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FORMAL ADAPTABILITY

A discussion of morphological changes and their impact on density in low-rise mass housing

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ABSTRACT

Upon building completion, housing value starts diminishing over time. If it fails to fulfil stakeholders' long-term needs, the building becomes obsolescent. While some housing schemes survive, others do not, being inflexible in changes over time. This paper explores physical adaptability as a design characteristic that other things being equal, adds to long-term viability in urban housing. It addresses the topic by investigating the adaptability of urban form and the impact of physical adaptations on space consumption and density in low-income mass residential developments. It studies urban form, buildings, plots and streets in and for themselves independent of their use. The objective is to understand how the three elements adapt over time and which morphological characteristics determine their capacity to adapt, a property that may contribute to greater socio-spatial sustainability in the built environment.

Taking 'Cité Ouvrière' as an example –a working-class housing scheme in Mulhouse (France)– the paper traces its transformation process from its birth till the beginning of 21st century. First, it focuses on the adaptability of the streets using space syntax analysis. Having the local network resisting to changes over time, its degree of adaptability has been subject to three factors: the morphology of blocks, the evolution of the wider city network, and the configurational relation of the two local and global networks.

The second part of the paper discusses the building and plot types of Cité Ouvrière and their bottom-up typo-morphological evolution. Based on empirical and archival data, the study identifies eight 'mechanisms' of physical change and examines their impact on the built density using Berghauser Pont and Haupt's *Spacematrix* density model at the level of building-plot compounds.

Ultimately, the same model is used to describe the degree of adaptability as a matter of built density for four housing typologies. For buildings and plots, adaptability refers to their ability to accommodate effectively changes in their form over time. In the context of Cité Ouvrière, physical adaptations have transformed an initially uniform garden city into a morphologically heterogeneous and compact urban quarter. Despite the original standardisation, a variety of formal outcomes and typological mutations have emerged as a result of three morphological characteristics inherent in the original design: location within the city, low built intensity and small plot coverage providing surplus open space.

KEYWORDS

adaptability, urban form, mass housing, density, *Spacemate*

1. RETHINKING HOUSING AS AN EVOLUTIONARY PROCESS

Mass housing for low-income population groups has constituted a major topic of discussion for contemporary cities, being debated as a political instrument to housing the masses, as a commodity traded for money, and as a social obstruction to community formation (Turner, 1979; Wakely, 1988; Pugh, 2001; Perlman, 2004; Simpson, 2013). It is mainly provided through top down centrally administered processes in which occupants rarely participate. The final designs are repetitive uniform environments with poor infrastructure, which fail to create liveable and sustainable spaces (Angélil and Hehl, 2014). Although architects and urbanists have been pushing for user-centric approaches, most of the times these have stayed limited to participatory processes at an early planning level or computer-aided simplifications without a real understanding of how buildings and lifestyles change with time. Housing is not a static entity, but a dynamic socio-spatial configuration that is affected by time, modes of living and socio-economic change. For this reason, it is worth rethinking mass housing not as a one-off design but as an accumulation of morphological refinements over time.

However, the housing that anticipates future growth, presumes an urban form¹ (streets, buildings, plots) that is adaptable enough to accommodate physical changes of shape, volume and configuration resulting from inhabitants' evolving needs. Most studies on adaptability so far focus on the environmental, economic or engineering aspect of buildings. Legislation, technology, energy consumption, economy and land uses are also important factors to consider when talking about adaptability. But designing buildings to be convertible, flexible, energy efficient or re-usable is different from designing them to be adaptable to physical changes (Psarra et al., 2012). While the above-mentioned factors can ensure buildings to be suitable for adaptation, the capacity of a building to adapt is specific to the design of its urban form and the possibilities this offers.

The paper explores the ways buildings, streets and plots can adapt over time in low-income mass residential developments, and the impact of these formal adaptations on space consumption and built density. First, it reviews relevant literature to understand how scholars have so far defined adaptability in the built environment, showcasing a multiplicity of often-contradictory definitions against which the following study is set. Second, it takes a nineteenth-century working-class settlement in Mulhouse, France as an example, to study the physical adaptations of the urban form over time. The paper analyses configurationally the local street network, whose layout has remained unchanged since its completion. At the same time, it studies the extensive bottom-up adaptations performed on individual building-plot compounds between 1853 and 2000. The research classifies all adaptations into eight 'mechanisms of change' and uses the *Spacematrix* density method introduced by Berghauser Pont and Haupt (2004, 2009) to capture first, the effect of each mechanism on the built density independently of other changes and second, the effect of all mechanisms per four housing types and for two historical dates. Ultimately, it is argued that in this context physical adaptations in the urban form had positive effects on its performance. They enhanced the accessibility of the local street network, intensified the open space consumption at the plot level and increased the compactness of the built form, turning an initially uniform settlement into a formally diverse urban quarter.

So far, space syntax studies have addressed adaptability in relation to changes of land use, socio-economic diversity and resilience as well as physical, functional and social changeability in non-domestic built environments (Griffiths et al 2008; Vaughan et al 2010, 2013; Törmä et al 2017). However, this study adopts a purely morphospacial approach to understand the physical dimension of bottom-up adaptability in urban housing. It provides knowledge on how urban form changes over time, the relation of these changes with the built density while linking the concept of adaptability across the three elements of urban form. The intention, however, is not

¹ Streets, buildings and plots constitute the three fundamental elements of town plan according to Conzen, the founder of the British school of urban morphology (Moudon, 1994).

to present an exhaustive research on adaptability and its overall implications on the future built environment. It would require a far more extensive discussion that extends beyond the limits of this paper. Still, results from this research may inform how architects and urbanists approach the design of mass housing in the future. Issues that address the greater societal challenge of housing sustainability regarding the longevity of buildings are also noted.

2. DEFINING ADAPTABILITY: A SHORT INTRODUCTION

Since the 1970s, scholars have explored the concept of adaptability in various overlapping and contradicting ways, making it almost impossible to agree on a single definition (Habraken, 2008). Table 1 presents a list of 16 'definition clusters' created according to the authors' understanding and analytical approach. It is a result of bibliographic research, which by no means claims to be comprehensive. However, it demonstrates the diversity in the vocabulary employed to capture the concept of adaptability. The main conclusion is that most clusters link 'adaptability' to the idea of *change over time* of either the form, use or performance (economic, environmental, social) of the built environment.

According to Douglas (2006, p. 14), adaptation includes "any work to a building over and above maintenance to change its capacity, function or performance". The purpose of the adaptation is to improve some or all of these aspects and ensure that the building fits for its users, purpose, the planet and the future (Gorgolewski, 2005). Nonetheless, scholars have offered contradicting definitions regarding the way a system can improve its performance through adaptation. In some cases, adaptability is described as the ability of a system to *receive* or *respond* effectively to changes in order to avoid obsolescence. In other cases, an adaptable system is one that resists changes and endures over time. In this sense, the concept identifies with longevity or resilience², expressing the capability of a system to last and perform equally well –if not better– than before. This is similar to what Marshall (2009) calls an 'evolutionary paradigm', that is, resiliency to change and persistence through time.

Schmidt III and Austin (2016) add two more critical dimensions to adaptability: time and scale (see also Schmidt III et al., 2010). On the one hand, time refers to the diachronic changes of space, function and built form. Vaughan et al (2013) have argued that any analysis of contemporary urban form without its historical precedents will fail to understand how urban environments emerge and grow. On the other hand, scale refers to both to the level of application and effect of adaptations. The extent to which the different elements of urban form change, are changed by each other and relate to the city whole are important elements to acknowledge when exploring adaptability.

