Assessing the efficiency of indoor and outdoor access-related infrastructure

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Abstract
How does urban density affect the efficiency of access infrastructure? A novel approach considers both 'outdoor' and 'indoor' access infrastructure. A hypothesis is developed and tested to determine if spatial costs shift from 'outdoors' to 'indoors' in rising building densities. Taking into account the significance of theoretical research and its impact on decision-making practices on development, a case study in a Chinese city is conducted to assess the spatial costs of building-internal and building-external access for different types of residential neighbourhoods, thereby exploring the relationship between the number of floors and accessibility costs in terms of area consumption. Three different types of residential neighbourhood representing diverse density situations are analysed and evaluated. Although based on a single case study, the results provide valid arguments to substantiate the shift hypothesis. The findings challenge the existing planning notions regarding gains in infrastructural efficiency and instead show reduced efficiencies can occur in high-density development when indoor access is taken into account. Under comparable factors of access quality, compact settlements may even display lower efficiencies than less compact areas. These considerations indicate the need for a more critical and wider view of the efficiency gains provided by dense settlement forms.

Policy relevance
When building densities increase, the burden of spatial costs for access infrastructure (mobility, traffic access, vertical circulation and parking) shifts from 'outdoors' to 'indoors', potentially increasing in overall terms. This challenges current ideas in urban planning that higher density leads to gains in infrastructural efficiency. Economic and resource efficiency are clearly reduced when indoor access is taken into account. Indeed, under comparable factors of access quality, compact settlements may have lower efficiencies than less compact areas. These new insights indicate the need for a more critical and wider reappraisal of the efficiency gains provided by dense settlement forms, particularly high-density and high-rise residential development. Developers, planners and designers will need to develop new processes and guidance for evaluating efficiencies of urban settlement and their sustainability.

Keywords: circulation; cities; efficiency; infrastructure; morphology; spatial planning; urban density; urban design; vertical infrastructure

1. Introduction
Urban factors such as the settlement form and morphology, density and compactness determine the ways in which citizens live and move, and hence the ensuing costs for the provision and maintenance of technical and social infrastructures (Peterson & Schäfer 2004; EEA 2015; UN-Habitat 2016). The United Nations' New Urban Agenda (Habitat III) points out that 'urban form, infrastructure and building design are among the greatest drivers of cost and resource efficiencies, through the benefits of economy of scale and agglomeration’ (United Nations 2017: 14). The performance of economies of scale with respect to access costs can be well observed in cities. Many studies have shown that higher

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densities are associated with increased efficiency (American Farmland Trust 1986; Burchell et al. 2002; Bettencourt et al. 2007; Carruthers & Ulfarsson 2003; Siedentop et al. 2006; Li, Wang, Zhang, & Wu 2015; Kurvinen & Saari 2020). Further, the relationship between large-scale urban forms and energy consumption has been investigated in depth (EEA 2015: 51). Based on empirical studies of German cities, Deilmann, Lehmann, Schumacher, & Behnisch (2017: 143) showed that ‘with increasing building compactness, the prerequisites for technical energy efficiency and resource efficiency are increasing’. In particular, significant work has already been done on individual aspects such as urban density and petrol consumption (Newman & Kenworthy 1989), urban physical conditions in response to long-term urban goals (Talen 2005), the floor space index and road development costs (Siedentop et al. 2006), population density and transport energy consumption (Daimon, Morimoto & Koike 2007), as well as urban form and building energy (Miller 2013). On the other hand, diseconomies of scale have also been observed by a few researchers, that is, higher urban densities generating higher costs. For example, Ladd (1992) addressed the higher administrative costs faced by larger cities for tasks such as for policing and ensuring public safety. Seitz (2002) demonstrated the rising wastewater disposal costs in extremely densely populated areas based on data from Germany. Most recently, evidence from a case study of Chicago has shown that the suburban low-rise lifestyle is more efficient than the downtown high-rise lifestyle in terms of per person operational energy consumption for buildings, transportation and transportation infrastructure (Du, Wood & Stephens 2016).

