



Housing growth: impacts on density, space consumption and urban morphology

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ABSTRACT

How and why do houses densify over time? What is the impact of that growth and what kind of constraints affect their potential to change? This research explores built form change and densification, providing historical evidence from the incremental transformation of a 19th-century housing scheme, Cité Ouvrière, in Mulhouse, eastern France. This granular longitudinal morphological study uses historical planning applications and images to map the external volumetric transformations of 1253 single-family houses over a 165-year period. The research combines archival work with three-dimensional (3D) architectural modelling and an advanced density method to record, visualise, analyse and evaluate the densification process at the microlevel. Statistical computing traces the densification process and the Spacematrix tool analyses the impact on open space consumption for different building typologies and for the neighbourhood as a whole. The results highlight seven types of transformations, affected by seven drivers of physical change. Densification is manifested either through built intensification or plot union/subdivision, and its degree is determined by the extent to which non-built space is consumed. These depend on socioeconomic, legal and physical constraints imposed by the original design.

PRACTICE RELEVANCE

This work informs architects and planners how the design of houses together with non-formal constraints affect buildings' resilience and longevity and their capacity to accommodate growth over time. By tracing the successful transformation of a suburban settlement to a dense and morphologically diverse city quarter, the results support the slow and contained densification of existing housing through small changes—an approach which can benefit the sustainability and energy agendas of cities and settlements in Europe and abroad. This expands the current understanding of built density, advances our knowledge in the simulation and forecasting of dynamic change in the building stock, and contributes methodologically to the fields of urban morphology, geography and data computation.

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Large-scale urban housing, either low- or high-rise, has over the last centuries been a typical response to recurring housing shortages in cities around the globe. The 20th century saw a major paradigm shift, which started to attach importance to the role of design in urban housing and cities. Modernist architects introduced ideas about high-rise apartment blocks spaced widely in designated city zones (Mumford 2000). This functionalistic approach, which ‘effectively paralyzed research into other forms of housing’ (Frampton 1985: 270), continued until the 1970s, characterising now 60% of the total number of dwellings in Europe (Eurostat 2016). It also formed a ‘disurbanism’ of segregated morphologies (Panerai *et al.* 2004; Marshall 2009), giving mass housing a bad name. The controlled implosion of the Pruitt-Igoe housing estate in the US city of St. Louis in 1972 started a series of demolitions, which still continue to this day. This has currently led to the paradox that while there is an acute housing demand due to urban population growth, many existing housing estates are being demolished and only a small number of them receive major refurbishments annually.

Built environment professionals have argued in favour of the refurbishment of existing housing (Power 2010) and the preservation of its heritage (Esher 1981), proposing the densification of built forms and the diversification of a built programme in and around the housing estates (Jacobs 1961; Alexander 1966; Frampton 1985; Jenks 2000; Campkin 2013). Especially a ‘soft’ densification (Dunning *et al.* 2017) is considered to bring environmental and social advantages in terms of service provision, transport, public amenities and energy use, while preventing urban sprawl. In the UK, such a soft version was encouraged after 2008 when minor developments in small houses, such as extensions and outbuildings, were allowed to be constructed in single-dwelling plots without planning permission (Knight & Williams 2012).

Physical densification as a process requires time and relies on existing built forms that can effectively accommodate transformations over time. Particularly amid discussions on climate change and energy consumption, there is a fundamental need to understand what this process entails and the factors that affect the potential of houses to grow and densify.

The focus of the present paper is on the company town of Cité Ouvrière in the city of Mulhouse in eastern France and its unusual transformation from a planned working-class settlement to domestic vernacular as a result of its densification over the course of 165 years. Cité Ouvrière was built between 1853 and 1897 for the workers of the DMC textile factory in one of the most prominent industrial cities of Europe at the time. It was the largest and most successful realised employer-constructed housing scheme during the second half of the 19th century. It functioned as an example for other settlements in Europe and abroad due to its innovations that included social benefits and a subsidised access to property for workers.

Upon its completion, a series of small-scale building extensions and plot modifications were made by the inhabitants and the local authorities piecemeal over the years. Unlike many other Western sites that declined or perished after de-industrialisation, Cité Ouvrière remained a fully functioning area, gradually densifying and diversifying its landscape to respond to the residents’ needs and the evolving socioeconomic conditions. This leads to a question being asked: How can the example of the Cité and its diachronic transformation help other cities in Europe and possibly elsewhere to understand the process of densification in the domestic building stock?

The remainder of the paper is structured as follows. Section 2 explains the methods and analysis. Section 3 describes the incremental densification of Cité Ouvrière and reports on the causes and agents involved in the process. Section 4 traces this process over time. Section 5 evaluates the degree of volumetric growth and measures its impact on the built density for both individual houses and the neighbourhood as a whole. Section 6 offers conclusions in response to how and why buildings change and extend over time, what is the impact of individual changes and how to measure it, and what kind of constraints affect the potential of buildings to grow and densify.

2. METHODS

This research integrates techniques of architectural and geographical information system (GIS) mapping with statistical computing and the density method of Spacematrix (Berghauser Pont & Haupt 2004) from the field of quantitative urban morphology. The method is applied to a three-dimensional (3D) digital model that features all 1253 single-family houses in Cité Ouvrière, including details of all external volumetric changes made to the houses in two chronological stages (original and current). The work also relies on archival data from historical building permits found in the municipal archives for a representative sample of 520 houses, which allows one to trace housing growth for the period between 1897 and 2018.

2.1. SPACEMATRIX: A DENSITY METHOD

Before conceiving Spacematrix, Berghauser Pont & Haupt (2009) reviewed all the density measures that existed throughout history, such as population and dwelling density, land-use intensity, coverage, building height and spaciousness, and demonstrated that none of these measures was sufficient in isolation to explain the urban form in terms of size, configuration or scale.¹ They argued that while the conventional density measurements alone can only hint at certain qualities of the urban form, their combination within the Spacematrix model is capable of relating density measures to the typo-morphology of urban blocks and their transformations through time.

Spacematrix is a multidimensional model that investigates the relationship between built form and density through the combination of four morphological variables (**Figure 1**):

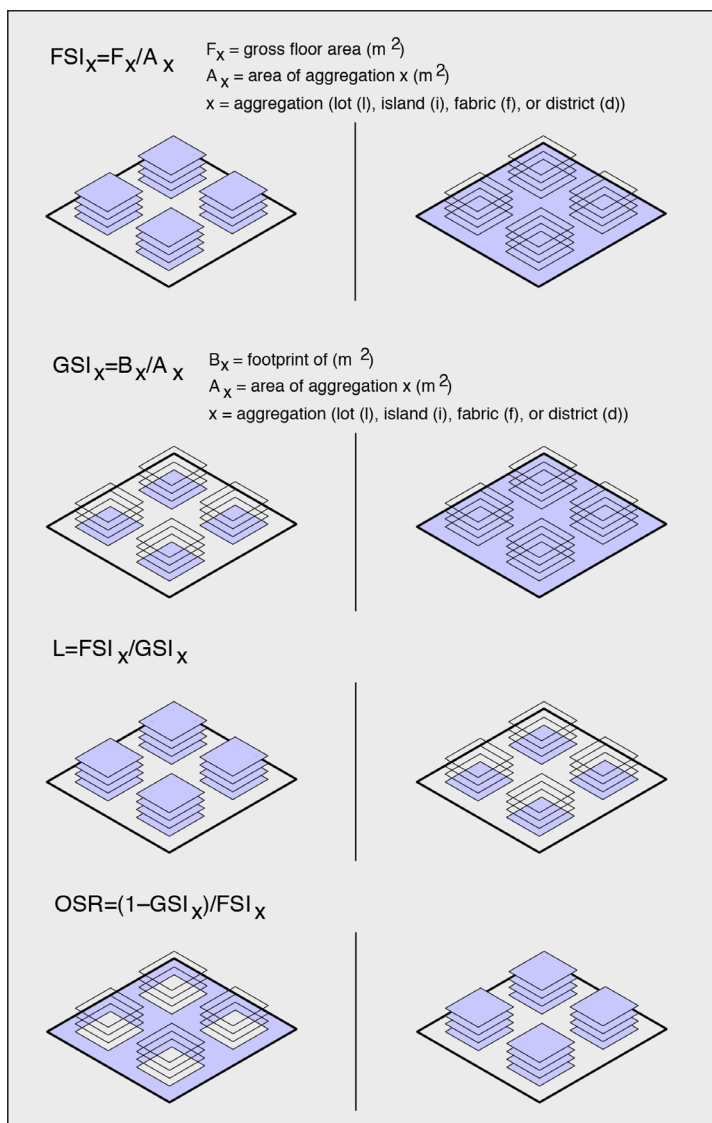


Figure 1: Morphological variables used in Spacematrix model.