At the level of street network, Vaughan et al (2010) have claimed that "the manner in which the smaller scale grid is knitted into the super-grid helps shape the relation between local places and the entire city, between city parts and wholes and the relationship in turn between society and space" (referencing work by Hillier and Penn, 1996 and Hillier and Vaughan, 2007). While this mainly concerned with distributions of movement and land uses, Koch and Miranda (2013) extended the concept further to include the effect of changes on the building interface and forms of inhabitation.

At the scale of the building-plot compound, changes in individual houses may occur without an idea of a larger pattern to which they may contribute (Kropf, 2001). Particularly in mass housing schemes, individual changes can be substantial due to their transformative aggregate effect (ibid, p. 31) that leads to an emergent pluralism in spatial configurations and built forms. These can be additions, extensions, alterations, upgrades, partial demolitions or any other modifications that takes place during the active use of a house, which once again affect the urban interface and forms of inhabitation. Effectively, each change on one of the parts of the urban form has an impact on the entire system (Carter, 1983).

2 The term resilience –firstly introduced by Holling in 1973 for natural environments– is widely used today in architectural and urban studies often in conjunction with sustainability.

Definitions of Adaptability	
Schmidt III et al 2010; Druot, Lacaton & Vassal 2012; Organization for Economic Co-Operation and Development 1976; Engel and Browning 2008; Li et al 2008; Random House 2010;	Adjust or modify fittingly to suit new conditions
Kronenburg 2007; Palani Rajan et al 2003; Gibb et al 2007; Wilkinson et al 2009; Schneider and Till 2005; Carroll et al 1999; Brewerton and Darton 1997; Woetman Nielsen and Ambrose 1999;	Respond [readily] to changing needs of the users
Leaman et al 2004; Groark 1992; Hasemain 2005; Schmidt III et al 2010; Bullen and Love 2010; Department of Environment Heritage (Australia) 2004; Krüger 1981; Li et al 2008; Griffiths et al 2008; Vaughan et al 2013;	Receive [long-term] changes of use; Reuse, allocate a variety of uses
Koch and Miranda 2013; Vaughan et al 2013;	Receive physical changes of configuration
Canadian Standards, 2006; Schmidt III et al 2010; Organization for Economic Co-Operation and Development 1976; Ross et al 2008;	Relocate, move location
OECD, 1976; Canadian Standards, 2006; Graham et al 2011; Gorgolewski 2005;	Accommodate and Anticipate subsequent changes, modifications
Brand 1994; Kasarda et al 2007; Bon 1972; Steadman 2015;	Evolve; grow
Douglas, 2006; Schmidt III et al 2010; Krüger 1981; Steadman 2015;	Capable for change (size, use, capacity, function, performance)
Graham 2001; Engel et al 2008; Ellison et al 2007; Schmidt III and Austin 2016;	Maximise value through life
Juneja 2007;	Endure [quick] transformations
Pearce 2004; Bullen and Love 2010; Brand 1994; Pickard 1996; Cooper 2001; Balaras et al 2004; Bromley et al 2005; Kurul 2007; Graham 2005;	Avoid decay, obsolescence or demolition; Sustainability
Schmidt III et al 2010; Beadle et al 2008; Graham et al 2011; Brand 1994; Kincaid 2000;	Longterm performance, longevity
Harper 2001; Friedman 2002; Blakstad, 2001; Ridder et al 2008; Slaughter 2001; Schmidt III et al 2010; Torma et al 2017;	Remain 'fit' for purpose

Table 1 - Definition clusters of adaptability reviewed by the authors in the literature building upon the work of Schmidt III et al (2010)

2.1 EMERGENT BOTTOM-UP MORPHOLOGICAL ADAPTABILITY

The study narrows down the definition of adaptability to the capability of buildings to accommodate effectively exterior formal changes introduced by the inhabitants. The effect is an authorless³, asynchronous and miscellaneous incremental adaptation of space and form as a result of socio-economic needs and technological advancements over time. At the very core of this incremental growth lies a gradual, yet firm process of if-and-when-needed changes that give inhabitants the sporadic opportunity to improve their everyday environment and enhance its performance. In the meantime, houses get altered with little consistency, yet it is possible for certain patterns to emerge due to some shared reasons such as heritage, legislation, technology, economy, society, aesthetics and architectural fashions (Mansfield and Pinder, 2008; Steadman, 2014).

Implicit in this work is the assumption that emergent bottom-up adaptability instigated by the residents themselves, engages them with the future of their house and their neighbourhood, and therefore, can be considered a design strategy that contributes to social empowerment and spatial sustainability⁴. The ability of a form to be adaptable and extend its life capacity encourages inhabitants to invest time, resources and effort to maintain it. From a social point of view, adapting existing housing is less disruptive than building anew since residents avoid being relocated and instead, retain their socio-cultural networks based on spatial proximity (Power, 2008). Especially, people with low levels of mobility, they are more likely to stick with their house and learn how to adapt it themselves. Then, according to Turner (1979 p.93), they are not only 'passive consumers' who use housing goods and services, but also 'active participants' who vigorously take care of their built environment when resources allow for it. Santo (2012) refers to the empowerment behind those 'advanced building-users' who have the freedom and capacity to appropriate and transform their houses on their own way.

3. MAPPING THE EVOLUTION OF THE URBAN FORM

Within this context, the study looks at a nineteenth-century mass factory housing: Cité Ouvrière in Mulhouse in northeast France. It seeks to trace the spatial evolution of the urban form from 1853 till 2000. To do so, it uses configurational analysis for the street network, graphical mapping techniques and quantitative research for the buildings and plots. Methodologically, it begins with a historical mapping of the city's growth and housing's development. With the use of space syntax theory and tools (Hillier and Hanson, 1984), it analyses the configurational relationship of the local grid with the entire city network and its immediate surroundings. The model includes 33,789 street segments within a circle of 15km diameter. The measures of segment angular integration (closeness centrality) and choice (betweenness centrality) for local and global radii are used to understand the accessibility potential of the network.

Furthermore, through on-site qualitative research and detailed archival work the study records the physical adaptations of houses and plots in two and three dimensions, and classifies the formal outcomes in eight 'mechanisms of change' (term coined by Ross et al. 2008)⁵. In an attempt to describe adaptability as a matter of density, it uses the *Spacematrix* density model (Berghauser Pont and Haupt, 2004) to measure the impact of adaptations on the built density at the level of building-plots.

3 It is of little interest here whether the changes are considered formal or informal from a legal framework point of view.

4 Sustainability is here linked to the idea of longevity. This is not to say that a sustainable building is one that lasts forever, but rather one that extends its life capacity and avoids obsolescence or demolition while accepting changes over time. For the purposes of this paper, financial and environmental sustainability are not being discussed. However, evidence show that bottom-up adaptations implemented to sound structures are an environmentally friendly and financially secure approach to upgrade the existing building stock.

5 According to Ross et al. (2008) any change can be characterised by three elements: the *agent*, the *mechanism* and the *effect* of change.

For the analysis of buildings and plots, density “contains valuable information about urban form and the performance of the built environment” (Berghauser Pont and Haupt, 2009, p. 21). The *Spacematrix* density method helps explain how the density of urban form changes as a result of bottom-up adaptability. It uses four morphological variables: ground coverage (or ground-space-index GSI), floor space index (FSI), number of floors (L) and open space ratio (OSR). These variables are combined in *Spacemate* charts giving every building-plot compound (plan area) a unique spatial ‘fingerprint’⁶. The same tool is used to evaluate with the use of density: (1) the evolution of urban housing as a whole; (2) the evolution of different housing typologies; and (3) the effect of each ‘mechanism of change’ independently of each other.