All the above-mentioned studies refer to public infrastructure, which is predominantly the responsibility of local or state authorities. Significantly, building-internal development such as stairwells or underground parking is generally neglected in the wider discussion on the spatial cost of access related infrastructure. In the building sector, economies of scale are achieved when an increase in the number of building storeys, for example, from low-rise to multi-storey, serves to lower the demand for external spatial costs of access considered at the neighbourhood scale. Yet, it can be assumed that, from a certain (high) level of building density and number of building storeys, savings made on roads and paths in open spaces are offset to some degree by higher spatial costs for internal circulation: stairways, lifts and other internal features of buildings. This can be understood as an expression of the diseconomy of scale, which has so far received little attention. A small number of evidence-based studies have considered the vertical transport of essential resources (e.g. water, energy) in individual tall buildings. (Elotefy, Abdelmagid, Morghany, & Ahmed 2015; de Wilde 2018). Yet, hitherto there has been no comprehensive investigation of infrastructural efficiency with regard to the accessibility of dwellings, even though, from a macroeconomic point of view, efficient cities can only be created if we also consider such internal access.

The focus of this paper is on the function of infrastructures to provide access to privately used spaces (apartments). It is outside its scope to consider whether the provision of such access is the responsibility of the public sector, as is usually the case with external infrastructure (Torissi 2009), or if private or public owners regulate the provision through contracts, as is usually the case with internal infrastructures. Aspects such as mono- or multifunctionality are ignored here for the infrastructures under consideration because they can differ.

Based on these necessary simplifications, the hypothesis is posited that at higher building densities, spatial costs for access infrastructure are shifted from ‘outdoors’ to ‘indoors’, and may even increase overall. ‘Indoor’ means building-internal access infrastructures such as circulation areas and parking areas, as well as underground garages; ‘outdoor’ can be defined as transport areas outside buildings including car lanes, parking areas or footpaths. A detailed definition is given in Table 1. The aim is to test this ‘shift hypothesis’. To achieve this, a comparative analysis of case studies is the most appropriate research method as this allows in-depth, multifaceted explorations of complex issues in different real-life settings (Crowe et al. 2011).

A major challenge for comparative research in the urban development research field is to ensure the requisite rigor and consistency. A crucial challenge when comparing indoor and outdoor access-related infrastructural efficiency is the great diversity in the design of such infrastructure in different urban contexts. Even in one city governed by one set of building codes, different types of residential neighbourhoods exist, for example, social housing, cooperative housing and commercial housing, all of which display a wide variety of infrastructural designs (in single buildings and at the neighbourhood scale) depending on the social attributes of the various residential communities. To address this problem, three types of residential neighbourhood are selected for comparative analysis and evaluation, each representing a different density situation. The three neighbourhoods, all located in one large residential settlement, were built by the same developer during a single construction period. This ensures sufficient rigor and consistency. More specifically, quantitative assessment is performed of the spatial costs (in terms of m²) of building-internal and

| Zone     | Net building land (m²) | Number of buildings | Number of basements | Number of dwellings | Gross floor area (m²) | Floor space index |
|----------|------------------------|---------------------|---------------------|---------------------|-----------------------|------------------|
| Terraced (a) | 35,140                | 14                  | 1                   | 74                  | 19,816                | 0.56             |
| Multi-storey (b) | 29,509                | 8                   | 2                   | 227                 | 39,732                | 1.35             |
| High-rise (c)  | 58,856                | 9                   | 1                   | 1048                | 146,959               | 2.50             |
Assessing the efficiency of indoor and outdoor access-related infrastructure for different types of residential neighbourhoods in order to explore the relationship between density and overall accessibility.

The paper is structured as follows. Section 2 discusses the selection of the case study and provides a brief introduction to the case study area including its base data. The analytical method is described in section 3, along with a definition of terminology. The findings of the analyses are given in section 4; distinctions are between indoor and outdoor infrastructure. These results are discussed in section 5 in terms of the shift hypothesis and with regard to their general applicability. Finally, section 6 presents some conclusions regarding sustainability and considers whether traditional concepts of infrastructural efficiency should be revised.