Source: Berghauser Pont & Haupt (2009: 95–96) and edited by the author.

- *ground space index* (GSI), which indicates the built compactness or ground coverage of the plan area
- *floor space index* (FSI), which describes the built intensity of the plan area
- average number of storeys or *layers* (L)
- *open space ratio* (OSR), which accounts for the spaciousness or pressure on the non-built space

The formula is applied at the plan area of building-plot compounds and the four variables are combined in a *Spacemate* chart (**Figure 2**)—diagram FSI(GSI)—which gives every building-plot compound a unique spatial ‘fingerprint’ that is a dot in the chart (Berghauser Pont & Haupt 2004: 30).²

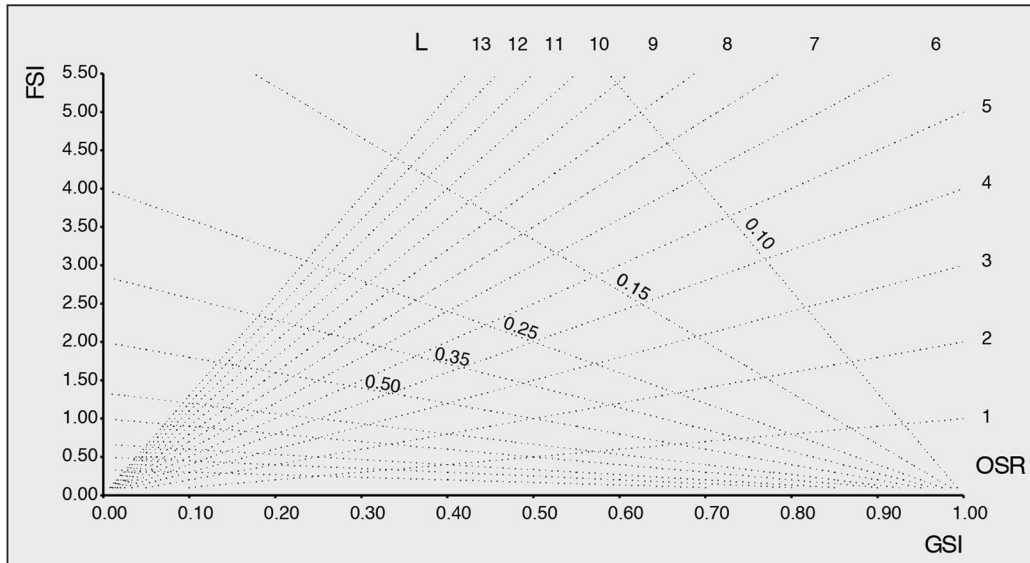


Figure 2: Spacemate or diagram FSI(GSI) as designed by Berghauser Pont & Haupt (2010) and computed for the first time in R-Studio software by the author.

This method is adapted to represent mathematically and graphically the impact of built form growth on built density and open-space consumption, while transitioning from Cité’s original to its current state. The same modelling space is used to trace the evolution of the entire scheme as a whole, the evolution of four different housing typologies—terraced (T), back-to-back (BtB), semi-detached (SD) and quarter-detached (QD) houses—and the effect of the observed types of transformations independently of each other. The evaluation is achieved not only visually but also numerically in a reproducible and systematic manner and helps to simulate past and present patterns of building growth to predict possible densification in the future.

2.2. 3D DIACHRONIC MODELLING

The method is applied to two detailed 3D digital models of the Cité Ouvrière (**Figure 3**): one in its original (c.1897) and one in its current (c.2018) state. The diachronic modelling process is as follows. The current building and plot geometries provided by the cadastre are imported in Rhino and a 3D model of the original scheme is constructed based on the drawings of the housing typologies found in the catalogue of the Exposition Universelle of 1889 (Müller & Cacheux 1889b) and on other historical studies such as that conducted by sociologist Jonas (2003). The model contains 1253 building-plot geometries and information on their exact dimensions, configuration and volumetric details. This first model serves as a basis to build the second one, representing the current situation, by adding volumes to (or subtracting them from) the exterior of original buildings following contemporary cadastral outlines in GIS and heights estimated from 3D Google View.³

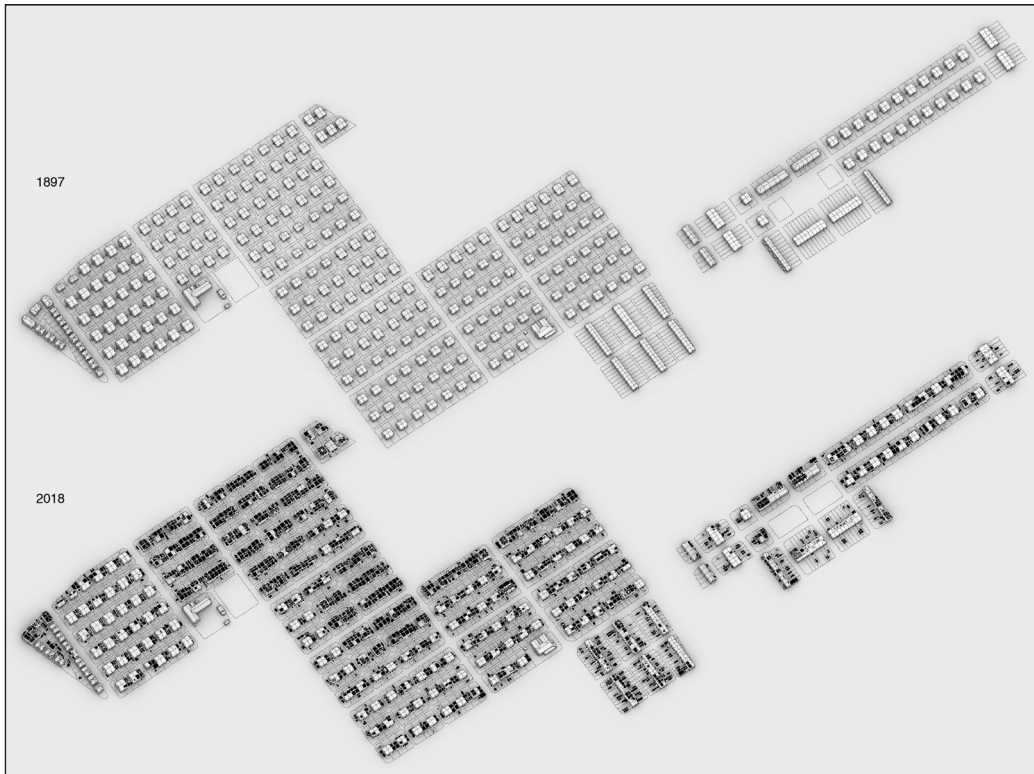


Figure 3: Three-dimensional model of the entire Cité Ouvrière in 1897 and 2018.

