena is investigated in [Chapter 3](#) through case studies. The investigation revealed that the overcrowding-underutilization phenomena are affected by ***spatial layouts, elements, and qualities***, confirming spatial design's potential in reducing O&U. For example, overcrowding can be exacerbated by elements potentially forming bottlenecks to the pedestrian flow and layouts that involve many bottlenecks; and it can be reduced by providing spare space. Underutilization—which can be reduced with commercial activities, other leisure activities, and leisure events—is respectively affected by a series of spatial aspects, such as commercial areas' accessibility and visibility, the size and qualities of spaces affecting user experiences, traffic elements' arrangement affecting pedestrian walking experience, and footbridges or tunnels form barriers to pedestrian flows. Certain spatial layout aspects, like stations' connections with neighboring city districts and layouts associated with flow organization—unidirectional vs bidirectional, are more fundamental, affecting both overcrowding and underutilization across multiple use scenarios. Spatial design's potential lies in intervening in these spatial aspects.

In addition to [Chapter 3](#), [Chapter 2](#) also briefly explains the spatial relevance of the overcrowding-underutilization phenomena, and inquires into the existing knowledge on potential solutions. It reveals the gaps in design principles and assessment frameworks that substantially deal with urban and architectural design.

8.1.2 Research question 2 (PART II, Chapters 4-5)

What are the *design principles* for station areas that support flexible use?

Six major **design principles** are developed in [Chapter 4](#), including: (1) prioritizing core spaces for humans rather than vehicles, (2) ensuring event visibility by aligning paths and spaces, (3) establishing high-quality connections at different scales, (4) incorporating temporary elements and reconfiguration-supportive layouts, (5) adopting dispersed layouts for transport capacity or urban vibrancy, and (6) enabling flexible use through program planning.

These principles were **validated** through research-by-design applied to a virtual case study ('Station Xtreme') and assessed using the assessment framework ([Chapter 5](#)). The evaluation confirmed that the principles are generally effective, while each has its own strengths and limitations.

8.1.3 Research question 3 (PART III, Chapters 6-7)

How can design proposals be *assessed* as supportive of flexible use?

A design-oriented assessment framework is developed in [Chapter 6](#). This framework comprises a theoretical model, various indicators, and multiple digital tools. Stations that support flexible use should satisfy users' needs (including safety, speed, ease, comfort, and experience) during peak and non-peak times. The assessment framework assesses the crowd density and direction changes in wayfinding during peak times, crowd density affected by events, the proximity of facilities, and the visual experience during non-peak times.

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 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.

A key component of this framework is a computational visual assessment model ([Chapter 7](#)), which quantifies perceptual qualities like 'liveness' from street-view imagery. Applied to the case of Rotterdam Central Station, the framework demonstrated its capacity to compare design alternatives, visualize user experience hotspots, and rigorously evaluate how spatial changes affect performance under different temporal conditions. It provides a design-decision support tool that is particularly valuable in early design stages when real-world data is scarce.

8.1.4 Synthesis of the findings

To achieve the research aim of using spatial design as a means to realize flexible use for reducing overcrowding and underutilization in stations, this research conducted a sequence of studies. Multiple methods were used to conduct a set of studies, as presented in this thesis's six chapters. First, case studies were taken, to investigate how spatial aspects affect the overcrowding-underutilization phenomena. Next,

through case studies, a set of design principles was developed, followed by evaluation using research-by-design and simulations. Last, an assessment framework was proposed, utilizing a theoretical model, multiple indicators, and technical tools. The conclusions are synthesized as follows:

1. The overcrowding-underutilization phenomena are affected by spatial aspects, including spatial layouts, elements, and qualities. Spatial aspects, such as spare space for circulation, spatial connections between stations and their adjacent urban areas, bottlenecks and barriers in pedestrian paths, space as event venues, and human-scale spaces that facilitate spontaneous leisure activities, all affect the activities of transport travelers during peak times and the activities of non-transport users during non-peak times.
2. Scenario analysis, incorporating existing scenarios and future potential scenarios, is shown to be effective in investigating cases, providing insights into existing and non-existing practices.
3. An assessment framework is developed to evaluate whether stations are supportive of flexible use during peak and non-peak times. In this framework, users' movement and visual experience are simulated, followed by the assessment of five types of travelers' needs: safety, speed, ease, comfort, and experience.
4. A linear regression model has been developed in this thesis to assess specifically the visual experience of users in an urban environment, where the 'lively' feeling of users is positively related to the following content in the view: the proportions of buildings, water, and trees, and the number of people.
5. Six major design principles are developed for designing stations that support flexible use: (1) prioritizing core spaces for humans rather than vehicles, (2) ensuring event visibility by aligning paths and spaces, (3) establishing high-quality connections at different scales, (4) incorporating temporary elements and reconfiguration-supportive layouts, (5) adopting dispersed layouts for transport capacity or urban vibrancy, and (6) enabling flexible use through program planning.
6. A multi-step methodological framework is established for systematically developing design principles, which includes: establishing design objectives and design dimensions, collecting data from cases and literature, processing the data iteratively through analytical visualization, formulating initial findings, and reflecting on the findings through expert interviews.
7. This research constructs a novel framework for evaluating design principles, which, combining research-by-design and agent-based simulation, is shown to be effective for evaluating design principles.
8. In cases like the current Rotterdam Central Station case and Shanghai Station, stations have easy connections with adjacent city districts. These connections are a primary physical manifestation of station-city integration and a key enabler of the flexible use. They consolidate the functional and conceptual correlation between the two topics—flexible use and station-city integration—flexible use is functional integration of stations and cities, hence being a new value enriching the meaning of station-city integration.

Together, these studies explain to designers and stakeholders how spatial configurations affect the overcrowding-underutilization phenomena and why there is a high potential of spatial design in realizing flexible use of stations. Meanwhile, it empowers designers with design principles and instruments to work on stations for flexible use and towards station-city integration.

This thesis builds its **novelty** in emphasizing the temporal dimension—a dimension that is central to the O&U issue and flexible use, and is largely missing in existing station research. This thesis also expands the meaning of station-city integration—it establishes a new form of integration where stations and cities support temporal function changes and sharing resources, beyond mere static and physical collocation.

8.2 Reflection on the research

8.2.1 Scientific contribution

This research made scientific contributions to the design research and practice towards flexible use of railway stations, by providing knowledge and analytical tools. First, it provides a detailed description of spatial relevance ([Chapter 3](#)), explaining how spatial factors affect the overcrowding-underutilization phenomena, in a complex relationships network ([Figure 3.23](#)), providing descriptive knowledge on the phenomena, which serves as a starting point for developing further solutions. By revealing the substantial layouts, elements, and qualities involved in spatial configurations, it confirms spatial design as an important means of intervention.