2. Case study
The discussion on how to make cities and urban spaces more liveable can be traced back to the 1960s when leading researchers such as William H. Whyte (Whyte 1956, 1980) and Jane Jacobs (Jacobs 1962) widened the focus of urban research to include a study of the quality of life and community well-being. Subsequently, a shift can be observed from concerns about ‘right’ to ‘adequate’ density. In the new millennium, there is now general agreement amongst scholars of the benefits of adopting a strategic approach to urban density (e.g. Williams, Burton, & Jenks 2000; Lehmann 2016). Some recent influential works such as Adapting Building and Cities for Climate Change—A 21st Century Survival Guide (Roaf, Crichton & Nicol 2015) have comprehensively addressed the drawbacks of high-rise buildings from various perspectives. Since the 1970s, a variety of composite social indicators has been developed to supplement the evaluation of important aspects related to well-being and quality of life beyond purely economic indicators such as gross domestic product (GDP). Two instances of these composite indicators are the quality of life index (Diener & Suh 1997) and the community well-being index (McHardy & O’Sullivan 2004). More recently, the Handbook of Community Well-Being Research (Phillips & Wong 2017) has explored social indicators and other assessment techniques from the framework of community perspectives concerned with enhancing the quality of life of community members.

However, governments in developing countries undergoing high-speed urbanisation (especially China) see high-density and high-rise residential development as a primary means to relieve housing shortages in cities (Bao & Li 2010, Li et al. 2018). The belief that high-rise buildings can reduce land consumption supports this approach at the political level. Against this background, China has shaped a distinct urban architectural landscape through the central government’s promotion of high-rise residential developments nationwide in large, medium sized or smaller cities. For the current study, a case study in China was undertaken in order to fill an important gap in the theoretical research and, hopefully, to exert some influence on the development of decision-making practices. Three ‘zones’ were selected within a large urban residential area in Zibo, a city with about 5 million population located in the province of Shandong in China. The term ‘zone’ corresponds to the socio-psychological definition of ‘home area neighborhood’ (Kearns & Parkinson 2001) and refers to a basic urban residential unit marked by a homogeneous urban structure which is similar in density and morphology.

In China, planning laws and local planning regulations usually specify limits for some technical indicators governing urban districts such as the floor space index, site occupancy index, building height or ratio of green area to the construction site. Within this framework, the developer can choose the specific technical indexes that best meet the needs of target groups in the real estate market. Therefore, although the boundary values prescribed by laws and regulations may be the same in one urban area, there can be very different planning solutions because of the positioning of target groups. In order to ensure good comparability of data, a site was chosen where all the various zones were built by the same developer. The three selected zones differ significantly from one another in terms of their construction design. However, the buildings within each individual zone are homogeneous. Figure 1 gives a bird’s-eye view of the investigated area borrowed from a project rendering. The coloured area designates the urban neighbourhoods considered in the case study. These consist of homogeneous housing, specifically: (a) terraced housing; (b) multi-storey housing; and (c) high-rise housing. The three zones selected for the empirical study are part of the first phase of a residential area project located in the centre of a new urban district of the city. All three zones have been completed and the residential units have been in use since 2018.

The total area of the site is 14.18 ha (gross building land), upon which 1275 apartments and 74 terraced houses have been built. In the terraced housing zone, each building is formed out of four (or six) two-storey terraced housing units. The multi-storey housing zone consists of eight buildings ranging from six to 11 storeys. Two buildings have one entrance, five buildings have two entrances and one building has three entrances. Each entrance connects two apartment units on a standard floor via an elevator and a staircase. The high-rise housing zone has nine buildings ranging from 22 to 28 storeys. These consist of two buildings with one entrance, three buildings with two entrances, three buildings with three entrances and one building with four entrances. Each entrance connects two apartment units on a standard floor with two elevators and one staircase.

There is considerable variation in the building densities (expressed as the floor space index) of the three zones (Table 1). Within each zone, buildings are accessed by car lanes and pedestrian walkways. Parking spaces for cars are mainly located in underground garages with only a few above-ground spaces planned for visitor parking. In addition, each zone enjoys semi-public green spaces. There are private green spaces in the courtyard of the terraced housing zone.
3. Methods