Figure 4 makes evident the striking difference between the original and the densified housing; the deficit of the available public and large-scale data to capture the actual built form at the micro-level; and the need to create the 3D diachronic dataset that carries detailed information at two chronological dates. Due to the size of the area, the models are laborious to produce and extensive in volume; yet, they combine the accuracy of small data with the extent of larger spatial data, overcoming a recurring problem of highly aggregate 3D stock models that smooth out fine-grained details. They also help to evaluate the impact on built density in a statistically sound manner.



Figure 4: Four representations of the same part of Cité Ouvrière: (a) the initial model which can be generated from large-scale height data obtained by photogrammetry by the Institut National de l'Information Géographique et Forestière (IGN); (b) the Google 3D view of the same area; (c) the first 3D model created for the scheme in 1897; and (d) the second 3D model integrating the original built volumes and their subsequent densifications (highlighted in black).

3. CITÉ OUVRIÈRE: THE CHRONICLE OF GROWTH

3.1. THE RISE AND DEMISE OF BUILT FORMS

The construction of Cité Ouvrière lasted for 44 years (**Figure 5**). During the first development (1853–55), the private association of Société Mulhousienne des Cités Ouvrières (SOMCO) and the architect Emile Müller constructed a total of 200 houses over five hectares, featuring terraced (T) and back-to-back houses (BtB) inspired by the British, and two-storey quarter-detached houses⁴ (QD1) on squared parcels, an invention of the architect called *carré Mulhousien*. The second development towards the west (1855–70) included 692 houses over 40 hectares and the one-storey quarter-detached houses (QD2) appeared. A mid-period (1871–86) also launched 190 new houses, mainly QD. The final phase (1887–97) saw the last 171 houses being built, during which another British type, the semi-detached (SD), was introduced.

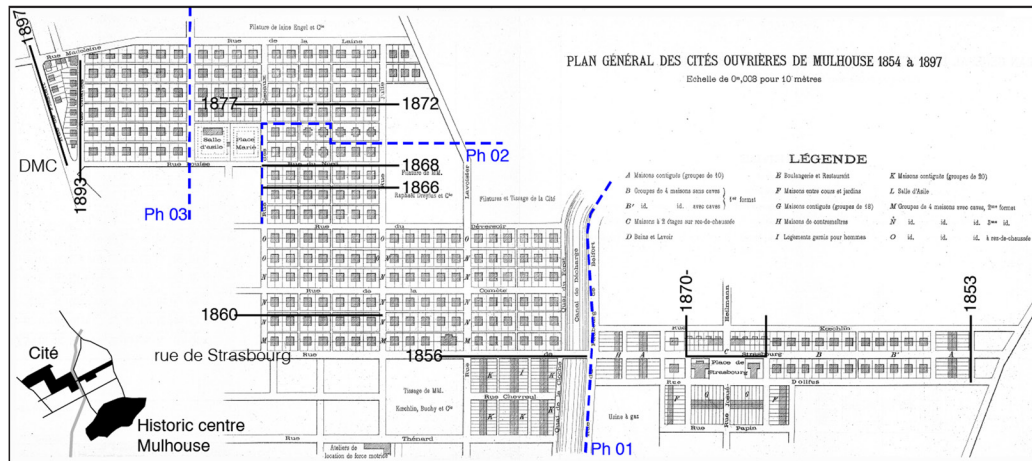


Figure 5: Realised plan of Cité Ouvrière with indications of the progression of construction (black lines) and the development phases (blue dashed lines).

Source: Archives de Mulhouse and edited by the author.

Already during construction some building types proved to be more successful than others. The terraces were quickly abandoned after the first phase. While they offered cross-ventilated and generous interior spaces, they were expensive and could not be afforded by low-paid employees (Jonas 2003). The BtB were the cheapest and smallest of all types. While SOMCO favoured their construction because of their thermal insulation properties and reduced purchase price, Müller & Cacheux (1889a) were not convinced about their size and poor performance in terms of ventilation, light, sanitation and privacy; so their production was ceased after the second phase.

Meanwhile, due to financial struggles and market competition, the association and the architect decided to reduce the variety of typologies and construct smaller houses. In the second *cité*, the BtB and QD were downsized in floor area and height, reaching a minimum of 36 m² for the BtB and 30 m² for the one-storey QD2. These types created cramped living conditions and were soon abandoned.

After that, the QD typology dominated the scheme due to its low price and the economy of its layout, leaving two continuous facades free and offering access to front and side gardens and the street. The only problem was that it was too demanding in terms of street area and frontage, facility and maintenance fees (Müller & Cacheux 1889a)—which may explain why this typology did not generally survive.

The delivery of the project ushered in a new ‘development’ period of major extensions and modifications that was not planned by SOMCO or the municipality. While the industrialists anticipated that smaller houses would receive extensive alterations, they considered the result an ‘aesthetic of the poor’ and ‘disgraceful’ (de Lacroix 1901: 447) for rupturing the uniform image of the scheme. Unable to prevent it, they built bigger QD (72–97 m²) and SD (92–139 m²) houses in the third period for affluent workers, who could sublet parts of the house to generate an income.

3.2. HOUSING GROWTH BETWEEN 1897 AND 2018

A comparison between the original and the current development of the Cité (**Figure 6** and **Table 1**) demonstrates an 82% increase in the ground coverage within 120 years (from 24% to 44%). Meanwhile, the 3D model counts a total of 3477 volumes added to the original 1253 houses and an increase of 68% in the built volume.

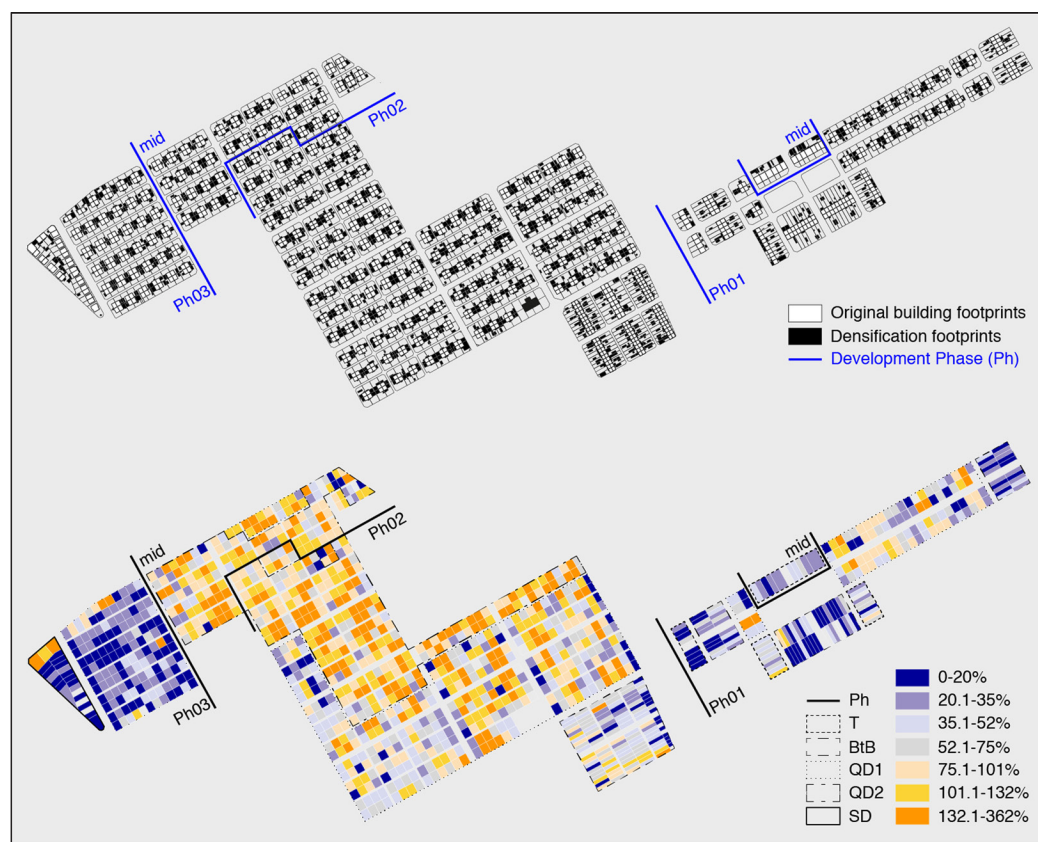


Figure 6: (top) Figure ground plan of Cité Ouvrière; and (bottom) percentage change of volume per original plot. Intervals are specified in quantiles.