Second, this thesis creates a transdisciplinary assessment framework ([Chapter 6](#)) that integrates spatial analysis, agent-based simulation, and computer vision-based perceptual modeling. This framework is not only useful for research on railway station areas, but also applicable to other types of urban districts. It provides a new methodological approach for evidence-based, performance-driven urban and architectural design, enriching the designers' toolbox of analysis.

Third, when developing the visual assessment component ([Chapter 7](#)) of the assessment framework, this research extracts scientific evidence through image segmentation and builds a mathematical model (i.e., linear regression model). The scientific evidence and mathematical model contribute to the knowledge base for understanding the visual quality associated with elements in the views.

Four, by examining existing as well as potential future scenarios in station cases, this

thesis produces a coherent set of design principles ([Chapter 4](#)) specifically targeted at mitigating O&U through flexible use. These principles provide practitioners with actionable guidance.

Last, with the description, the assessment framework, and design principles combined, this thesis enriches academic discussions on flexible use ([Carr and Dionisio, 2017](#)), as well as similar topics that convey a dynamic temporal essence, such as ‘resilience’ ([Shafiei Dastjerdi et al., 2021](#)), ‘temporary use’ ([Madanipour, 2018](#)), urban open space, responsive landscape with a ‘loose-fit’ feature ([Thompson, 2002](#)), and traffic space as public space ([Bendiks and Degros, 2020](#)).

8.2.2 Societal contribution

The research provides guidance, tools, and insights for practice. First, for designers and planners, it offers a set of design principles and a design-oriented assessment framework to support the design practice of station areas for flexible use. Second, for stakeholders and decision-makers, it provides a clear explanation of the O&U problem’s spatial dimension, facilitating more informed discussions about investments in station development. It makes the case for flexible use as a strategy that enhances user experience, space usage, and urban integration. Third, for the public, ultimately, it will contribute to the vision of creating better, more human-centered station environments that are capable during busy times, and are vibrant, welcoming public spaces at all times.

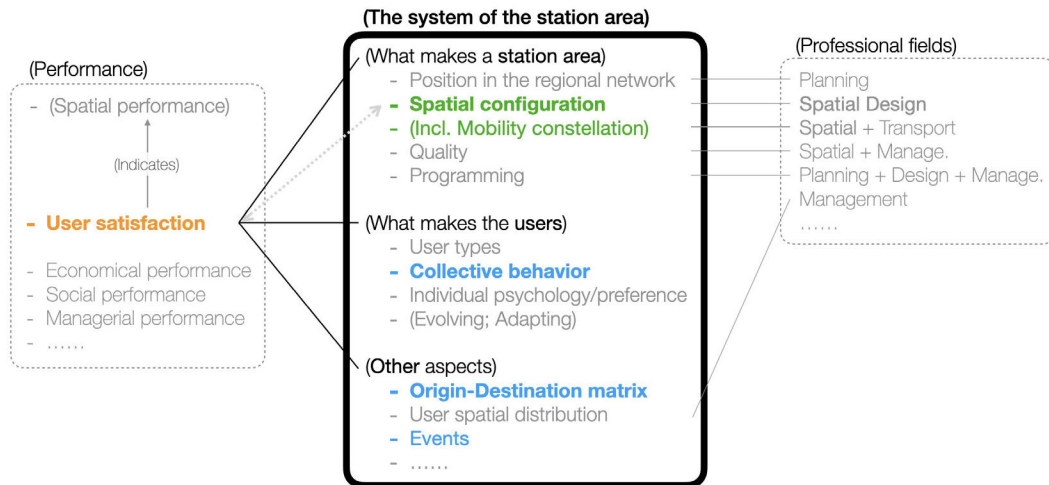
8.2.3 Research limitation

When utilizing the research results, readers should be aware of the limitations of this research, due to the research focus and constraints. The research findings are primarily grounded in Chinese and Dutch contexts; While the principles are designed for transferability, their application requires adaptation to different cultural, regulatory, and urban contexts. This research focuses on cases with high fluctuations; therefore, the findings are less relevant for stations with low fluctuations.

Based on the author’s background and interests in design, this research is centered on spatial design as the intervention means. However, spatial design is just one means of intervention to support dynamic use, while other interventions like management, policy making, planning, etc., remain powerful means. Centered on design, this research prioritized users’ experience as the perspective to analyze stations’ performance; However, in the development and daily operations of railway stations, there are many other types of performance that other actors—beyond users, including developers,

railway companies, governments, NGOs, and local residents—care about. For example, the cost and return to build stations (financial performance), the programming adaptability to future changes, the managerial capacity needed to run stations, and the vehicle transportation efficiency, the reserved spaces for nature (Zemp et al., 2011; Van Den Berg and Pol, 1998; Bertolini and Spit, 1998; Wang, 2022; Boorsma, 2024).

The assessment framework in this thesis is based on simulation, and only a limited reality is simulated (Figure 8.1). Railway station areas are complex systems consisting of physical environments, users, etc., influenced by higher-level positioning in the railway and urban networks. Users are of many types, with features on collective and individual levels, and they are evolving and adaptive. Other things, including passengers' mode split, different types of events, and spatial distribution of activities, all determine stations' performance. In the simulation study (Chapter 6), this research treated spatial configuration as a changeable factor, treated some other factors as fixed settings, and skipped the rest factors (Figure 8.1). This is due to the research project's limited time, as well as due to some factors being understudied in existing literature. Much remains unknown about station users, station facilities, spatial qualities, etc., and their interactions.



Legend in terms of colored text: (Output) (Input) (Settings) (Not simulated factors) (Description)

FIG. 8.1 Limited parts of reality have been simulated. (Source: Author)

The principles developed in this thesis were reviewed by experts, but they may still contain unforeseen limitations. Meanwhile, during interviews with field experts, it is noted that the design principles primarily address the spatial form of station buildings and their surrounding urban districts, while other crucial aspects—such as programming, spatial qualities, and nature-based solutions remain largely unexplored.

8.3 Recommendations

8.3.1 Recommendations for future research

Recognizing the above research limitations, this thesis suggests future research to address them. For example, future research should conduct similar research in diverse geographical and cultural contexts to refine the findings' universality and identify new context-specific variables.

Particularly, this thesis sees a research spectrum where emerging technologies can be incorporated to further the understanding of station systems (Figure 8.2) and enrich designers' toolboxes. New research is needed to understand station users' types, psychology, and behavior, and new tools are needed to better simulate station systems and assess their performance. New technologies, such as biometrics-related, VR, agent-based modeling, machine learning, big data, digital twins, can be utilized to facilitate such research.