3.1. Terms and definitions

The focus of this study is on the development area needed to provide access to the dwellings. Three types of development area can be distinguished (Figure 2), which are defined as follows:
• Indoor vertical: Circulation areas used to access dwellings as well as other usable/service areas inside the buildings
  The areas for the vertical development of buildings (indoor vertical) are determined by evaluating floor plans of the
  buildings using ISO 9836: 2017–09 area categories (ISO 2017). This ISO standard divides net floor area into usable
  area (main and residual usable area), service area and circulation area (CA). CAs within buildings are defined as
  vertical indoor areas. These are mainly vertical-access elements, such as stairwells and lift shafts (elevators), as well
  as horizontal corridors providing access to dwellings (from the stairwell or elevator to the dwelling) according to
  ISO (2017).
• Indoor parking: Areas in underground structures and building basements used for car parking
  The indoor parking areas are defined as underground garages within the buildings and in separate underground
  car parks adjacent to buildings.
• Outdoor: Areas for the horizontal circulation
  Surface areas within zones for car lanes, parking lots and pedestrian walkways (sealed footpaths) above ground and
  outside the buildings. These areas are at the centre of debates on urban planning and infrastructural costs.

3.2. Data
The planning documents of the design office that developed the area were used to derive the base data. Available as
dwg files, these included a site plan for the entire case study area, floorplans and basement floor plans, elevation plans
and sections, and details for staircases and important construction nodes.

3.3. Calculation method
The plans were evaluated and analysed using CAD software. The steps involved in calculating the three different area
categories are described below and shown in Table 2.

A typology approach was applied to analyse the indoor vertical areas for accessibility. Each of the three investigated
zones consists of buildings of a specific type, each with identical construction methods and almost identical floorplans.
One representative building was analysed for each zone in order to determine the proportionate areas. Specifically, these
representative buildings are: one building comprised of six terraced housing units for the terraced housing zone; one six-
storey building with two entrances for the multi-storey housing zone; and one 28-storey building with three entrances
for the high-rise housing zone. Areas were measured from plans and classified according to the specifications of the ISO
area categories. These resulting areas were differentiated according to useable area, service, parking, circulation and
gross floor area (GFA). CAs were defined as indoor vertical areas. These indoor vertical areas were extrapolated to the
total area of the zones based on specific values, taking the GFA as a reference value (equation 1). The total GFA of a zone
was derived from information in the site plan.

\[ A_{IVZ} = \frac{CA_B}{GFA_Z} \times GFA_Z \]

where \( A_{IVZ} \) is the indoor vertical access area of a zone; \( CA_B \) is the circulation area of a representative building; \( GFA_B \) is the
gross floor area of a representative building; and \( GFA_Z \) is the gross floor area of a zone.

The indoor parking areas are located in underground garages within the buildings and in separate underground car
parks adjacent to the buildings (equation 2). Underground garages within the buildings were measured using basement
floor plans and extrapolated to the zone according to the method used for indoor vertical. The areas of the underground

| Categories of access area | Data sources | Areas taken into account |
|--------------------------|--------------|--------------------------|
| Total access area        | Floor plans, elevation plans, sections, details | Stairwells, lift shafts, corridors, escape routes, waiting areas |
| Indoor                  |              |                          |
| Indoor vertical          |              |                          |
| Circulation area         |              |                          |
| Indoor parking           | Basement floor plans, sections, details         | Separate underground car park areas labelled in the plan |
| Separate underground car parks |              | Parking areas as labelled in the plan |
| Underground garages in buildings | Site plan, sections, basement floor plans, details |                          |
| Outdoor                 | Site plan    | Car lanes as labelled in the plan |
| Traffic areas           |              | Pedestrian walkways as labelled in the plan |
| Sealed footpath         | Site plan    | Pedestrian walkways as labelled in the plan |
| Outdoor parking         | Site plan    | Parking lots as labelled in the plan |
car parks adjacent to the buildings were taken from the site plans, which contain corresponding information. The allocation of the latter category to the respective zones is clearly based on their location.

\[ A_{IPZ} = \frac{PA_B}{GFA_B} + GFA_Z + PAad_Z \]

where \( A_{IPZ} \) is the area for indoor parking within a zone; \( PA_B \) is the area for indoor parking in the basement of a representative building; and \( PAad \) is the area for indoor parking in underground car park areas that are adjacent to the buildings in a zone. \( GFA_B \) and \( GFA_Z \) are as defined in (equation 1).