3.1 THE USE OF DENSITY

Density as a descriptive and prescriptive⁷ concept of urban form has been repeatedly disputed because it quantitatively homogenises building types and built forms, while its definitions and measurements vary across contexts (Churchman, 1999). Berghauser Pont and Haupt reviewed existing density measures, such as population and dwelling density, land use intensity (FSI), coverage (GSI), building height and spaciousness (OSR), and showed that there is little or no relation between these and urban form. Using any of these measures alone does not help depict the size, configuration and scale of buildings, plots and streets. The reason being that scientific representations and resolutions of density tend to be generic and simplified, due to wide variations of forms across scales. Furthermore, some measurements do not take into consideration the un-built space (open, water, green or streets). And when they do, not all types are included. Neither is consistency kept among the measurements. Additionally, different built types can affect occupancy possibilities, while different social and cultural practices can dictate changes of occupancy rates⁸ without changes in the urban form. Essentially, conventional density measurements hint at certain qualities of urban form, but do not fully convey our perception of it. Yet as Berghauser Pont and Haupt (2009, p. 18) conclude, “the concept of density as such cannot be blamed for [these] explanatory shortcomings; this is caused more by the formulation of specific definitions and their applications”.

Thus, Berghauser Pont and Haupt proposed a comprehensive multi-variable density model that combines some of the conventional measurements (FSI, GSI) and introduces network density (N). Network density describes the amount of network per area unit, focusing on the form of the street system, and compensates for the absence of this variable from precedent density studies. Based on the mutual dependence of the elements within the urban fabric, the new model is more inclusive, differentiates between built types and overcomes issues of scalelessness.

6 This is a term coined by Berghauser Pont and Haupt to describe the position of each building entry on the *Spacemate* chart.

7 Density was initially used to describe crammed urban conditions of nineteenth-century city centres leading to high population density, getting associated with poor health conditions and social disorder. This led architects and urbanists of the time to redirect their theories towards lower densities propagating in favour of decentralised urban models such as the Garden City movement. Modernism followed suit with low densities in high-rise tabula rasa developments and suburban spread-overs leading professionals and academics to question the true value of the concept. Since then, density gradually became an integral part of debates regarding the future of the cities shifting from a descriptive tool to a measurement of prescriptive agendas for compactness, liveability, walkability, diversity, and sustainability –environmental, economic and social– in the built environment.

8 Average number of people per residential dwelling

4. THE EVOLUTION OF CITE OUVRIERE

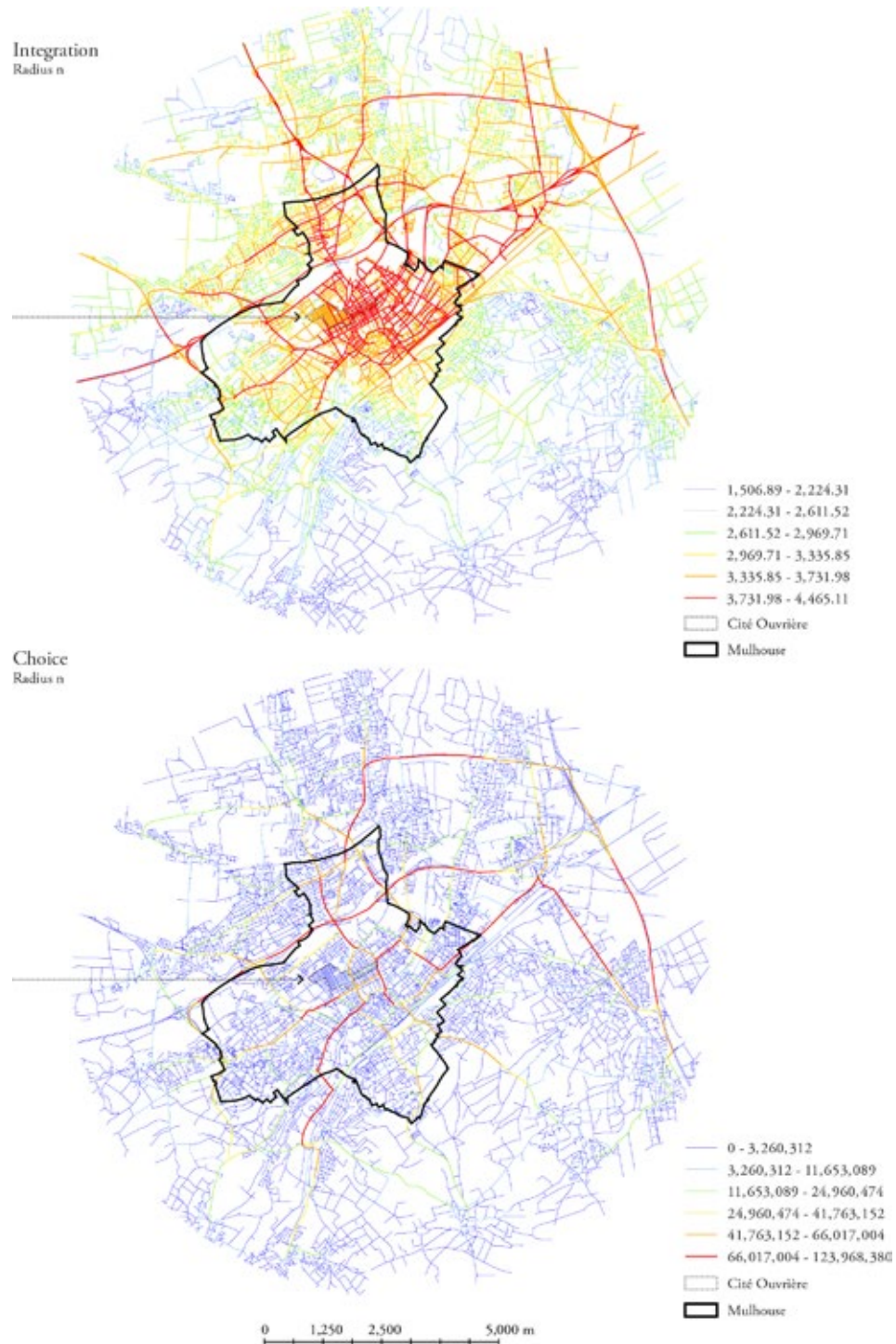


Figure 1 - Segment angular analysis of Integration and Choice Radius n (global scale) of the wider area around the city of Mulhouse.

Cité Ouvrière is a 19th century mass factory housing built for the workers of the *Dollfus, Mieg & Cie* textile factory (DMC) in the city of Mulhouse. Situated in the Alsatian region of east France close to Switzerland and Germany, Mulhouse has experienced a glorious industrial past. As part of this and a series of philanthropist infrastructural projects, Cité Ouvrière was realised by the *Société Mulhousienne des Cités Ouvrières* (SOMCO) with the aim to provide the workforce with salutary and affordable houses as well as subsidised access to property.