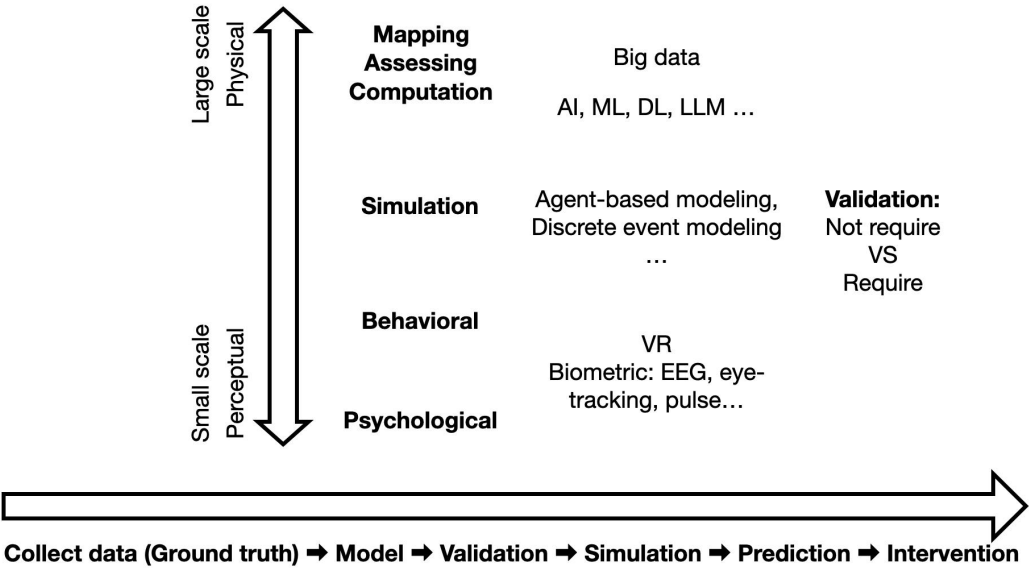


FIG. 8.2 A spectrum of future research that incorporates technology. (Source: Author)

8.3.1.1 Business model for valuation of flexibly used station space

Developing a dedicated business model to evaluate the economic and functional viability of flexibly used station spaces is essential to justify upfront investments, negotiate public-private partnerships, and coordinate complex spatial-temporal management, because flexibly used station spaces—optimally utilized during different times for various functions—should yield higher functional and economic value compared to standard station spaces that remain underutilized during non-peak times. Such an evaluation of space also suits the ‘assetization’ of railway stations, where stations are treated as not only infrastructure but also as real estate assets and market place ([Riot, 2025](#)).

This thesis suggests that the valuation of such flexibly used space should be conceptualized as an extension to the financial evaluation of conventional station spaces and static investments, where a suitable business model would require weighing specific additional benefits against extra costs. This conceptual approach of calculating the “extra” is inspired by [De Wilde, 2006](#), (Chapter 9 in his book), who calculated the incremental benefits and costs of adding office buildings over railway tracks.

Although a detailed valuation model lies outside the scope of this research, this thesis expects the following aspects to be considered in the calculation: (1) the total space-time supply provided by the station space; (2) the potential spatial-temporal occupancy ratio ([subsection 1.6.2](#)) as a key indicator of spatial efficiency; (3) the diverse values that main activities bring, including direct commercial revenues for railway operators and retail businesses, alongside indirect social benefits generated for citizens when the spaces serve as public plazas; (4) the extra operational costs associated with the supportive and managerial activities required to maintain and shift different functions across scenarios; and (5) the shares of vestment and interests among the various stakeholders involved ([subsection 1.6.3](#)).

8.3.2 Recommendations for design practice

It is recommended for practitioners involved in planning, design, and management of stations with high fluctuations to adopt a temporal and scenario-based approach, explicitly planning for peak and off-peak conditions and fostering flexible use. For urban designers, it is recommended to implement the developed design principles as a checklist in master planning and design competitions for station areas, and utilize agent-based simulation and visual assessment tools in the early design phases to test concepts and optimize layouts for flexible use.

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Glossary

(Terms related to Railway Stations)

‘Node’ and ‘Place’: This pair of concepts is proposed by [Bertolini and Spit \(1998\)](#), describing the two different identities of railway stations, as nodes in transport networks, and as places in cities.

Station-city integration: It is a developing concept with no definitive definition yet. In general, it is an ideal scenario of stations being properly integrated with cities to achieve positive benefits like bringing financial interests and creating vibrant environments, and to resolve negative issues like poor user experience caused by heavy traffic, and urban sprawl caused by car dominance ([Shikata et al., 2013](#); [Novy and Peters, 2012](#); [Dai et al., 2019](#)). (See also [section 1.1.](#))

Transit-oriented development (TOD): It is an idea promoted to develop communities around transit stations, like train, tram, or metro stations. It is assumed to bring benefits such as promoting public transport to limit car use and curb the urban sprawl pattern in urban planning, and creating vibrant community environments ([Calthorpe and Poticha, 1993](#); [Knowles et al., 2020](#)). The concepts of ‘transit-oriented development’ and ‘station-city integration’ share similarities as well as differ in the existing literature. One difference is that TOD is now often used for metro stations, while station-city integration is more commonly used for train stations. (See also [subsection 1.3.4.](#))

(Terms related to Flexible Use in the spatial planning and design fields)

Adaptive reuse: It refers to interventions such as renovating historical buildings for new functions ([Remøy and Van Der Voordt, 2014](#)). In terms of time, these interventions typically occur over long periods, often taking place every few years or even decades.

Assemblage: In the architecture and urban design fields, assemblage is a concept that views buildings and cities from a dynamic perspective—seeing them as composed of constantly interacting elements rather than as fixed, stable structures. Assemblage often associated with informal settlement, disorder, or non-regulatory contexts ([Dovey, 2012](#)).

Demand-responsive: ‘Demand-responsive’ is a concept aiming to have dynamic mobility supply to meet changing demand, through mobility services like scheduling of buses ([Hunkin and Krell, 2018](#)). It is a concept centered on transport management, without spatial aspects involved.

Flexibility: The word ‘flexible’ linguistically means ‘able to change easily according to the situation’ ([Dictionary, n.d.](#)). Flexibility in the design field has been addressed regarding purely non-physical subjects such as urban planning processes ([Carr and Dionisio, 2017](#); [Xu, 2013](#)), space value management ([Madanipour, 2018](#)), design methodology ([Duarte and Beirão, 2011](#)), design strategy ([Coppens et al., 2021](#)), and design education ([Palazzo and Shirleyana, 2024](#)). Research on flexibility in relation to physical content remains scarce (e.g., [John Habraken, 2008](#)).

Flexible use: In this thesis, flexible use particularly means transport use and non-transport use of station areas.