The building footprints, car lanes on roads, sealed footpaths, green spaces and areas of water are indicated in the site plan for the entire area. On this basis, the areas providing outdoor access (i.e. areas used for traffic development of the zones) can be measured and summed. The allocation of the zone-internal traffic areas depends on their location. Roads with a zonal boundary are assigned half the diameter of the adjacent zone (equation 3):\(^1\)

\[ A_{OZ} = CLA_{iZ} + \frac{CLA_{oZ}}{2} + PWA_{iZ} + OPA_{iZ} \]

where \( A_{OZ} \) is the area for outdoor access inside a zone; \( CLA_{iZ} \) is the area for car lanes inside a zone; \( CLA_{oZ} \) is the area for car lanes outside a zone; \( PWA_{iZ} \) is the area for pathways inside a zone; and \( OPA_{iZ} \) is the area for outdoor parking inside a zone.

4. Results

The results are given, first, for areas inside the buildings (indoor vertical), second, for zones (indoor underground and outdoor) and, third, in summary. Usable areas, service areas, CAs and parking areas are distinguished at the building level. **Figure 3** and **Table 3** provides the total values for buildings in each zone.

**Figure 3:** Indoor vertical net floor area (inside the buildings). *Note: All areas are in m\(^2\).*

|                | High-rise          | Multi-storey       | Terraced          |
|----------------|--------------------|--------------------|-------------------|
|                | m\(^2\)   | %    | m\(^2\)   | %    | m\(^2\)   | %    |
| Useable area   | 145,641 | 75%  | 31,548 | 75%  | 22,948 | 81%  |
| Service area   | 13,649  | 7%   | 6540   | 15%  | 623    | 2%   |
| Circulation area | 35,048 | 18%  | 4257   | 10%  | 2363   | 8%   |
| Parking        | –       | –    | –      | –    | 2520   | 9%   |
| Net floor area | 194,338 | 100% | 42,346 | 100% | 28,453 | 100% |
At just over 80% of the total floor area, the proportion of usable space in terraced houses is approximately 5% higher than in high-rise and multi-storey buildings. This is in contrast to the CA of vertical development, which is required in order to access individual dwellings within the buildings. Here the ratio increases significantly with building size: At 18%, the proportion of CAs in high-rise buildings is more than twice that of small buildings at 8%. The special feature of the parking spaces in the basement of the terraced houses (as described above) accounts for 9% of the net floor area. The service area in terraced houses is remarkably low at only 2%. The largest proportion of service space is found in multi-storey buildings at 15%, more than twice that of high-rise buildings. In the latter type, it can be assumed that economies of scale are responsible for the smaller proportion of service space.

**Figure 4** and **Table 4** give an overview of various development features considered at the level of the zones (see also Figure A1 in Appendix A in the supplemental data online). The proportionate area occupied by the building footprint increases with decreasing building density. This accounts for 27% of the zone of terraced buildings, in contrast to only 16% the zone of high-rise buildings. The opposite trend occurs in traffic areas. Here the proportionate area increases significantly with increasing density. While 58% of the zone of high-rise buildings is dedicated to traffic (traffic area and sealed footpath), in the zone of terraced houses the ratio is only 41%. There is much less disparity with regard to green space and areas of water, which only slightly decrease with higher building densities.

The high-rise housing zone and multi-storey housing zone have additional underground structures outside the buildings used for car parking (indoor parking). In the zone of high-rise buildings, the total parking area is 31,228 m² compared with 13,163 m² in the multi-storey zone. The main focus of the paper is on the development area, or rather on the spatial costs of development (in terms of m²) and its characteristics at different building densities. For this purpose, the corresponding areas described above are considered together as development areas:

- Above-ground traffic areas, sealed footpaths and above-ground parking for visitors (outdoor development).
- CAs inside the buildings (indoor vertical development).
- Areas for separate underground car parks adjacent to buildings as well as the underground garages in the basements of the buildings (indoor parking development) (see section 3.1).

**Figure 4:** Analysis of land use. *Note:* All areas are in m².

**Table 4:** Analysis of land use.

|                | High-rise |         | Multi-storey |         | Terraced |         |
|----------------|-----------|---------|--------------|---------|----------|---------|
|                | m²        | %       | m²           | %       | m²       | %       |
| Building footprint | 10,692    | 16%     | 8169         | 25%     | 10,975   | 27%     |
| Green/water     | 18,158    | 26%     | 9244         | 28%     | 13,160   | 33%     |
| Traffic area    | 17,709    | 26%     | 6665         | 20%     | 6,237    | 16%     |
| Sealed footpath | 22,004    | 32%     | 8786         | 27%     | 9,947    | 25%     |
| Gross building land | 68,563   | 100%    | 32,846       | 100%    | 40,355   | 100%    |
In order to merge and compare these data sets addressing CAs, they are standardised in relation to the GFA in the three respective zones under consideration (Figure 5 and Table 5; see also Table A1 in Appendix A in the supplemental data online).