4.1 STREET NETWORK

The scheme was originally built at the north periphery of Mulhouse. Following the city growth, the urban boundaries shifted. While the local layout remained unchanged throughout the years, subsequent expansions of the wider city network encircled the area, making it centrally located within the city. Previous research (Kostourou, 2015) argued that the original morphology and the configurational evolution of the street network have contributed to its 'spatial sustainability' (as defined by Hillier (2009)). Space syntax analysis (Figure 1) highlighted: first, the syntactic integration of Cité's network at all scales and second, a morphologically distinct grid with small and dense blocks that minimise metric distances between any two points. From a functional point of view, this intensified morphology can generate more intimate social encounters between inhabitants-inhabitants and inhabitants-strangers. Moreover, results from the same study using segment angular analysis for integration and choice measures for consecutive metric radii (200, 400, 800, 1200, 2400 and n) showed that the neighbourhood is metrically integrated at local scales and surrounded by streets of high choice value at the global scale. The peripheral and main streets are likely to receive higher pedestrian movement flow and attract more non-domestic uses than the alleys inside the purely residential area. The small blocks are also not able to accommodate these uses that require larger area and are fit for higher integration values. Finally, it was found that the intensified morphology as defined by the blocks' configuration, shape and size, gives all houses direct access to the street and improves accessibility from the rest of the city.

4.2 BUILDINGS AND PLOTS

The construction of the scheme began in 1853 and lasted for 44 years, counting at the end a sum of 1243 single-family dwellings homogeneously repeated in space. The final scheme of 1897 demonstrated a collection of housing types: 28 terraced (T), 190 back-to-back row houses (BtB), 998 quarter-detached (QD) and 27 semi-detached (SD) (Jonas, 2003, p.289) in four rectangular plot types: corner, terrace, through, and end sites (Steadman, 2014, figure p.209). Three main periods of construction are identified (Figure 2)⁹.

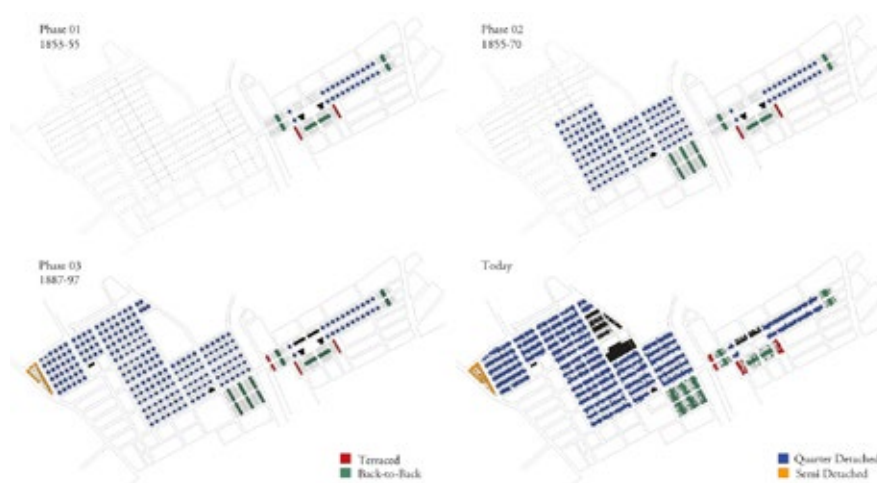


Figure 2 - Development of Cité Ouvrière's figure ground plan over time: from 1853 till its current situation and the location of the four typologies

⁹ Political and economic situations such as wars and financial crisis forced the process to halt during certain years.

During the first development (1853-55), a total of 200 houses were launched in 5ha: 28 terraced (T)¹⁰ and 76 back-to-back houses (BtB), which were two-storey row houses with two or three sidewalls respectively, built on elongated parcels; and 96 quarter-detached houses (QD) on squared parcels, an invention of the architect Emile Muller called *Carré Mulhousien*. These were two-storey houses grouped in four with two adjacent facades sharing sidewalls. The second stage of development towards the west (1855-70) included 660 houses (774QD and 114BtB), while the final phase (1887-97) built another 381 houses (144 QD and 27SD), occupying a total of more than 55ha¹¹. In this third period, the semi-detached type (SD) was introduced, a pair of mirrored houses sharing a common wall.

It is important to notice that already from the development phase of the scheme some types proved to be more successful than others (Figure 3). At the beginning, the terraced houses were the biggest types, but expensive to build and hence unpopular to sale. The back-to-back were typical working class houses. They were the cheapest and smallest of all, and continued being built until the beginning of the second cité. However, they shared three out of their four walls and performed poorly in terms of ventilation, light and sanitation. Both British typologies became quickly obsolete, letting the French *Carré Mulhousien* dominate the scheme. What made this typology popular was the economy of the layout, the configuration of the built-unbuilt space and the hygiene benefits of lighting and cross ventilation. Throughout the following periods, the houses became bigger in size, and in 1891, larger semi-detached types were built for the more affluent populations.

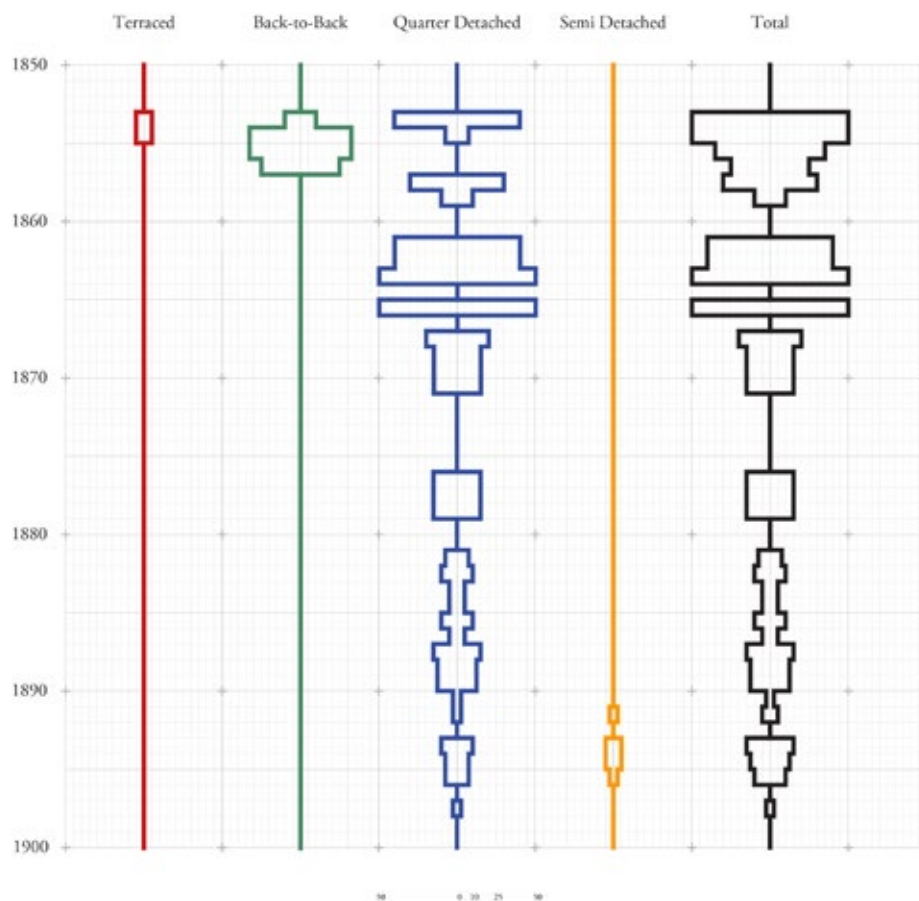


Figure 3 - Battleship graph for domestic built types in Cité Ouvrière from 1850 till 1900. Time (dates of construction) is mentioned on the vertical axis. The widths of bars give absolute numbers of cases built in successive years.