Fluctuations: In this thesis, fluctuations specifically refer to the variations in the quantity of people, human activities, or space usage in stations during peak and non-peak times.

Kinetic architecture: A kind of building with kinetic components—components that are driven by mechanical engines. It has been studied in relation to building facades, movable structures, and buildings designed to be dismantled and reassembled ([Engadget, 2019](#); [Johnson et al., 2019](#); [Megahed, 2017](#); [Miguel, 2024](#); [Smith, 2023](#)). (See also [subsection 1.3.3.](#))

Mixed-use: (See [subsection 1.3.3.](#))

Place-making: A human-centered approach to designing and activating public spaces that promotes social interaction, community identity, and meaningful experiences ([Project For Public Spaces, 2018](#)). In existing literature, it has addressed urban planning aspects such as land use (e.g., see [Dai, 2015](#)).

Resilience: ‘Resilience’ initially describes the ability of an (eco)system to bounce back to equilibrium after disruption ([Holling, 1973](#)), which means the system is flexible during normal and disruption times. Resilience’s meaning is ever-expanding and has developed into numerous fields ([Hosseini et al., 2016](#)), including spatial planning and design ([subsection 1.3.3](#)) as well as transport planning. In transport research, studies typically address the resilience of railway systems at the city, regional, national, or international levels ([Bešinović, 2020](#)), testing the systems’ ability to sustain failures of nodes or links in the networks. Network or graph analysis is usually used in this context, simplifying much of the reality of the 3D world. Besides network structures of railway systems, existing research also investigated the mode transfer during disasters ([Martins et al., 2019](#)). Research has paid little attention to single railway stations at the district or building levels, addressing disruptions and crowding within a single station area as associated with spatial aspects. A rare example is the study by [Xu et al. \(2020\)](#), which examined the resilience of stations as urban public spaces; however, their focus extended broadly to facilities, electrical systems, and managerial preparedness, with spatial aspects representing only a minor component.

Staging urban landscape: The phrase ‘staging urban landscape,’ introduced by [Ivers \(2018\)](#), refers to the activation and curation of flexible public spaces. Ivers observed and documented urban landscapes, such as plazas and parks, where recurring events take place. Similarly, [Smith et al. \(2021\)](#) used the term ‘staging city events in public spaces’ and proposed a typology of urban spaces based on different types of urban events.

Temporary use: In the urban design and architecture fields, temporary use refers to the short-term occupation or utilization of urban spaces or buildings ([Bråten, 2024](#); [Madanipour, 2018](#)), and is often associated also with non-regulatory or minimum regulatory use.

(Terms related to Spatial Design)

‘District level’ and ‘Building level’: These terms refer to two different spatial scales within the context of urban design and planning. The district level generally refers to larger areas, often encompassing multiple buildings or urban blocks, while the building level pertains to the specific scale of an individual building. In this thesis, the station area at the district level is specifically defined within a range of around 250 meters ([subsection 1.6.6](#)).

‘Layout’ and ‘Element’: This pair of words shares a fundamental whole-to-part relationship. The Layout is the overarching organizational strategy—the arrangement of spaces, structures, and pathways—that defines the overall function and experience of a place. Elements are the individual components, such as buildings, trees, or walls, that are strategically selected and composed within that layout. (In this thesis, the elements of station areas are defined in [subsubsection 1.6.4.1](#).)

‘Temporal scale’: Temporal scale refers to the time dimension or duration over which events or activities occur. In this thesis, the temporal scales of events causing fluctuations, or overcrowding and underutilization, in stations, are specifically defined as between multi-weekly to yearly ([subsection 1.6.2](#)).

(Terms related to Technology)

‘Online’ simulation: Simulation that is directly connected to a real system, possibly receiving live data inputs and updating in real time. It’s ‘online’ in the sense of being coupled to a process or experiment while it runs.

‘Offline’ simulation: Simulation that runs without real-time constraints, often for testing, calibration, or exploring multiple scenarios without live data input.

Feedback control loops: This is a term that originates from control theory. A feedback control loop is an iterative mechanism in which system outputs (e.g., user behavior, pedestrian flows, or intervention performance) are monitored, compared with desired objectives, and fed back into the system, so that system parameters can be adjusted to achieve the desired objectives.

The details for developing the design principles

The diagrams of station areas

As shown in the following diagrams, and the on-site visits, the station areas are hardly perceivable (by vision) outside the 250m range.

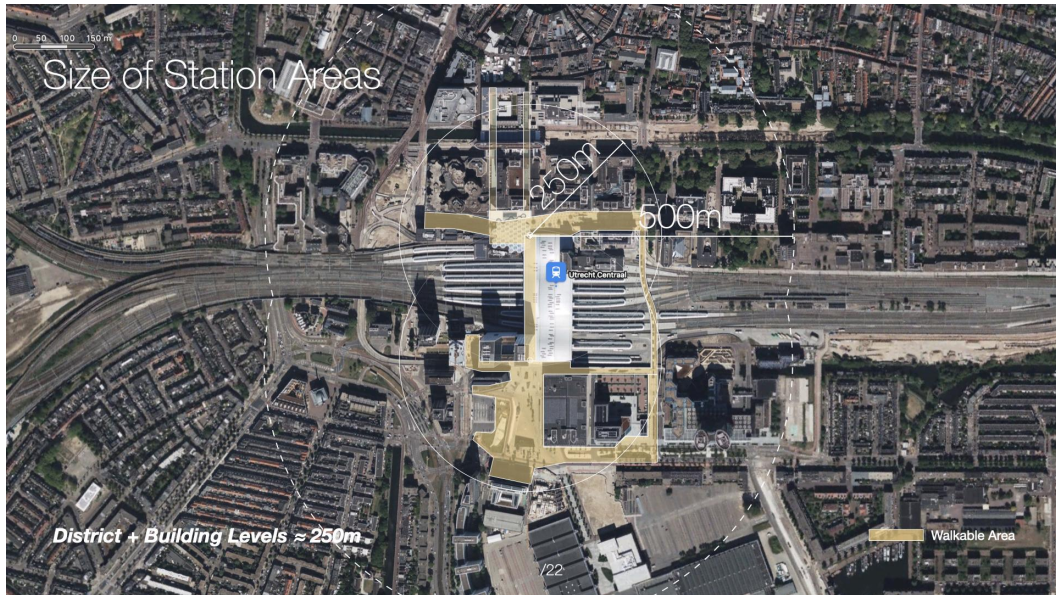


FIG. APP. B.1 The Utrecht Central Station area - 250m vs 500m. (Source: Author)