The spatial costs of outdoor development shown in Figure 5 reflect the common understanding of how compact settlements produce efficiency gains. The values follow a typical relationship, as confirmed by numerous studies (see section 1): Spatial costs are high for low-density forms of housing, then decrease sharply with increasing density. When density is already high, any further increase only achieves small efficiency gains.

The ‘indoor’ spatial costs of development show contrary behaviour, at least for low- and medium-density areas: indoor spatial costs rise at a similar rate as outdoor spatial costs fall. Overall, the rise in indoor spatial costs slightly exceeds the drop in outdoor spatial costs, so that total spatial costs of development increase somewhat (cumulative curve ‘indoor plus outdoor’).

![Figure 5: Specific spatial costs of access (m² circulation area (CA) per m² gross floor area (GFA)).](image)

### Table 5: Specific spatial costs of access (m² circulation area (CA) per m² gross floor area (GFA)).

| Specific spatial costs of access (m² CA/m² GFA) | Terraced | Multi-storey | High-rise |
|-----------------------------------------------|----------|--------------|-----------|
| Outdoor                                       | 0.421    | 0.255        | 0.212     |
|                                                | (100%)   | (50%)        |           |
| Indoor (total)                                | 0.128    | 0.304        | 0.294     |
|                                                | 23%      | 54%          | 58%       |
| Indoor vertical                               | 0.070    | 0.086        | 0.128     |
|                                                | 13%      | 15%          | 25%       |
| Indoor parking                                | 0.058    | 0.217        | 0.166     |
|                                                | 10%      | 39%          | 33%       |
| Total (outdoor plus indoor)                   | 0.549    | 0.559        | 0.505     |
|                                                | 100%     | 100%         | 100%      |
|                                                | (100%)   |              | (92%)     |
Further, in areas of higher density housing, indoor spatial costs of development clearly exceed the outdoor spatial costs. However, the increase in ‘indoor’ spatial costs is (slightly) more than compensated by the reduction in ‘outdoor’ spatial costs. The overall development curve, therefore, shows declining spatial costs, although at a much slower pace than the trend observed for outdoor spatial costs alone.

5. Discussion

The results show that an increase in building density is not necessarily accompanied by efficiency gains in relation to spatial costs of development if the total spatial costs for such infrastructure are taken into account. As a result, there is less variation in the spatial costs of development of different areas. On the one hand, this is because of the features needed within buildings to provide vertical access to individual dwelling units, that is, stairwells and corridors. Spatial costs for such vertical service infrastructure increase relatively smoothly from the low- to the high-density area.

A significantly different picture emerges with regard to indoor parking for parked vehicles, the second component of the discussed indoor infrastructure. Here the spatial costs of development are much higher in the high- than in the low-density area than was the case with indoor vertical development. There is a straightforward explanation: If the absolute area of a zone is considered, it becomes clear that in the high-density site the proportion of land occupied by the buildings themselves (building footprint) is smaller compared with the lower density sites. On the other hand, the proportion of land required for roads and footpaths is so large that there is hardly any space left to accommodate parked vehicles. Parking must therefore be shifted to within buildings in such a way that no additional land is consumed, for example, in underground garages.

Particularly noticeable is the high spatial costs for infrastructure in the medium-density site. Here there seems to be no obvious pattern. On closer inspection, it becomes clear that this is because of the varying design of indoor parking: The individual parking space per dwelling is largest in multi-storey buildings at 55 m². The corresponding space in terraced houses is much smaller at 29 m² per dwelling, and even smaller in high-rise buildings at only 24 m² per dwelling. The provision of parking space differs between the three zones. At the same time, for the case study under consideration, it can be assumed that the zones enjoy a similar level of access to public transport, based on a survey of bus stops in the area.  