10 Eight houses from the first cité were built after 1870. Hence, only 192 were completed in the first phase.

11 Including the territory of the DMC factory

5. THE DENSIFICATION PROCESS

Quickly after the completion of each phase, the standardised houses got extensively modified through piecemeal transformations made by the owners (Figure 4). Inhabitants expanded and demolished their houses, changed the roofs, facades, fences, doors, windows and gardens, opened and closed down local shops and workshops, rented out and sold entire buildings or parts of them. After WWII, many of the buildings were refurbished and in the 1960s, a high number of immigrants from Turkey, Maghreb, Italy etc arrived to Cité Ouvrière to work in the factories (Meichler et al, 1998), contributing to the properties changing many hands. The status of ownership, the flexible legislation at the level of individual buildings (Palaïologou and Kostourou, 2016) as well as the succession of multiple owners from various cultural backgrounds allowed for physical adaptations to be freely exercised, and for a variety of formal outcomes to emerge.

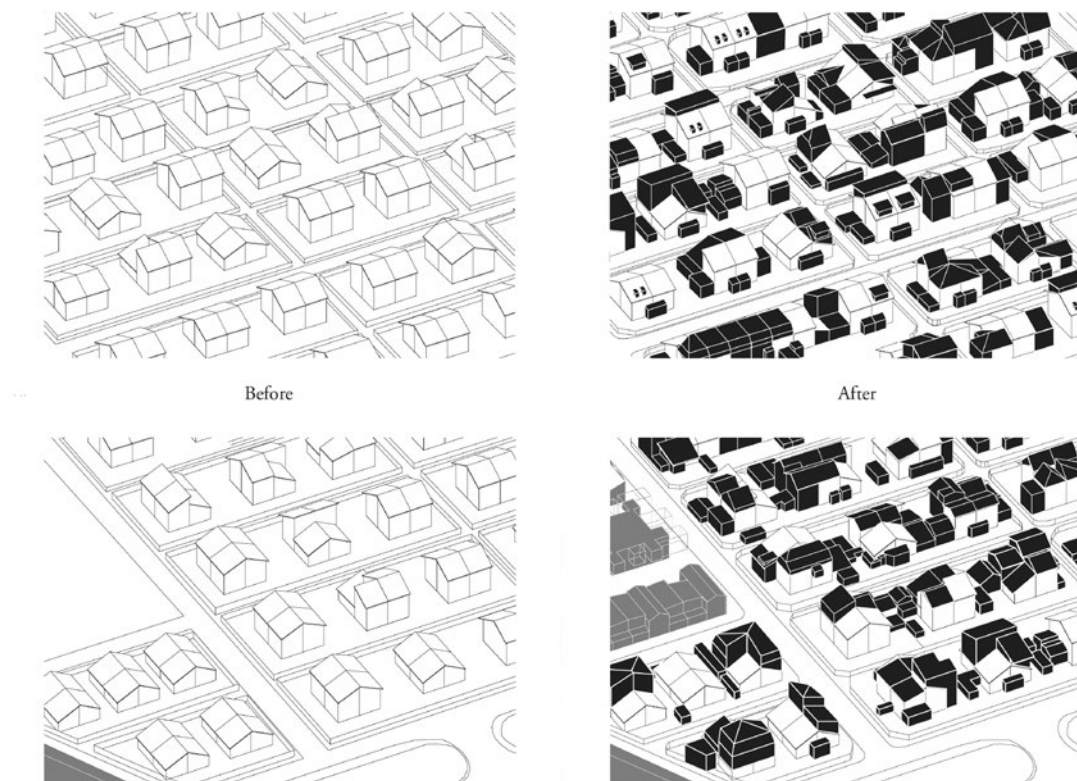


Figure 4 - Mapping of physical adaptations in three dimensions. Axonometric drawing based on Bing Maps Birds' eye view.

5.1 THE MECHANISMS OF CHANGE

A detailed on-site survey and archival research of official building permits from 1850s till 2000 shed light on the shared patterns behind the physical adaptations of the houses. We distinguish eight 'mechanisms of physical change' that impact the exterior articulation of the built form (Figure 5):

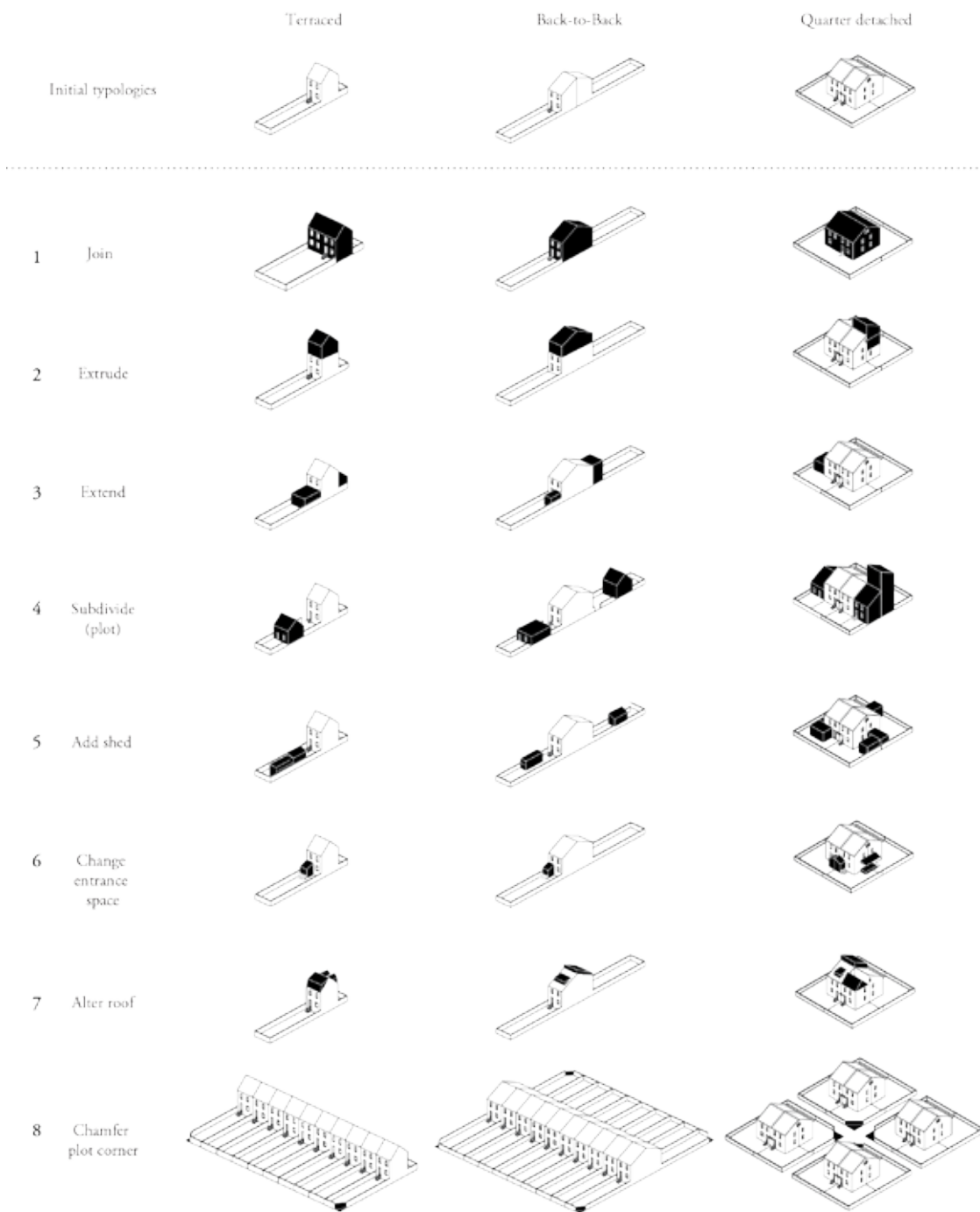


Figure 5 - Catalogue of formal adaptations for the three main housing types.