PHASE	TYPE	N	FOOTPRINT AREA (M ²), OR/CR	FOOTPRINT AREA (±%)	GSI (%), OR/CR	GSI (±%)	VOLUME (M ³), OR/CR	VOLUME (±%)
1 (1853–55)	T	28	46/85	+85	26/48	+85	369/545	+48
	BtB	76	39/62	+59	24/37	+54	274/366	+34
	QD1	96	41/73	+78	24/44	+83	329/542	+65
	Average		41/71	+73	24/41	+70	314/477	+52
2 (1856–70)	BtB	114	28/56	+100	25/45	+80	193/320	+66
	QD1	356	34/69	+103	19/42	+121	274/466	+70
	QD2	222	41/81	+98	25/47	+88	238/544	+129
	Average		35/71	+103	22/44	+100	249/466	+87
2.5 (1871–86)	QD1	38	41/83	+102	26/44	+69	224/595	+166
	QD2	142	44/76	+73	28/46	+64	241/483	+100
	T	10	104/157	+51	36/55	+53	1071/1410	+32
	Average		47/82	+74	28/47	+68	282/552	+96
3 (1887–97)	QD1	144	45/74	+64	28/46	+64	389/495	+27
	SD	27	65/82	+26	33/47	+42	545/713	+31
	Average		49/75	+53	29/46	+59	414/530	+28
Total	Average		40/73	+83	24/44	+83	287/489	+70

Table 1 Descriptive statistics of housing growth based on the three-dimensional model

Note: N = number of houses; OR = original state; CR = current state; GSI = ground site coverage; T = terraced; BtB = back-to-back houses; QD1 = two-storey quarter-detached houses; QD2 = one-storey quarter-detached houses; SD = semi-detached houses.

By examining the data closely, the following main observations can be made. All houses have been densified, but they have done so in different degrees. The smaller houses of the second and mid-periods are those that exhibit the greatest growth, while the larger houses of the third period have only undergone a minor areal and volumetric increase, partly because they did not have so much pressure to do so. This means that densification relates to the size of the original house, thus arguing that the smaller the houses, the greater the potential and need for subsequent adaptations and, design permitting, the greater their tendency for volumetric growth.

The row typologies have mainly afforded changes on the ground level. This is the case for T houses from the first *cité* and the BtB houses of the second phase. Although they accommodate several adaptations per plot, their volumetric increase is minor. For these types, it is easier to extend horizontally than vertically, given the available open space on the plot. The BtB houses are located on plots 23 m deep × 5 m wide, while the T houses are on 30 m × 6 m plots, leaving around 100–140 m² of land available to occupy between the building and the street.

The QD houses have afforded greater physical growth over time than the British typologies BtB, T and SD. Especially, those from the second and mid-period have doubled, affording at some instances an excess part of more than twice the size of the original building.

3.3. CAUSES OF CHANGE

As mentioned above, one major driver of change was the small size of the original houses. After the survey of 1867, the industrialists and the architect realised the inhabitants' need to add new spaces and convert existing spaces (e.g. stores and attics) to accommodate enlarged family structures.

A second reason was household finances. The pressure of paying off the mortgage loan debt meant homeowners needed to generate a source of income by renting out a room (or a flat) or opening a small business. This led to architectural embellishments of gables and annexes (Jonas 2003: 239).

The archival research of the historical building permits shed a light on additional causes for change, also identified by previous scholars (Boudon 1972; Whitehand & Carr 2001; Steadman 2014). The main ones were: physical damage or poor maintenance; infrastructural developments such as the installation of sewage and drainage networks; technological advancements such as the introduction of cars; changes in the use of the building or part of it; the conservation or individualisation of the architecture and its aesthetic aspect including passing fashions; and the reproduction of formal solutions through copying—the 'neighbour effect' (Whitehand & Carr 2001: 167).

3.4. AGENTS OF CHANGE

The research found that the main agents involved in housing growth were the inhabitants, the architect, SOMCO and the local authorities. The last two were responsible for shaping the original plan of the scheme, securing land, providing public infrastructure, and introducing an innovative financial model and a new building typology. The municipality also had to implement and update the building regulations, which in some cases were only formally enacted after the submission of the applications, mainly because that degree of growth was never really anticipated. Archival research also showed that, within this legal frame, there was considerable room for interpretation by the authorities. Regulations were customised or revised on a case-by-case basis, and to this day change if and when needed in response to the demands and needs of the residents, the local culture and the architectural image of the *Cité*.

Furthermore, the original design by Müller had a major influence on the potential of houses to grow and densify. The selected building types and plots, their shapes and sizes, and the configuration of buildings within the plots and in relation to the street imposed geometrical and formal constraints that allowed certain possibilities to occur while inhibiting others. One example is the narrow and deep plots of row houses which encouraged extensions on the front of the site. The squared plots of QD houses allowed for side extensions and accessibility from multiple points, *i.e.* diagonally. The surplus open space in the original design proved to be a key enabler and a precondition for densification. Low-rise buildings could be extended vertically by raising additional floors, while generous front gardens—initially for the cultivation of vegetables—left considerable space for the erection of annexes, workshops and garages.

The last agents were the inhabitants, especially those who accessed ownership and took an interest in investing time, money and resources into the transformation of their houses over time. Their agency was mainly affected by the internal logic of households, namely the relations, growth, shrinkage and migration of their families, the integration of micro-businesses in the same premises, and land ownership changes. Through their close involvement in the process, the inhabitants shifted:

from being ‘passive consumers’ of housing goods and services to ‘active participants’ in the aging of their homes and neighborhood. (Kostourou 2019: 92)

extending the longevity of their houses for more than 160 years.

3.5. TYPES OF CHANGE

Eight types of changes that affect built density and open space consumption were observed (Figure 7) (Kostourou & Psarra 2017):

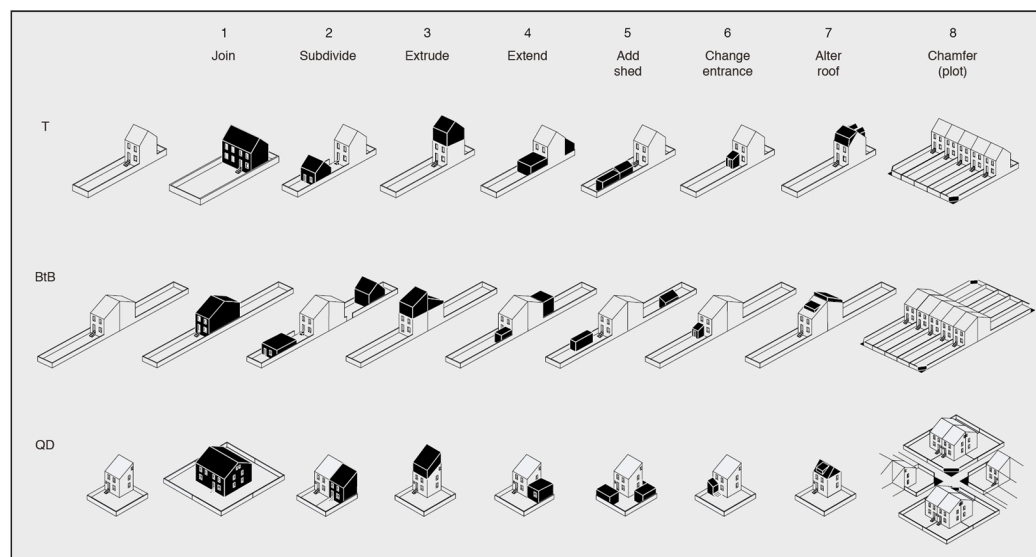


Figure 7: Formal operations of the three main building types in Cité Ouvrière.