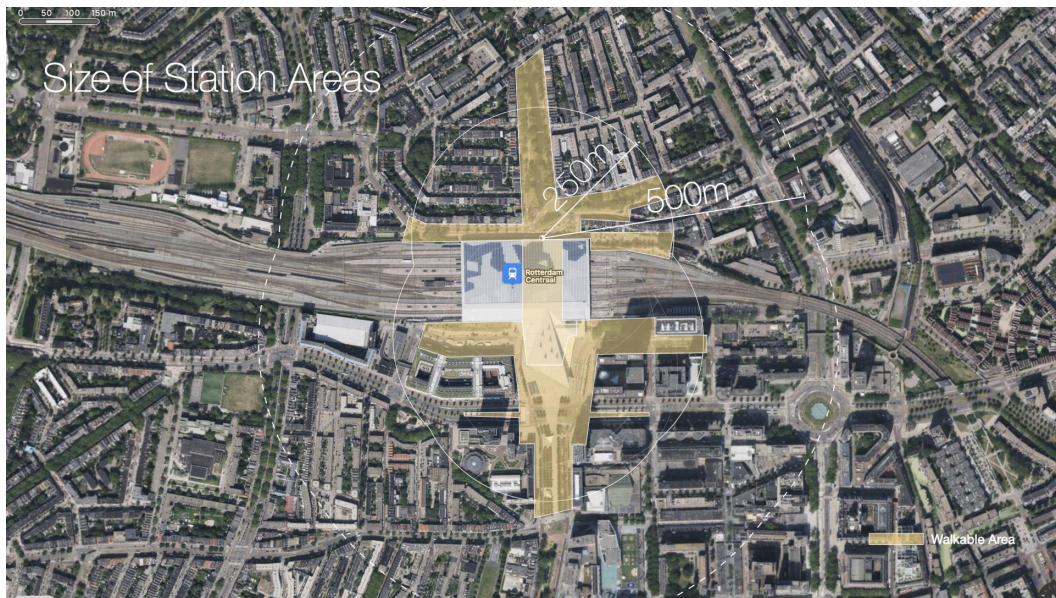


FIG. APP. B.2 The Rotterdam Central Station area - 250m vs 500m. (Source: Author)



FIG. APP. B.3 The Beijing West Railway Station area - 250m vs 500m. (Source: Author)

Literature selection

Enrich the meaning of 'fluctuation-responsive station areas' and establish the first theme for literature searching

Since overcrowding and underutilization are very particular issues that are barely addressed by any existing spatial design research, therefore if directly using 'railway station area' + 'fluctuation-responsive' as the keywords for searching, hardly any relevant papers can be found, and no heuristics can be gained. An enriched meaning of 'fluctuation-responsive station areas' is needed to serve as a basis for literature selection. This paper enriches the term's meaning by reinterpreting the identities of 'railway station areas' and the nature of 'overcrowding' and 'underutilization.'

The identities of railway stations: According to Bertolini and Spit (1998), 'railway

stations' are 'nodes' of the transport networks and 'places' of the cities, so stations are fundamentally 'transport infrastructures' for transportation activities and 'public spaces' for other leisure activities.

'Station areas' include the 'station buildings' and the outdoor 'spaces,' therefore, 'open/urban/public space' and 'landscape' are relevant. 'Overcrowding' can be seen as a type of 'risk' to the station system, which can be addressed by 'resilience' as a quality of the system. 'Underutilization' is a lack of use of public spaces; therefore, 'flexible' use can be helpful. Both 'resilience' and 'flexible' mean a system that is capable of changing, and similar words can include 'dynamic,' 'adaptive,' 'robust,' 'moveable,' 'reconfigurable,' 'multi-functional (in the time dimension),' 'temporary,' 'kinetic', and so on. The combination of these concepts facilitates this paper in finding relevant literature.

Paper selection criteria

The papers that are used as the heuristics for research-by-design meet at least one of the following criteria: 1) The papers are related to design aspects, including design qualities, programming/functions, layouts, spaces, elements, and so on. 2) The papers deal with demands and users in station areas. 3) The papers' knowledge is preferably applicable on both building and outdoor spaces, otherwise too specific and not generalizable. In paper selection, I excluded plenty of papers that are purely about planning, or managerial solutions, which can hardly be transformed to spatial interventions.

Initial papers selected through each searching strategy and their relevance to the layouts and elements of design principles:

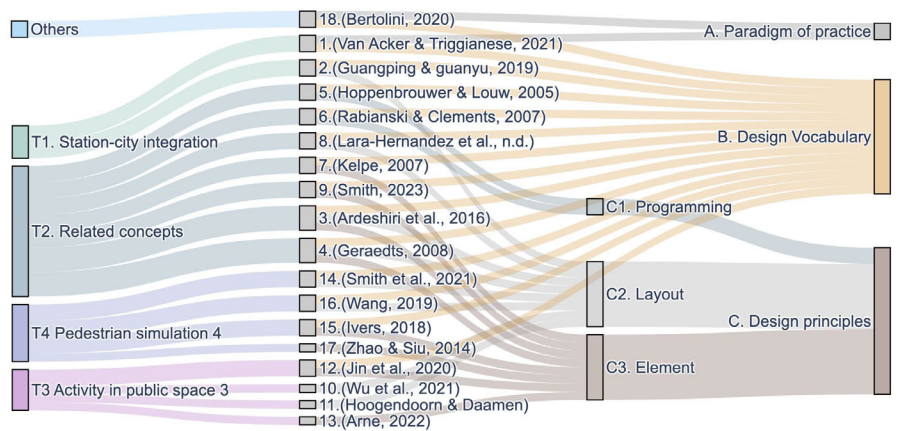


FIG. APP. B.4 The literature selected and the relevance to the research findings

FIG. APP. B.5 Examine relevance and compare cases

308 Towards Flexible Use of railway station areas that promotes Station-City Integration

Internal reflections of design principles

(Internal evaluations of Design Principles)