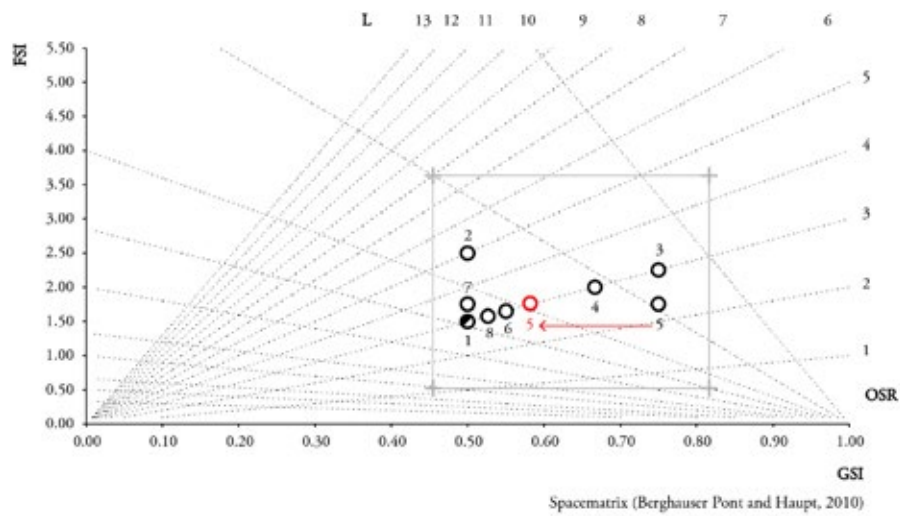
1. *Join together.* This mechanism occurs after one or more units are joined together to form a larger unit. It is more common for the quarter-detached type to get combined with adjacent buildings next or behind it. Sometimes, houses were joined and occupied by a single family since their construction. This mechanism has created typological mutations: quarter-detached houses turned into semi-detached, terraced or back-to-back; semi-detached to terraced; and back-to-back to terraced types.
2. *Extrude.* This mechanism refers to the addition of one or more storeys up to 11m.
3. *Extend.* This mechanism increases the floor area of the house through the addition of habitable rooms with interior connection or the elongation of existing ones owing to household needs. Again mutations of building types are created: quarter-detached have transformed into back-to-back. It is indicative that from the original 998QD, only 572 survive today.
4. *Subdivide the plot.* Upon becoming owners, the workers not only rented or sold part of the houses, but also part of the land. In many quarter-detached types, half of the original plot is sold and built by another owner.
5. *Add shed.* This mechanism considers solely detached annexations within the plots. Common annexations in the front or side yards include garages, 'gloriettes' and sheds for storage and workshops. Additions of this kind were subject to regulations with regards to building alignment, setback, access, floor area, distance from main building or neighbouring limits etc. The idea was to keep at least one third of the garden surface area unoccupied for social and hygienic purposes.
6. *Change entrance space.* Additions or modifications of the entrance porch were extremely popular and referred to horizontal growth of the house at the entrance point by adding usually non-habitable space with interior connection. Between the 1910s and 1920s, sewer and drainage systems were built, and the toilet facilities were incorporated in the entrance porches.
7. *Alter roof structure.* This mechanism summarises every possible transformation of the roof structure, such as changes of inclination, construction of dormer windows, the addition or enlargement of an attic, roof rotations and divisions.
8. *Chamfer plot corner.* This mechanism was very common to corner parcels especially after the introduction of cars as a means of transportation. The clipping followed the street alignment, and the cut-off surface was granted to the municipality.

5.2 THE EFFECT OF CHANGE PER MECHANISM OF CHANGE

The next part investigates the impact of each individual mechanism –all other mechanisms aside– on the built density with the use of the *Spacematrix* model applied at the building-plot area. In short, the *Spacematrix* formula can represent each built form as a 'spatial fingerprint' (Berghauser Pont and Haupt, 2004, p. 30) on a chart defined by four morphological variables of floor space index (FSI), ground space index (GSI), number of floors (L) and open space ratio (OSR)¹². It calculates the simultaneous relationship of these variables for the specific form. Applying the formula for every building-plot compound before and after the implementation of a single mechanism demonstrates the impact of this mechanism on the density and space consumption (Figure 6)¹³.

12 The FSI (gross floor area per plan area) expresses the built intensity of the scheme. The GSI refers to the ratio of built area to total plan area, representing the ground coverage or compactness of the scheme. The OSR variable indicates the three-dimensional spaciousness of a cubic area when the gross built area is subtracted. Finally the L expresses the average number of floors in the scheme (Berghauser Pont and Haupt, 2004, p. 25).

13 For this exercise, the eight mechanisms are applied to a building-plot area of random dimensions.



	plan area (m ²)	gross floor area (m ²)	built footprint (m ²)	FSI	CSI	OSR	L
Original	200	300	100	1.50	0.50	0.33	3.0
Mech 01	400	600	200	1.50	0.50	0.33	3.0
Mech 02	200	500	100	2.50	0.50	0.20	5.0
Mech 03	200	450	150	2.25	0.75	0.11	3.0
Mech 04	150	300	100	2.00	0.67	0.17	3.0
Mech 05	200	350	150	1.75	0.75	0.14	2.3
Mech 06	200	330	110	1.65	0.55	0.27	3.0
Mech 07	200	350	100	1.75	0.50	0.29	3.5
Mech 08	190	300	100	1.58	0.53	0.30	3.0
(average) Mech 05	200	350	150	1.75	0.58	0.24	3.0

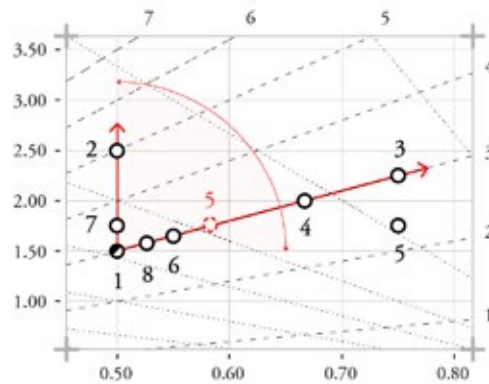


Figure 6 - Spacematrix chart and calculations for showing the transformation process for every mechanism of change found in Cité OUVRIÈRE.
This is tested on a building of 50m² (footprint) situated in plan area of 200m².
Original diagram and formula by Berghauser Pont and Haupt (2010).