1. *Join*: when one or more houses are joined together to form a larger unit. This created typological mutations: QD houses turned into SD, T or BtB; SD to T; and BtB to T types.
2. *Subdivide*: when inhabitants and owners rent out or sell part of the house or land. This was common for the squared plots of the QD types because their lengthwise or frontage division allowed subdivided plots to maintain street access.
3. *Extrude*: when one or more storeys are added.
4. *Extend*: when horizontal extensions take place at the ground level either through the addition of habitable rooms with interior connection or the elongation of existing ones. The direction of extension was defined by the building-plot configuration and the regulations, namely the building line, the distance from neighbouring property and the setback zone from the street.
5. *Add shed*: the creation of detached annexes within the plots, e.g. garages, *gloriettes* (garden houses), shacks for domestic activities such as storage and laundry, and outhouses for non-domestic uses (22 recorded uses including workshops, shops and livestock farms). Annexes have always been subject to several regulations prescribing the building line, setback zone, accessibility, dimensions, and distance from the main building, the street and the neighbouring limits.
6. *Change entrance*: when covered extensions adjoin the house entrances. They were enforced by the laying of sewage and drainage pipe networks in the 1910s and 1920s, during which lavatories became attached to the houses in the form of entrance porches.

7. *Alter roof*: various transformations of the roof structure, e.g. changes of inclination, construction of dormer windows and skylights, roof rotations and divisions. Mansard and gable roofs maximised headroom and allowed the attic to be used as a bedroom.
8. *Chamfer the plot*: the creation of bevelled edges for corner plots improved visibility at the crossroads, enlarged previously narrow streets and facilitated the circulation of the cars.

4. MAPPING GROWTH

4.1. TRACING MORPHOLOGICAL TRAJECTORIES

To demonstrate the sequence of transformations, the example of one statistical block (*îlot*) of the second period featuring three street blocks, 16 QD1 houses and 12 QD2 houses is visually recorded based on historical building permits found in the local archives (**Figure 8**). While not all events can be described here, their succession reveals the following:

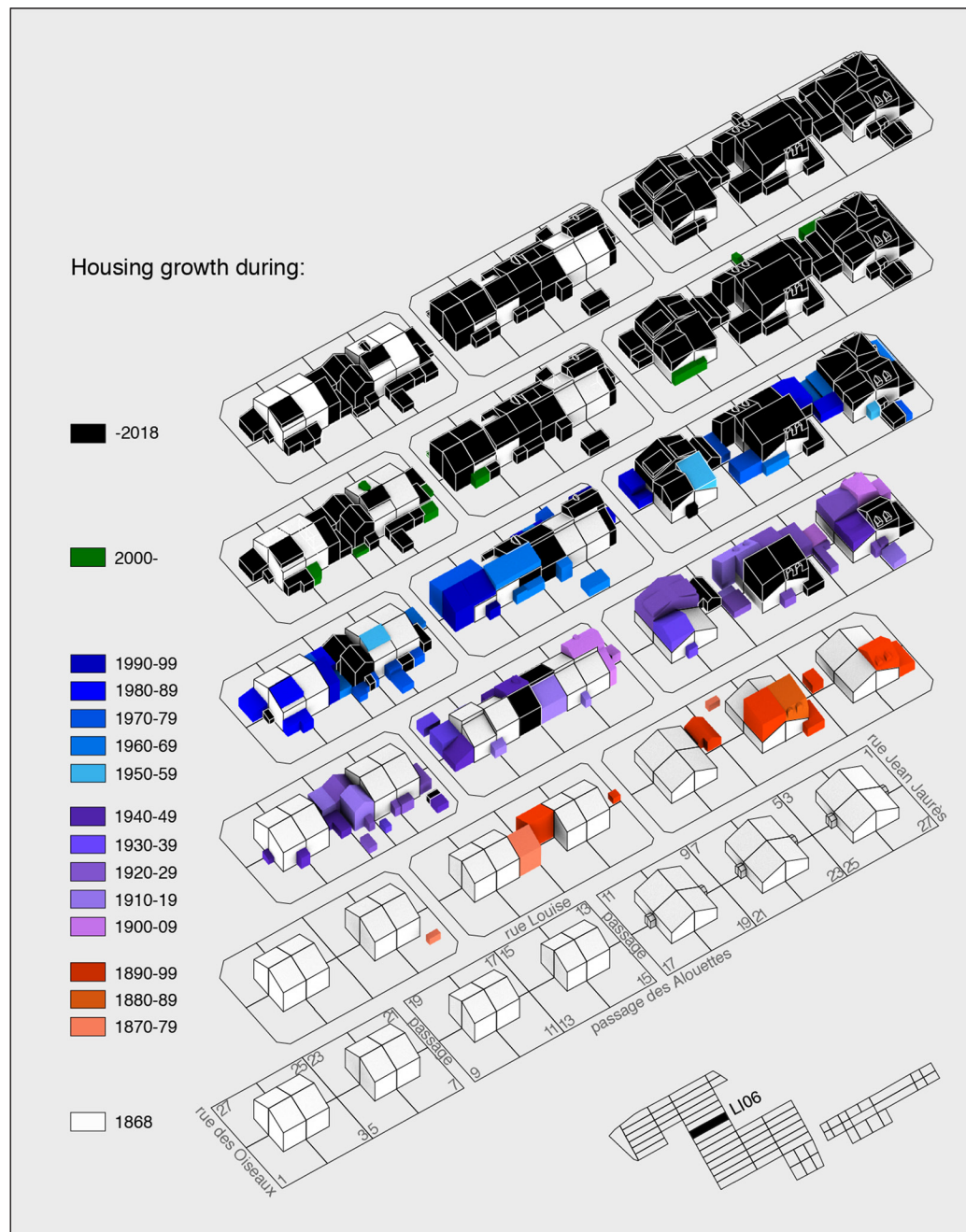


Figure 8: Housing growth of 28 quarter-detached (QD) houses from 1868 to 2018 (150 years).

After the completion of the houses (period 1870–99), the residents started to transform them, mainly the QD2 types. Four properties were amalgamated, while the larger QD1 types grew significantly with extensions on the side.

The next 50 years (1900–49) were the most prolific. First, entrance porches appeared in front of the houses; small in size at first (c.1914) and bigger later (c.1922–23). Furthermore, almost all the QD1 houses in the middle doubled their ground coverage through house extensions, and all but one of the small QD2 houses grew vertically by adding floors and changing their roofs. One land parcel split to two and an independent building was erected. Last, all the corner plots were chamfered after the turn of century. It was in 1946 that the first garage appeared in this block.

The following decades (1950–99) saw the consolidation of the housing growth process. The main operation was the accommodation of parking spaces either as independent structures in the gardens mainly during the 1960s and 1970s or as extensions of the principal buildings (semi-buried), which became popular in the 1970s and 1980s. Besides this, vertical additions of the already extended QD1 types and horizontal extensions of the already extruded QD2 types were observed. This implies that the two-storey houses extended first horizontally then vertically, whereas the shorter ones did the opposite.

In the last period (2000–18), very few volumetric changes took place; instead, there were significant ownership changes, which historically coincides with the large influx of immigrants into the neighbourhood. Three property sales were found in the archives.

4.2. QUANTIFYING THE ARCHIVAL DATA

Table 2 summarises the findings of the archival research for the representative sample of 520 houses in 27 *ilots* and a total of 46 street blocks (**Figure 9**).