Index	Names of Design Principles	Meet Design Objectives?									Have Spatial Relevance ?
		Problem-oriented (Macro-level)				User (Passenger)-based (Micro-level)					
		Reduce Overcrowding	Reduce Emptiness	Add city value	Reduce conflicts of use between the station and the city?	Improve Safety (Overcrowding or Eyes-on-the-Street)	Improve Speed	Improve Ease (of Wayfinding)	Improve Comfort (of Facilities and Weather-Protected areas)	Improve (Visual) Experience	
1	Flexible use	√#	√#	√#	○	√#	#	#	√#	√+	√ (Programming)
2	Suitable general layouts of the station and city	√#	√#	√#	√#	√#	√#	√#	√#	√#	√ (Spatial Layout)
3	Set apart non-transport function	√+	○	○	√+	√#	○	√+	○	√#	√ (Spatial Layout)
4	Vibrate city environment by scattered mobility nodes	○	√+	√+	○	○	√-	√-	○	○	√ (Spatial Layout)
5	Increase accommodating capacity by scattered mobility nodes	√+	○	○	○	√+	√-	√-	○	○	√ (Spatial Layout)
6	Make events visible by aligning main paths and open spaces	○	√+	○	○	○	○	○	○	√+	√ (Spatial Layout; PathFlow)
7	Human-oriented spaces	○	√+	○	√+	○	○	○	○	√+	√ (Spatial Layout; Flow)
8	Connect with neighborhoods	√#	○	√#	√#	√+	○	○	○	○	√ (Layout)
9	Smooth level changes by landscape design (District level)	○	√+	○	○	○	○	○	○	○	√ (Spatial Element (District level))
10	Smooth level changes by landscape design (Building level)	○	√+	○	○	√+	○	○	○	○	√ (Spatial Element (Building level))
11	Adaptive redundant spaces with path regulation	√+	√+	○	○	√+	√+	○	○	○	√ (Spatial Layout; PathFlow)
12	Programming considering the time dimension	√+	√+	√+	○	○	○	○	○	○	√ (Programming)
13	Shortcuts or optimizing paths	○	○	○	√+	√-	√+	√-	○	√-	√ (Spatial Layout; PathFlow)
14	Flexible buildings	√+	√+	○	○	○	○	○	○	○	√ (Spatial Element (District level))
15	Flexible building components	√+	√+	○	○	○	○	○	√#	√#	√ (Spatial Element (Building level))
16	Add installations and facilities	○	√+	○	○	○	○	○	√+	√+	√ (Spatial Element)
17	Reconfigurable elements	○	√+	○	○	○	○	○	○	○	√ (Spatial Layout)
18	Redundant spaces	√+	√-	○	○	√+	√-	○	○	√-	√ (District level) Spatial Layout)
19	Set apart bottlenecks	√+	√-	○	○	√+	√-	○	○	○	√ (Building level) Spatial Layout)
20	City passage	○	√+	√+	○	○	√#	○	○	○	√ (Spatial Element; PathFlow)
21	Position city passages	√#	√+	√+	√#	○	○	○	○	○	√ (Spatial Layout; PathFlow)
22	Reduce barriers to ease flow (District level)	√#	√+	√+	√#	○	○	○	√+	○	√ (District level) Spatial Element; PathFlow)
23	Reduce barriers to ease flow (Building level)	√#	√+	√+	√#	○	○	○	√+	○	√ (Building level) Spatial Element; PathFlow)
24	Stairs as stages or seats	○	√+	○	○	○	○	○	○	√+	√ (Spatial Element)
25	City axes	√#	√+	√+	○	○	○	√+	√+	○	√ (Spatial Layout; PathFlow)
26	Reconfigurable spaces	○	√+	○	○	○	○	○	○	√+	√ (Spatial Element)

Legend:

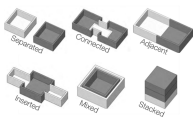
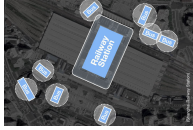
○	No relevance
√	Has relevance
√+	Has relevance, with Positive effects
√-	Has relevance, with Negative effects
√#	Has relevance, and the effects depend on the contexts
#	Uncertain

FIG. APP. B.6 The table of internal evaluation of design principles

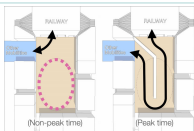
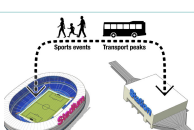
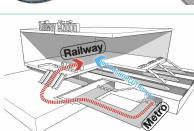
Results and interpretations

Sources of heuristics for each design principle

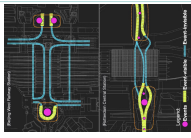
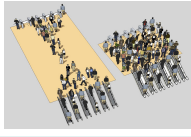
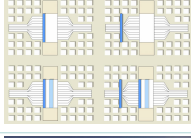
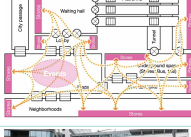
TABLE APP. B.1 Sources of heuristics for each design principle

Diagrams	Minor design principles	Cases	Literature	Analytical visualization	Reflections from experts
	1) Flexible use	Paris Beaches	Hoppenbrouwer and Louw 2005	-	-
	2) Suitable general layouts of the station and city	-	Qi and Lu 2019; Shikata et al. 2013	Apply different layouts	-
	3) Set apart non-transport function	Utrecht RS current vs former; -	-	-	-
	4) Enliven city environment by dispersed mobility nodes	-	-	Transformed from principle 5 to a larger scale	-
	5) Increase accommodating capacity by dispersed mobility sites	Beijing West RS vs Shanghai RS	-	-	-
	6) Make events visible by aligning main paths and open spaces	Beijing West RS; Rotterdam RS current vs former	-	Virtually add events to see the effects	-
	7) Human-oriented spaces	Rotterdam RS current vs former	-	Virtually add events to see the effects	-

Continued on next page

	8) Connect with neighborhoods	Beijing West RS; Rotterdam RS; Utrecht RS	Peters and Tolkoﬀ 2016	-	Mind transport and non-transport interferences
	9) Smooth level changes by landscape design (District level)	Jiaxing RS	-	Transformed from principle 10 to a larger scale	-
	10) Smooth level changes by landscape design (Building level)	Arnhem RS	-	-	Costly, harder wayfinding
	11) Layouts that support path reconfigurations	Shanghai RS; (Path regulations in Airports; Shopping malls)	-	Transformed from non-station case experience	Path regulation being intrusive, managerial efforts
	12) Programming considering the time dimension	Guangzhou; TOD mixed-use practice	Calthorpe and Poticha 1993	Transformed from higher-frequency events	-
	13) Shortcuts or optimizing paths	Beijing West RS	-	Design shortcuts as a new solution	Extra cost
	14) Flexible buildings	The Shed; Stadium 974	Ivers 2018; Smith et al. 2021	-	Costly
	15) Flexible building components	-	-	Transformed from principle 14 to a smaller scale	-
	16) Add installations and facilities	Antwerpen RS	Ivers 2018; Kelpe 2007	Transformed from non-station cases	Installations' quality matters
	17) Reconfigurable elements	-	Ivers 2018	Transformed from non-station cases	-

Continued on next page

	18) redundant spaces	Allianz Arena	-	Transformed from non-station cases	-
	19) Setting apart bottlenecks	-	Hoogendoorn and Daamen 2004	-	-
	20) City passages	Rotterdam RS; Utrecht RS; Bijlmer RS	-	-	-
	21) Position city passages	Rotterdam; Utrecht; Amsterdam	-	Apply this as a context for principle 20	-
	22) Reduce barriers to ease flow (District level)	Beijing West RS; Rotterdam RS; Utrecht RS	-	-	-
	23) Reduce barriers to ease flow (Building level)	Beijing West RS	-	Transformed from principle 22 to a smaller scale	-
	24) Stairs as stages or seats	Utrecht RS; Cologne RS; Antwerp RS	-	-	-
	25) City axes	Rotterdam RS; Utrecht RS	-	-	-
	26) Reconfigurable spaces	-	Ivers 2018	Transformed from non-station cases	Managerial efforts

Relate design principles to an event typology

Events are an important aspect of this research, as they are the causes of fluctuations in station areas and are a solution to address underutilization. As part of the exploration of design solutions, we investigated the relationship between event types and design principles.