All mechanisms of change apart from o1 [join]¹⁴ increase the floor space index (FSI) and ground space index (GSI) values, and decrease the open space ratio (OSR). This is obvious finding if no demolitions are happening. As the built form grows, it puts pressure on the non-built space. Furthermore, the 'spatial fingerprints' of all adapted forms fall within the same quadrant (red hatch of Figure 6), but differ in their trajectory of growth (red lines). For example, both mechanisms o2 [extrude] and o7 [alter roof] lead to an increase in the number of storeys (L), and therefore their trajectory follows a vertical path parallel to y-axis. This translates into a sharp rise of built intensity (FSI) without changing the figure-ground plan. In turn, the 'fingerprints' of mechanisms o3 [extend], o4 [subdivide], o6 [change entrance] and o8 [chamfer] retain the same height, but grow by occupying part of the open space, increasing the built intensity and compactness. This is evident when looking at Figure 4. Interestingly, *Spacemate* diagram fails to successfully capture mechanism o5 [add shed] for it only considers averages in the measurement¹⁵, and cannot distinguish between the addition of one-storey detached shed and the extension of the main two-storey house. And while in the examples of Berghauser Pont and Haupt, homogeneity was not a problem, here it seems to be.

5.3 THE EFFECT OF CHANGE PER HOUSING TYPOLOGY

The same methodology¹⁶ is further used to describe the bottom-up adaptation process of the four housing typologies in Cité Ouvrière. *Spacematrix* model is applied separately for all the buildings falling under the same type and at two discreet chronological dates: in 1897 (original state) and in 2015 (end state). The 'fingerprints' (positions on the chart) are overlaid to discuss the overall performance of the scheme.

Originally, all buildings under the same type shared the same spatial fingerprint (red dots). However, since then all the different mechanisms and combinations of those applied by different owners, have led to a variety of formal outcomes, a finding which can be measured by the large number and spread of the 2015 'spatial fingerprints' (Figure 7). Terraced houses demonstrate an average of 3.31 mechanisms of physical change per house, showing a preference for altering the roof [o7] and adding separate spaces [o5]. The average gross floor area (FSI) and ground coverage (GSI) have almost doubled, hinting at rather closed forms. However, the adapted built forms do not show a clear pattern, and the reason being the popularity of shed [o5] amongst the adaptations.

Back-to-back houses have tripled in number owing to typological mutations from initially quarter-detached types. Mechanisms of adaptations are limited as the facades of houses are restricted from three sides. Hence, the morphological impact is an increase in compactness. The most popular mechanisms are: change the entrance space [o6] and add sheds in the front garden [o5]. Similarly, quarter detached houses have grown extensively—more horizontally than vertically owing to the plot configuration which provides open space for horizontal expansion in two directions (in front and beside). Last, even if the sample of semi-detached cases is small (similar to T), the fingerprints cluster better. The truth is that these types were already big when constructed, and no dramatic changes have been observed, apart from the addition of sheds [o5].

By superimposing the 'spatial fingerprints' of all types (Figure 8), the overall performance of Cité Ouvrière is made visible. After the incremental densification, two clusters can be detected, indicative of two different degrees of adaptability: low (left circle) representing houses that have not received many changes or whose changes have kept the ratio between the four morphological variables unchanged; and high (right circle) which gathers the most adapted cases together. The centroids of these two clusters (average 'spatial fingerprint') demonstrate a clear trajectory of growth in the density of the urban form. Cité Ouvrière was and still is a

¹⁴ Mechanism 1 has exactly the same 'spatial fingerprint' with that of the original building because all the input values were doubled, so the variables remain constant.

¹⁵ While the FSI, GSI and OSR values increase, the L drops, which is not the case if the building height is not affected.

¹⁶ Due to the abovementioned shortcoming of the application concerning the heterogeneity of the sample, there are many outliers when processing the data. However, we believe the investigation remains valid as far as patterns of densification effects are concerned.

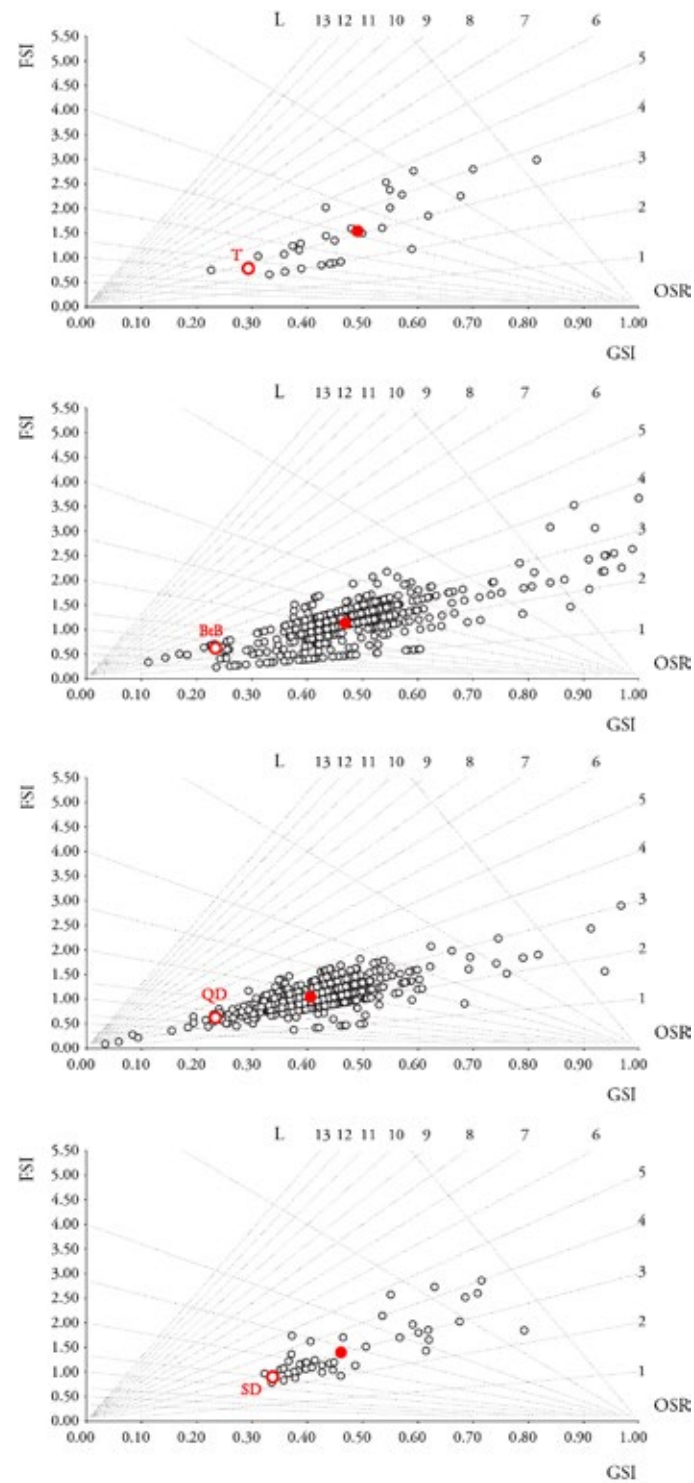


Figure 6 - Spacemate diagrams for every housing type in Cité Ouvrière. From top to bottom: terraced (T), back-to-back (BtB), quarter detached (QD) and semi-detached (SD). The red circles indicate the spatial fingerprint of the original buildings from 1897, the black dots correspond to all the contemporary cases, and the red dots on their average. Original diagram and formula by Berghauser Pont and Haupt (2010)

low-rise development (below 3 floors), which managed over time and through bottom-up adaptations to turn into a rather compact and closed built environment by consuming open space. Cité has densified its ground coverage (GSI) by almost 87.5%, increased its land intensity (FSI) while remaining low-rise. Building regulations have prohibited elevations of more than 11m, and have thus restrained changes in the number of floors (L). This forced the houses to extend horizontally, occupy more ground space, and put pressure on the garden area. As the built form became more compact and dense, the amount of non-built private space available for the inhabitants reduced. And as a consequence, regulations were soon developed to preserve at least one third of the garden area unoccupied.