In order to discuss the effect of a comparable level of parking provision (which has a considerable impact on development expenditure), one can—for the sake of argument—simply consider the case that all three zones provide the same extent of parking as to be found in the multi-storey housing zone. In this theoretical case, the spatial costs of development will increase in both the terraced housing zone and the high-rise housing zone. In particular, the spatial costs of development for indoor parking will increase in the terraced housing zone and the high-rise housing zone (Figure 6, adaptation of indoor parking). The end result is a ‘U’-shaped curve of spatial cost. This indicates that an optimum infrastructural efficiency is likely to be found in the intermediate range rather than at very low or very high densities.

The findings are based only on three individual examples and can be criticised as randomly selected cases. In order to mitigate this charge, the case study was selected in consultation with local experts (employees of a local architectural firm) so as to model current designs for the development of new settlement areas in Chinese cities. While this alone is insufficient to draw reliable conclusions on how to ensure greater efficiency in the design of access infrastructure within urban zones, the results clearly point to the need for more in-depth studies of these interrelationships. In this context, certain qualitative infrastructural elements have a crucial role. This is illustrated by the above-mentioned simulation calculation, which made clear the impact of similarly sized parking areas.

A further methodological problem relates to the allocation of open spaces to individual zones. In the analyses, it is assumed that the open spaces within the zones are precisely assigned to them. Even though the urban design suggests this assignment, it cannot be excluded that parts of the open spaces such as green space and water areas may also be used by residents of neighbouring areas. This fuzziness of demarcation and classification can never be completely excluded in small-scale urban structural studies. However, the underlying design principles and conventional allocation rules for spatial costs suggest that such assets should—as a first step—be allocated to the units of use of the zones concerned. Nevertheless, the hypothetical nature of the results must be clearly pointed out because of these methodological limitations, even though recent studies provide some support for these hypotheses (Kurvinen & Saari 2020).

Note that building regulations can also greatly influence the results. This is especially the case for the provision of parking spaces, which may differ considerably between building types and as well as between cities. Anticipating this uncertainty, standard configurations of parking spaces were also simulated. However, this does not replace a more in-depth examination of this aspect in future research.

Another topic worthy of some discussion is the disparate types of areas that make up a single zone. Of course, the size of such a zone is fixed and cannot simply be extended. For this reason, the allocation of one subarea to a certain type of use (e.g. built-up area) is always at the expense of another type of use (e.g. green space). The situation is different regarding areas within buildings. Here, exploitation of the third dimension offers a comparatively large range of options for altering the size of indoor areas. For example, the construction of basement levels will provide indoor parking spaces, while keeping the building density and also avoiding additional land use outdoors. However, this is associated with increased costs, which can be quantified, for example, in terms of the additional material resources (e.g. reinforced concrete for underground car parks) required for the buildings or indeed in additional
energy consumption (e.g. monetary costs/person by the construction and management of the underground car parks) or environmental impact (e.g. the greenhouse gases produced per m² floor area induced by the production of the building materials (embodied emissions) and the operation of the additional indoor structures). In contrast, the layout of the buildings with centrally located supply cores (stairwell, elevator shafts) and short distances to the apartments contributes to a more efficient use of internal traffic areas. Widening the focus of the current study to take into account additional features will help standardise the observed increase in material resources and costs, thereby enabling a better comparison of values.

6. Conclusions

By adopting a wider perspective of sustainability in urban development, new issues become apparent. The focus on access infrastructure to buildings has been too simplistic and needs reframing in order to account for high infrastructural efficiency. Owing to simple and robust geometric interrelationships, it cannot be denied that high-density areas can be developed more efficiently than low-density areas, and that the former should therefore be preferred with regard to their higher efficiency. Yet, this ignores a further critical factor, namely the vertical access infrastructure within buildings. Taking this into account, the differences in infrastructural efficiency between low- and high-density areas tend to disappear when 'spatial area' is used a metric. Such an approach brings some methodological difficulties because of the disparate nature of the various types of areas within the zone and within buildings that are brought together here. Therefore, it is advisable for researchers to adopt a standardised