In this research, we adopted an event typology developed by [Smith et al. \(2021\)](#). This typology is framed based on access and mobility, including nine types of events: E1) large indoor arenas, E2) concerts and screenings, E3) pleasure gardens, E4) parades and street races, E5) roadshows, E6) markets and fairs, E7) mass gatherings, E8) micro-performances, and E9) marches and street parties. Two events - E4 and E9, primarily happen on streets, which are irrelevant for most spaces in railway stations, so we excluded (×) them ([Figure B.7](#)).

The relationships between event types and design principles, are explained as follows (Note: 'E' stands for Event types, and 'D' stands for Design principles):

- Large open-air events with concentrated distributions, including E2, E3, and E7, need large coherent outdoor spaces and should not block city passages. Therefore, these events have relevance to design principles (DPs) (11) Adaptive redundant spaces with path regulation, (7) Human-oriented spaces, and (21) City passages' positioning. (Links: [E2-D7](#), [E3-D7](#), [E6-D7](#); [E7-D7](#); [E2-D11](#), [E3-D11](#), [E6-D11](#), [E7-D11](#); [E2-D21](#), [E3-D21](#), [E6-D21](#), [E7-D21](#))
- For large events with performances - E2, (24) Stairs as stages or seats can be used. (Link: [E2-D24](#))
- Small spaces are common in a dispersed layout (D4), and small events - E8 can be held in these small spaces. (15) Flexible building components can also be the small spaces to hold small events. (Links: [E8-D4](#), [E8-D15](#))
- For events that require user participation and are open-access, including E7, E5, E6, and E8, it is necessary to (6) Make events visible by aligning main paths and open spaces. (Links: [E7-D6](#), [E5-D6](#), [E6-D6](#), [E8-D6](#))
- Small performances and markets can help promote a vibrant environment, and it is a prerequisite to (23) Reduce barriers to ease flow at the building level. (Links: [E6-D23](#), [E8-D23](#))
- Large indoor arenas can be Flexible buildings (14). Flexible and Shared use between arenas and stations can be realized if the station areas are Programmed considering the time dimension. The arenas should be located in Suitable general layouts of the station and city (2). (Links: [E1-D2](#), [E1-D14](#), [E1-D12](#))
- In events E3 and E6, it is necessary to (16) Add installations and facilities, which can be (17) Reconfigurable elements. (Links: [E3-D11](#), [E6-D11](#); [E3-D16](#))
- For all possible events happening in railway stations, the event spaces should support flexible use and be configurable, and pedestrians should be able to walk smoothly to the event spots. Therefore, several design principles are relevant, including (22)

Reduce barriers to ease flow at the district level, (25) City axes, (1) Flexible use, (26) Reconfigurable spaces. (Links: [All-D25](#), [All-D22](#), [All-D26](#), [All-D1](#))

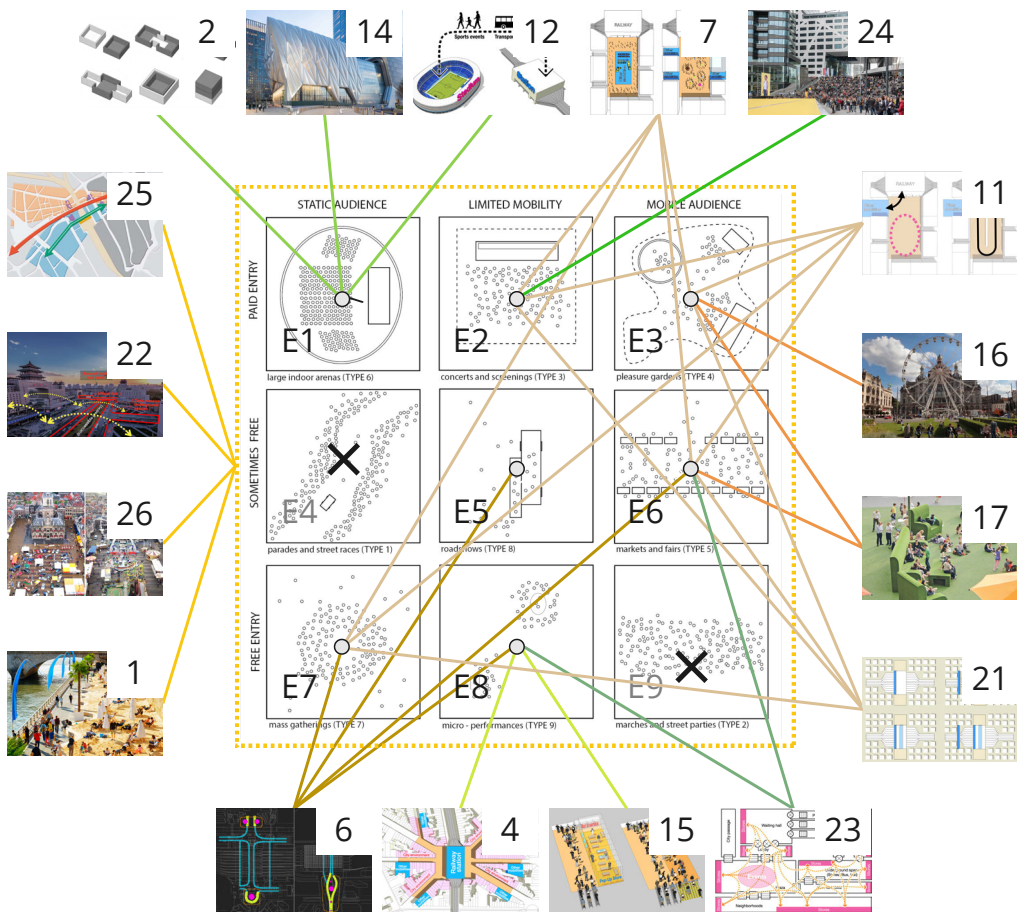


FIG. APP. B.7 The design principles related to the event typology (Source: Author; The event typology diagram is reused from Smith et al. 2021;