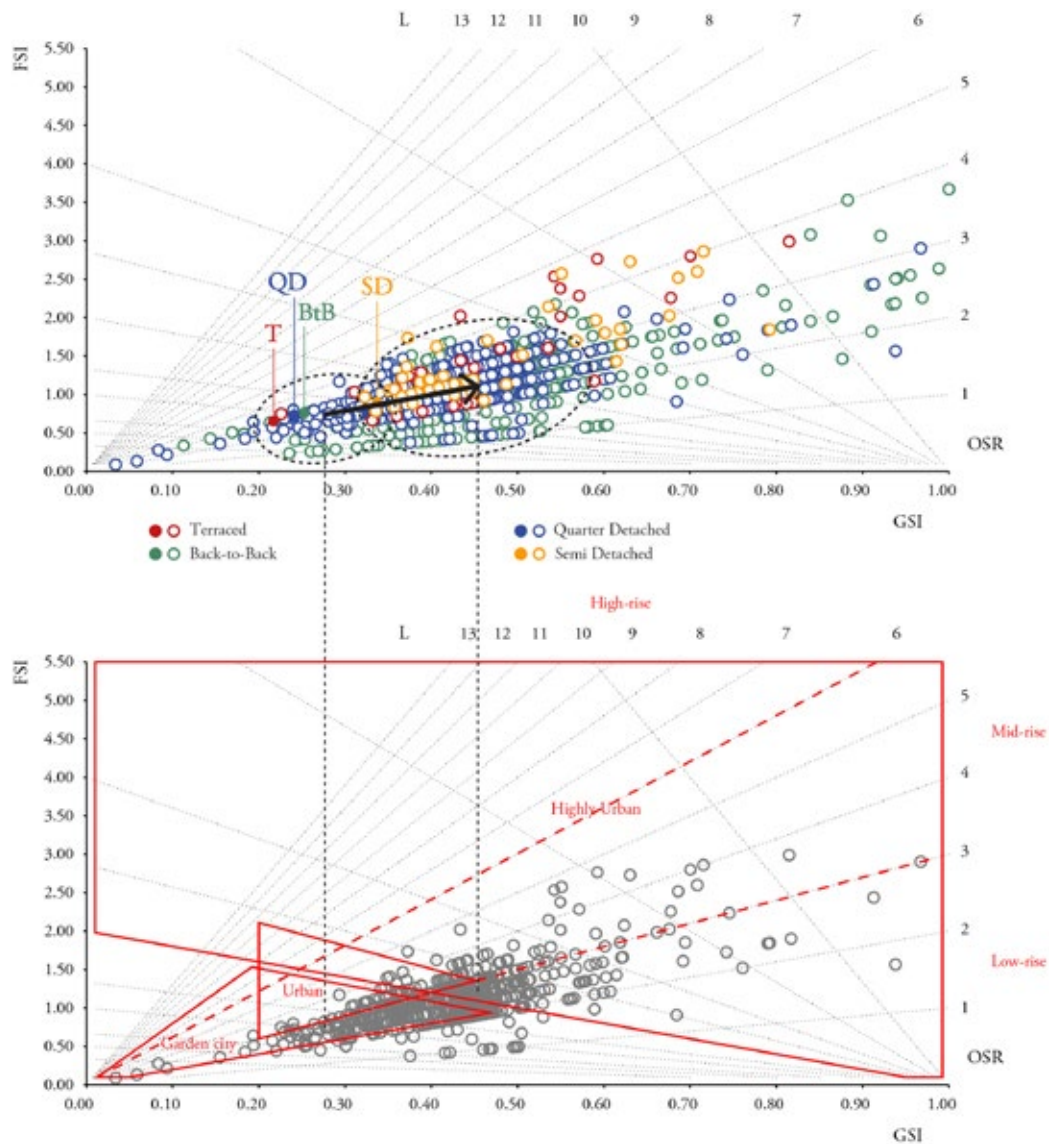


Figure 8 - Top: Spacemate diagram with all the residential types. The filled dots show the original 'spatial fingerprint', while the ones without infill correspond to the built forms currently found on site. Bottom: Reference areas with different degrees of urbanisation defined by Berghauser Pont and Haupt (2004, p.76-77) are superimposed on the top diagram.

According to Berhauser Pont and Haupt (2004, p. 59), it is this open space ratio [OSR] and the pressure on the non-built space that determines the degree of urbanisation in an area. In other words, we can argue that the urban model of Cité Ouvrière has gradually shifted from a garden city ($OSR > 0.6$ and $L = 2-10$) to a more urban ($GSI > 0.2$, $OSR > 0.4$ and $L > 3$) and in cases, to a highly urban area ($OSR < 0.5$). Implications of this urbanisation process were also observed in the increase and diversification of the volume geometry, which led a large number of identical houses to end up looking fairly different from each other (Figure 4). This was the result of an indefinite combination of different types of changes per house. So, despite the apparent standardisation of built forms and subsequently building regulations and planning policies at the neighbourhood level, a variety of formal and typological outcomes have emerged as a result of the spatial affordance of the original design at the level of the individual block-plot compound.

6. CONCLUSION

This paper looked at the physical adaptations of the street network, buildings and plots in Cité Ouvrière, a nineteenth-century mass factory housing from 1853 till now. It adopted a morphospacial methodological approach, which studied adaptability as an evolutionary process in time and at different scales. The aim was twofold: to describe the evolution of the urban form (streets, buildings and plots), and understand adaptability as a matter of density.

One main conclusion is that depending on whether mass housing is defined as the sum of its parts –buildings and plots– or by its position in the city –street network–, the definition of adaptability changes. On the one hand, for the street network, adaptability is defined as the ability of the system to withstand and endure changes. Over time, its configurational performance has been enhanced by adaptations that took place in its immediate surroundings. In the context of Cité Ouvrière, adaptability at the street level was dependent on three factors: first, the internal morphology of local layout; second, the way the city expanded to encircle the area and third, the self-refining relation of the local grid to the city network. On the other hand, for the buildings and plots adaptability is defined as the capacity of the built form to accommodate effectively changes over time. In this low-rise mass housing the transformative aggregate effect of individual physical adaptations contributed to the transformations of a uniform garden city into a formally diverse and dense old city quarter.

Effectively, it can be argued that for low-income housing schemes physical adaptations can have positive effect on the performance of the built form, when certain morphological characteristics have been integrated in the original design: first, location of the scheme which allows adequate accessibility to plots; secondly, low built intensity which does not maximises plot coverage and third, provision of small plots with high ratio of non-built space in double adjacency. Evidence indicates that the surplus open space is a key enabler for individual building-plot compounds to accommodate future growth, and a precondition for densification.

Finally further research needs to follow to fully understand the relation of adaptability at the three levels: the street network, the buildings and the plots form the single perspective of form. Recently, Törmä et al (2017) argued that although morphological properties in the street network such as accessibility afford socio-economic changeability, there is no straightforward link between network configuration and physical changeability. We speculate that future explorations could link the characteristics of the street network with adaptations of buildings and plots by focusing on the properties of the interface.

ACKNOWLEDGEMENTS

The authors wish to thank Meta Berghauser Pont for her valuable comments on earliest stages of this study, and the generous provision of the Spacematrix model. Furthermore, the first author has been supported for this research by the Engineering and Physical Sciences Research Council in the form of a PhD studentship.

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