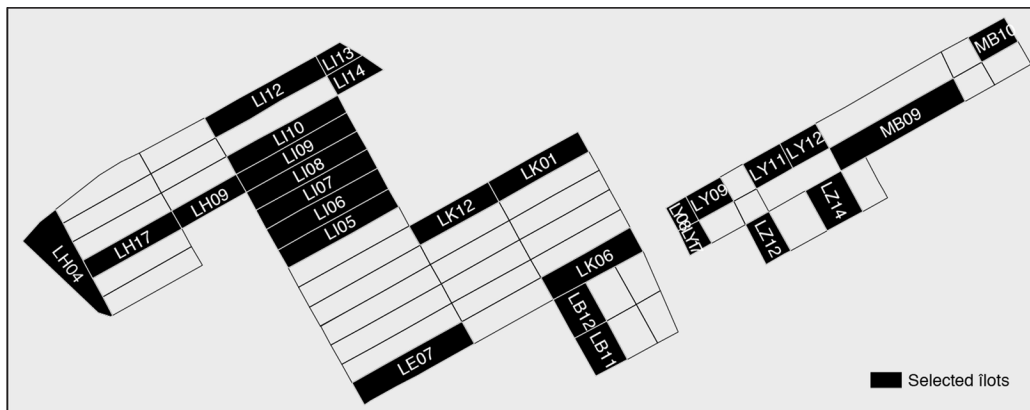


Figure 9: Representative sample of archival research, 27 selected *ilots* and 520 houses.

The most prevalent types of change across all cases are horizontal extensions (operation No. 4 or [04]), installations of sheds [05] owing to the availability of plot land, and changes in the entrance [06], often expressed as additions of entrance porches.

The highest number of physical changes is observed in the QD houses, especially in those of the second and mid-development phases. A total of 14 out of the 16 QD blocks feature on average four changes per house. The exceptions are the LI13 and LI14 truncated blocks on the north side of the scheme and the LH17 and MB09 blocks, despite their houses having 36 years of difference on average. The houses of LH17 were originally built much larger, so there was less pressure to make changes, while the houses of MB09 were intended for occupation by the poorer workers with the least means to afford changes. In any case, the QD typologies have sustained all types of formal operations, but plot subdivisions [02] are only encountered in seven of the 16 *ilots*.

A discrepancy in the degree of transformation is observed between the BtB houses of the first (LY09, LZ14 and MB10) and the second periods (LB12 and LB11): a difference of 1.7 physical changes per house in favour of the latter. One possible reason is the reduction of the dwellings' physical dimensions. The building depth decreased from 6.7 to 4.7 m and the frontage width

Table 2 Descriptive statistics for 27 statistical blocks (*ilots*), including the construction phase, average house age, building typology, number of houses per block, number of volumetric changes per block including demolitions, number of changes per house normalised for 100 years and averaged per type and phase, types of changes that did not occur (missing changes), frequent types of changes (prevalent changes), number of owners, number of owners per house and 100 years and averaged per type and phase, and number of years per owner per house

Notes: Numbers in the columns ‘Average changes’ and ‘Average owners’ are normalised by the average house age and multiplied by 100 for clarity.

Measurements in changes in ownership rely on the family names of applicants (and owners) for each address. Their numbers should only be treated as proxies rather than as precise data because they were retrieved from the building permit applications, meaning that if owners did not wish or were not able to make changes or made them informally, their proprietorship was not recorded.

ILOTS	PHASE	AGE	TYPE	HOUSES	CHANGES	AVERAGE CHANGES		MISSING CHANGES	PREVALENT CHANGES	OWNERS	AVERAGE OWNERS		AVERAGE YEARS
							/TYPE					/TYPE	
LH04	3	105	SD	27	61	2.2	2.2	6;8	5;7	55	1.9	1.9	38
LH17	3	110	QD	24	83	3.1	3.1	1;2	5;4	63	2.4	2.4	39
LH09	2.5	123	QD	16	87	4.4	4	–	4;5;6	46	2.3	1.9	39
LI12	2.5	124	QD	28	153	4.4		2	4;5;6	72	2.1		32
LI13	2.5	125	QD	8	34	3.3		2	5;6	15	1.5		47
LI14	2.5	126	QD	12	49	3.2		2	5;4	24	1.6		37
LI10	2/2.5	127	QD	28	164	4.6		2	4;5	74	2.1		35
LI09	2	128	QD	28	143	4	4.3	2	4;5	79	2.2	2.2	33
LI08	2	129	QD	28	157	4.3		–	4;5	82	2.3		38
LI07	2	131	QD	28	164	4.5		–	4;5	87	2.4		29
LI06	2	133	QD	28	177	4.8		–	4;5	93	2.5		34
LI05	2	134	QD	28	143	3.8		–	4;5	82	2.2		37
LE07	2	141	QD	28	158	4		–	4;6;5	92	2.3		30
LK12	2	142	QD	20	117	4.1		–	4;5	67	2.4		32
LK01	2	142	QD	24	142	4.2		–	4;5	53	1.6		35
LK06	2	143	QD	24	160	4.7		–	4;5	76	2.2		31
LB12	2	144	BtB	20	100	3.5	4	1;2	6;4;5	55	1.9	2.2	32
LB11	2	144	BtB	20	128	4.4		2	6;4;5	70	2.4		28
LY11	2	130	T	5	28	4.3	4	2;6;8	5	12	1.8	2.2	47
LY12	2	130	T	5	24	3.7		1;2;3	5	16	2.5		36
LY08	1	145	T	4	12	2.1	2.2	1;2;3;7;8	5	7	1.2	1.6	66
LY17	1	145	T	4	8	1.4		1;2;3;8	5	9	1.6		53
LZ12	1	146	T	10	45	3.1		1;2	5;4	28	1.9		36
LY09	1	145	BtB	10	41	2.8	2.3	1;2	5	38	2.6	2.1	28
LZ14	1	146	BtB	17	42	1.7		3	5	49	2		35
MB10	1	147	BtB	10	37	2.5		–	5	25	1.7		38
MB09	1	146	QD	36	142	2.7	2.7	2	5;4	108	2.1	2.1	35

shrank from 5.6 to 5.4 m (on average), which, as Brown & Steadman (1991) have found, increase the need for extensions to provide for extra living space.

The three blocks of the first *cité* containing T houses (LY08, LY17 and LZ12) demonstrate a low ratio of changes. These types were seen as market failures by SOMCO because they were expensive to build and sell, and their (re)production ceased after 1855. In contrast, the T houses completed after 1870 (LY11 and LY12) feature a high average of four changes per house, equalling that of the smaller QD2 houses.

Both the SD (LH04) and T houses of LY11, LY08 and LY17 have fewer changes in the entrance [06], amalgamations [01], subdivisions [02] and chamfers of plots [08] because they were built very close to or exactly at the plot edge.

There is little variation in the average number of owners per house, from a lowest of 1.2 to a highest of 2.6. Particularly, the QD and BtB houses as well as the T houses of the second period demonstrate the highest ratio of owners per house—more than 2.1—with the truncated LI13 and LI14 blocks being once again the outliers of this trend. Meanwhile, the terraces of the first *cité* seem to have changed the fewest hands.

The majority of the blocks with a high ratio of owners demonstrate a high ratio of physical changes independent of the period of ownership. Nine out of the 13 blocks with the highest ratio of adaptations (above 4) have an average of more than 2.2 owners per house. Evidence for the reverse appears to have a substance as well, meaning blocks with fewer changes had fewer owners. Thus, the assumption that the inhabitants who reside longer in their houses are more likely to have materialised more changes over time cannot be supported. A possible reason is the socio-demographics, notably as the houses age and residents tend to stay put, their average age rises too. Mature households are less likely to instigate changes.