Curriculum Vitae

Enshan Chen

– 1993

Born in Wuhu, Anhui Province, China

– 2011 - 2016

Bachelor of Agriculture at the Department of Architecture, Chongqing University, Chongqing, China

– 2018 - 2021

Master of Architecture at the Section of Urban Design and Theory, the Department of Architecture, Tongji University, Shanghai, China

– 2021 - 2025

PhD candidate at the Section of Urban Design, Department of Urbanism, Faculty of Architecture and Built Environment, Delft University of Technology, Delft, The Netherlands

Enshan Chen (1993) was born in Wuhu, and finished his high school in Ma'anshan, China. He obtained a Bachelor of Agriculture at Chongqing University and a Master of Architecture at Tongji University, China. His master's thesis is about the urban form of railway station areas. In 2021, Enshan was appointed as a PhD candidate at the Delft University of Technology, the Netherlands, under the supervision of Dr. Frank Van der Hoeven, Dr. Stefan Van der Spek, and Dr. Manuela Triggianese. His PhD research focuses on the issues of overcrowding and underutilization in railway station areas. The research resulted in software and multiple papers in journals, as well as international conferences across several countries. During his PhD research, Enshan collaborated with researchers at Tongji University who study railway station development, and practitioners at the Dutch railway company. Enshan has served as a reviewer for international journals such as Sustainable Cities and Society, Transportation Research

Part A, and Architecture Engineering and Design Management.

Besides the academic journeys, Enshan takes opportunities to conduct design practice. He worked for two years after obtaining his Bachelor's degree, designing shopping malls and residential districts in Shanghai. During his master's and PhD degrees, he participated in commissioned projects and competitions in urban design and architectural design. He is a certified architect in China.

Throughout his practice and academic journey, Enshan has demonstrated a keen interest in dealing with complex projects and seeking interdisciplinary approaches to urban design and architecture, combining insights from fields including transport, computer science, and environmental psychology.

Publications during the PhD time

Journal articles (peer-reviewed) published

Enshan, C., Van der Spek, S., Tian, A., Triggianese, M., & Van der Hoeven, F. 2025. Evaluate design principles for flexible use of railway station areas: Through research-by-design and agent-based simulation. *Journal of Building Engineering*, 112, 113775. <https://doi.org/10.1016/j.jobe.2025.113775>

Enshan, C., Van der Spek, S., Van der Hoeven, F., & Triggianese, M. 2025. Evaluate user satisfaction for urban design of railway station areas: An assessment framework using agent-based simulation. *Environmental Impact Assessment Review*, 110, 107685. <https://doi.org/10.1016/j.eiar.2024.107685>

Enshan, C., & Zhuang, Y. 2022. The Stakeholder gaming and element organization: Research on the station-city integration development of Utrecht Central Railway Station [In Chinese]. *The Architect*. 3, 52–60. <https://doi.org/10.12285/jzs.20211015002>

Conference papers/posters (peer-reviewed) published

Enshan, C., Van der Spek, S., Van der Hoeven, F., & Triggianese, M. 2024. [Investigating the Design Principles for Fluctuation-Responsive Railway Station Areas](#). The 16th Conference of the International Forum on Urbanism (IFoU), Multi-city Online. [Abstract and full paper]

Enshan, C., Stefan, Van der S., Frank, Van der H., & Manuela, T. 2024. [Assessing user satisfaction for urban design of railway station areas](#). ACSP 64th Annual Conference, 1257-1258. [Abstract]

Chen, E., Van der Spek, S. C., Van der Hoeven, F. D., & Triggianese, M. 2022. [Station City Integration in China: Towards Mobility Resilience and Public Space Flexibility](#). Urban Transitions 2022: Integrating Urban and Transport Planning, Environment and Health for Healthier Urban Living. [Poster]

Book chapter published

Yu, Z., & **Enshan, C.** 2022. The urban form of the railway station area. In [Station-city integration: Urban design](#) [In Chinese], 191-226. China Architecture & Building Press.

Journal articles in submission/writing

[As of July 2026]

Enshan, C., Van der Spek, S., Triggianese, M., Lin, J., & Van der Hoeven, F. 2026. Aiming to potentially reduce overcrowding and underutilization in railway station areas: A review of existing knowledge on flexible use from a spatial design perspective (SSRN)

Scholarly Paper No. 6182523). Social Science Research Network.
<https://doi.org/10.2139/ssrn.6182523>

Enshan, C., Van der Spek, S., Van der Hoeven, F., & Triggianese. Understand the phenomena of overcrowding and underutilization in railway station areas and the potential of spatial design for flexible use: Case studies through scenario analyses.

Enshan, C., Anan, T., Junting, L., Van der Spek, S., Van der Hoeven, F., & Triggianese, M. Assessing visual experience: Evidence extracted from image segmentation

Enshan, C., Van der Spek, S., Van der Hoeven, F., & Triggianese, M. Investigating the design principles for flexible use of railway station areas

Software plugins published

PandaAnalytics – A Rhino plugin for assessing user experience in station areas (based on the study of the assessment framework, chapter 6). (Written in Python and C#)

PandaMeasuring – A Rhino plugin that automates the measuring of floor areas, which is useful for mapping density and urban form. (Written in Grasshopper)

PandaModeling – A Rhino plugin that uses large language models to build 3D models. (Written in C#)

Statement on the Use of AI

Author Declaration:

In the preparation of this thesis, I have utilized AI—large language models like Gemini, DeepSeek, and ChatGPT—to assist with proofreading, grammatical refinement, and enhancing the linguistic clarity of the manuscript.

Towards Flexible Use of railway station areas that promotes Station-City Integration

The spatial relevance, design, and assessment

Enshan Chen

Railway station areas with periodic event-driven demand experience overcrowding during peak periods and underutilization during off-peak periods. Traditional design standards mandate static dimensions tailored exclusively to peak capacities, creating oversized spatial voids off-peak. This thesis investigates how spatial design can enable flexible use—a dynamic strategy in which stations utilize neighboring urban spaces as temporary buffers during peak periods and open underutilized spaces for civic and leisure activities during off-peak periods—to mitigate overcrowding and underutilization while promoting station-city integration. Using case studies, research-by-design, and agent-based simulation (ABS), this research establishes the spatial relevance of operational bottlenecks and spatial configurations. It formulates six actionable design principles—focusing on visibility, reconfigurability, high-quality connections, dispersed layouts, human-centered spaces, and dynamic programming—and develops an ABS-driven assessment framework to evaluate multi-layered user needs (safety, speed, ease, comfort, experience). By shifting the design paradigm toward dynamic temporal-spatial utilization, this study offers actionable insights, guidance, and tools to create resilient, efficient, and integrated station areas.

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