**Figure 6:** Specific spatial costs of access assuming an identical provision of parking space.
assessing the efficiency of indoor and outdoor access-related infrastructure

there is no doubt that density plays a fundamental role in the design of efficient settlement structures. the case study presented here is to be understood as an argument in favour of considering the vertical dimension of access infrastructure in any discussion of efficiency. in this way, it will be possible to expand greatly the number of new urban developments provided with efficient and high-quality access infrastructure and other design features. parked vehicles seem to be a critical factor. since densely populated areas, in particular, have scarcely any open spaces available for parking, there are only two remaining options: either to abandon traditional automobile-based concepts of urban living or to provide parking space within buildings, leading to the dramatic loss in efficiency revealed in this study. clearly, there is some scope for designing more efficient access infrastructure in densely populated areas. a discussion of this, however, requires an expansion of the current system boundaries as well as an integration of wide-ranging urban planning concepts to ensure that the influence of different configurations of public transport is taken into account. based on the individual examples considered here, there are presumably fewer options for the optimisation of infrastructure within buildings. in fact, there already exists comprehensive knowledge on this topic, which is already adopted as common practice in building design.

future research could continue this approach developed and presented here by extending the number and diversity of samples in order to test the robustness of the hypothetical results. it will be necessary to conduct a more systematic statistical analysis of the relation between inner/outer infrastructures and density. for instance, studies based on geographical information system (gis) data, which classify all typical zones with dominant residential buildings in a case study city, could provide a more representative analysis and thereby increase the accuracy of the (dis)economy of scale curve for infrastructural efficiency as related to indoor and outdoor access.

another promising avenue of research would be to integrate socio-spatial qualitative factors that go beyond the strictly quantitative assessment of natural resources such as m² of land, monetary costs, raw material or energy units. one interesting finding of this study is that the extent of sealed land surface area is higher for high-rise buildings and that there are smaller green/water areas. this contradicts the belief that high-rise building can reduce land consumption and thus increase the extent of urban green space. furthermore, this finding points to a promising avenue of further research, namely the influence of different urban morphological forms on microclimates (e.g. the urban heat island) as well as the likely impact on energy consumption.

notes

1. as a general rule, a red line is defined in the middle of roads in china. therefore, a road with a zonal boundary can be assigned half the diameter of the adjacent zones as it is in the most common situation that there is only one zone on each side of the road. in some specific cases, for example, when zones are adjacent to a traffic circle, roads may be divided equally among multiple zones, but they are usually divided equally, regardless of the size of the zones (area or number of dwelling units).

2. the service area is that portion of the net floor area with technical installations which service the building or parts of it, such as: a) installations and pipes for the disposal of waste water; b) water supply; c) heating and hot water systems; d) gas installations (other than for heating purposes) and installations for liquids; e) electricity supply generators; f) ventilations, air-conditioning and cooling systems; g) telephone switchboard apparatus; ... (iso 2017: 7).

3. buses are the only form of public transport in the city.

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competing interests

the authors have no competing interests to declare.

author contributions

g.s., k.g. and x.x. conceived and designed the research. k.g. and x.x. performed the data selection and curation. g.s. and x.x. prepared the original draft paper. k.g. and x.x. reviewed and edited the paper.

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**Appendix A**

| Area (m²)                                   | Terraced | Multi-storey | High-rise |
|---------------------------------------------|----------|--------------|-----------|
| Gross floor area (GFA), total              | 38,498   | 60,548       | 187,766   |
| GFA, above ground                          | 19,816   | 39,732       | 146,959   |
| GFA, underground                           | 18,682   | 20,816       | 40,807    |
| Circulation area (CA), total               | 21,138   | 33,821       | 94,897    |
| CA, indoor                                 | 4918     | 18,388       | 55,184    |
| CA, indoor vertical                        | 2698     | 5225         | 23,956    |
| CA, indoor residential                     | 2678     | 2815         | 17,153    |
| CA, indoor commercial                      | 20       | 2409         | 6803      |
| CA, indoor parking                         | 2220     | 13,163       | 31,228    |
| CA, outdoor                                | 16,220   | 15,433       | 39,713    |
| CA, public traffic area                    | 5215     | 3337         | 9707      |
| CA, private traffic area                   | 1058     | 3065         | 7173      |
| CA, sealed footpath                        | 9947     | 8768         | 22,004    |
| CA, parking (commercial)                   | 0        | 263          | 829       |

**Figure A1**: Breakdown of the gross building land (absolute m²) (supplemental material for Figure 4).

**Table A1**: Gross floor areas and circulation areas for the three housing zones (supplemental material for Figure 5).