5. MEASURING GROWTH

5.1. OPEN SPACE VOLUME (OSV) AND AFFORDANCE (A_{bp})

To measure growth, this work computes the degree of *affordance* of building-plot compounds in receiving further densification in the future.⁵ It introduces the concept of *open space volume* (OSV), defined as the volumetric difference between the volume of the maximum bounding box or polyhedron (V_{bb}) that can be afforded in a plot according to the applicable building regulations,⁶ and the volume of the actual building (V_b) (**Figure 10**). Affordance (A_{bp}) then equals to the ratio of the actual OSV to the theoretical V_{bb} :

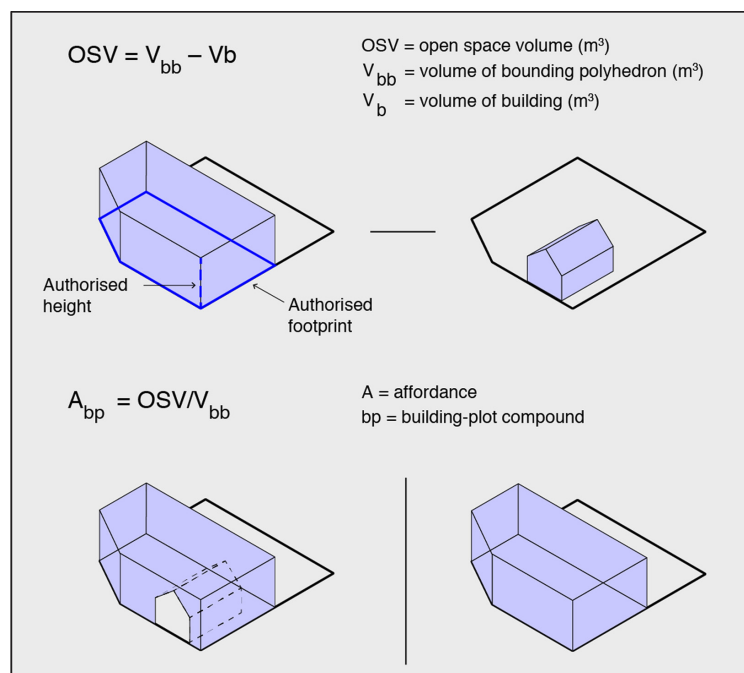


Figure 10: Variables of open space volume (OSV) and affordance (A_{bp}) in building-plot compounds.

$$A_{bp} = \frac{OSV}{V_{bb}}$$

where OSV is the open space volume and V_{bb} is the volume of the authorised bounding polyhedron. In a perfectly rectangular plot, the bounding polyhedron is a cuboid bounding box.

OSV describes the three-dimensional non-built space of a plot that could be potentially built in the future. Before any construction, OSV equals V_{bb} and the site is entirely available for construction. When a building is erected and as it grows larger, OSV decreases. A_{bp} represents the potential of building growth in relation to the open space of the plot, i.e. how much mass is dimensionally and topologically (theoretically) feasible to build within the available open space. Therefore, it is inversely proportional to the *actual* densification degree. A_{bp} ranges from 0 to 1, with 0 accounting for volumetric repletion with no space left for further expansion and 1 for complete absence of building. It is implied that if a house maximises its built volume ($V_b = V_{bb}$) right from the beginning, it minimises its potential to grow over time ($OSV, A_{bp} = 0$).

Table 3 summarises the calculations of the new variables for the original and current state of the houses in Cité Ouvrière. For these, local building regulations for a UP3 zone of architectural heritage are taken into consideration. The authorised maximum footprint area is 60% of the plot area and the maximum permitted height is 11 m, unless this has already been exceeded due to past operations, in which case the new height is kept. Note that the T houses of the mid-period were built as an R+2+C type (ground floor plus two floors and attic) with a limitation of 12.5 m height.

Table 3 Summary of the calculations for the proposed variables for each development phase of the original (OR) and current (CR) schemes

Notes: V_b = summary of building volume; V_{bb} = volume of bounding polyhedron; OSV = open space volume; A_{bp} = affordance and ($\pm\%$) percentage of change of A_{bp} or of consumption of open space per building type; T = terraced houses; BtB = back-to-back houses; QD1 = two-storey quarter-detached houses; QD2 = one-storey quarter-detached houses; and SD = semi-detached houses.

PHASE	TYPE	N	BUILDING VOLUME (V_b) (M ³)		BOUNDING BOX VOLUME (V_{bb}) (M ³)		OPEN SPACE VOLUME (OSV) (M ³)		AFFORDANCE (A_{bp})		±%
			OR	CR	OR	CR	OR	CR	OR	CR	
1 (1853–55)	T	28	369	545	1171	1253	802	708	0.68	0.56	–18
	BtB	76	274	366	1076	1127	801	761	0.74	0.68	–9
	QD1	96	329	542	1136	1138	808	597	0.71	0.52	–27
	Average		314	477	1118	1140	805	662	0.72	0.58	–2
2 and 2.5 (1856–86)	BtB	114	193	314	797	851	604	536	0.73	0.62	–16
	QD1	394	273	494	1146	1128	873	634	0.76	0.56	–26
	QD2	364	236	448	1092	1055	856	607	0.78	0.57	–27
	T	10	1071	1410	2261	2323	1190	913	0.51	0.37	–27
	Average		256	484	1088	1095	831	611	0.76	0.56	–27
3 (1887–97)	QD1	144	389	495	1067	1078	679	583	0.63	0.54	–15
	SD	27	545	713	1417	1196	872	520	0.58	0.42	–27
	Average		414	530	1124	1087	710	557	0.62	0.51	–18

Overall, the houses of the first *cité* occupied originally 28% of the three-dimensional permitted building space on average (V_b/V_{bb}), but the abandonment of certain typologies and the reduction of houses' size increased their affordance for subsequent growth to 0.76 (A_{bp}). Later, the large houses of the third period pushed the percentage up again to 36%.

Independent of their age, all building types have increased their V_b and decreased their OSV and A_{bp} . As the houses acquired extensions and additions, the three-dimensional spaciousness of their plots was consumed and their capacity to afford additional densification was reduced.

In some cases, V_{bb} has been amplified and in others reduced depending on changes to the existing plot area and maximum height. For instance, the QD houses (QD1 and QD2) of the second and mid-periods and the SD buildings present a decrease in V_{bb} due to the shrinkage of their original plots. In the case of SD houses, plots have been divided or reduced in area by an average of 18%. In QD2 houses, plots have shrunk, but extrusions have increased the building height above the legal threshold of 11 m.

Interestingly, the houses that have grown more, meaning the QD houses of the first, second and mid-periods and the BtB houses of the second period still feature an affordance percentage of more than 50%. This means that while they have already expanded significantly (consuming open space by 16–27%), it is very likely, given the current regulations, they will receive further densification in the future; QD houses currently display an affordance of 0.52–0.57 and BtB houses 0.62–0.68.

5.2. EFFECT OF GROWTH ON THE BUILT DENSITY

The impact of housing growth on the built density is now examined by applying the Spacematrix method to the aggregation area of individual building-plot compounds. The combination of the four morphological variables (FSI, GSI, L and OSR) used in the model helps reveal the pressure densification puts on the non-built space.

5.2.1. The effect of formal changes

To evaluate the effect of individual types of formal changes, the formulas are applied to a hypothetical building-plot compound with roughly the same dimensions as the original houses in the Cité (building footprint of 40 m², plot area of 166 m² and three floors). The calculations trace the extent to which each operation affects the original built form, and the results are mapped as dots on the Spacematrix chart (Figure 11). What is important to capture is the movement of dots, or trajectories of growth (blue lines), which demarcate the area of potential densification (blue hatch).

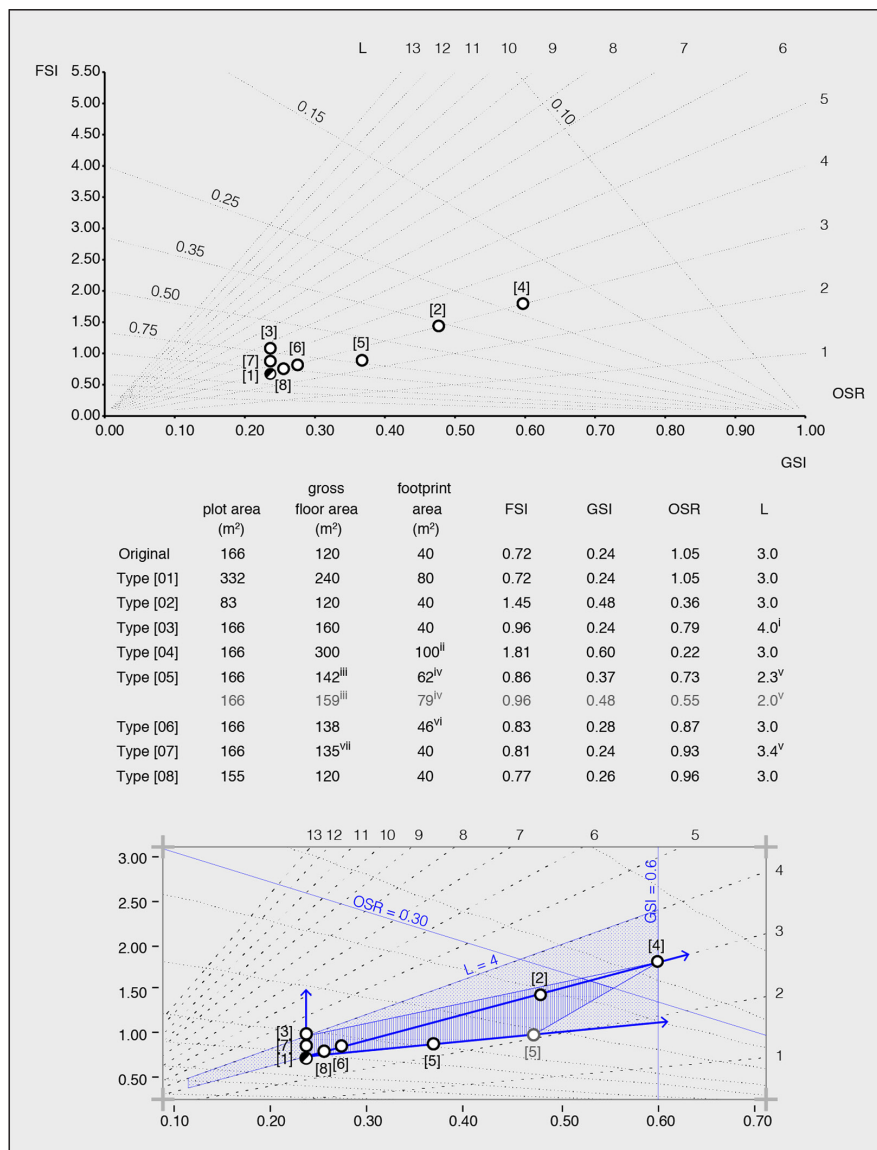


Figure 11: Spacematrix chart showing the transformation of density description for every type of formal change. Blue hatching indicates the Spacematrix area where dots can move and still comply with the applicable building regulations.

Notes: i, authorised maximum height = 11 m, which translates to maximum $L = 4$; ii, authorised maximum footprint = 60% of the plot area; iii, sheds are one-storey buildings; iv, authorised maximum area of the first shed = 22 m² and of the second shed (in grey) = 17 m²; v, L is calculated by FSI/GSI, but in reality the main building has still three floors⁷; vi, authorised maximum area of entrance porch = 6 m²; and vii, alterations of the roof make part of the floor area in the attic available (approximately 15 m²).

Source: Base diagram and formula by Berghauser Pont & Haupt (2010).

It can be observed the main tendency of the dots is to move upwards and to the right, suggesting that as the built space expands over time, it puts pressure on the non-built space. All formal operations apart from join [01] increase the FSI and GSI and decrease the OSR.

In the case of join [01], calculations double the original footprint and plot area, so the modified fingerprint coincides with that of the original building (filled half black half white). However, if the adjoining unit has the same built footprint but a larger plot area or has the same plot area but a smaller built footprint than the original one, then both the FSI and GSI decrease and the dot moves towards the origin of the diagram along the $L = 3$ line. Otherwise, the dot moves towards the right side of the chart. This behaviour indicates the reverse effect that plot and building growth have on density. With a fixed building footprint, an increase in the plot area decreases density and, vice versa, a growing building in a fixed plot size increases it.

Formal changes constrained by the building regulations in force (see [Figure 11](#) notes) affect the movement of the dots on the chart, and thus the effect on the built density. Extrusions [03] and roof alterations [07] lead to an increase in the number of storeys, and therefore their trajectory follows a vertical path parallel to y-axis, resulting in a rise of built intensity (FSI) without affecting the figure-ground plan. Due to height restrictions, though, their dots are crammed in the chart. In turn, changes [02], [04], [06] and [08] lead to an increase of the built intensity (FSI) and compactness (GSI), retaining the same height (L). Plot chamfers [08] and additions of entrance porches and verandas [06] shift the original dot slightly to the right along the $L = 3$ line, but do not cause a major displacement due to areal restrictions. Cut-off angles decrease the size of plots by only 2–10 m², while porches increase the footprint area by a maximum of 6 m². Plot divisions [02] and horizontal extensions [04] cause the larger transposition of the fingerprint, maximising the permitted GSI (0.6). This is the reverse effect mentioned above.

The only operation that slightly deviates from the two main trajectories of growth is change [05]. Outbuildings move the original spatial fingerprint to the right, affecting more the GSI rather than the FSI since they consume open space at the ground level. However, the dot does not stick to the same L line because the average height of the entire compound decreases. This behaviour does not fully represent what happens to the main building (which retains its L), but makes evident the impact of using building-plot compounds as aggregation areas in the analysis.

5.2.2. The effect of changes on building typologies

The same method is further used to describe the actual evolution of the four building typologies in Cité Ouvrière ([Figure 12](#)). The tool is applied separately to all the buildings falling under the same type at two discreet chronological dates: the original (graphically represented by diamonds) and the current (circles) state. Note that the original fingerprints vary in their location on the chart because despite the standardisation of the layout, individual blocks and plots have slightly different dimensions. The calculations are based on an approximation of L by dividing the height of the building by an average floor height of 2.7 m.

The first chart maps the evolution of terraces. The original GSI and FSI prove their low density, lingering between an average of 0.27 and 0.80 for houses built in the first *cité* (Phase 1) and 0.36 and 1.42 for the substantially larger houses (four levels) of the second phase (Phase 2). At the current stage, the density of the houses from the first period has almost doubled and that of the second period has increased by 70–80%. This hints at more compact building-plot compounds that pack more volumes in their original plot space. Indeed, the T types demonstrate an average of 4.36 operations of physical change per house, showing a preference for horizontal growth through sheds [05] and extensions [04] ([Figure 13](#)). Notably, one can detect few outliers, all of which are end plots whose significant clipping (5 m cutaway) has reduced the plot area.

The second diagram in [Figure 12](#) maps the evolution of BtB houses. Here the spatial fingerprints of the original houses concentrate along the $L = 2$ line, since the pitched angle of the attic, as it was designed, did not permit inhabitable space on the third level. The houses are substantially less dense than the T ones—GSI = 0.22–0.26 for the larger BtB of Phase 1—but as opposed to them, they have managed to grow more intensively over time, demonstrating a 70% steeper trajectory

path. Compounds from Phase 1 have well doubled their floor space, while buildings from Phase 2 have tripled it; yet, the increase in ground coverage is less significant. Even though BtB have received greater densification, their average number of formal operations is smaller than that of T houses (2.39). Practically, the narrow and elongated parcels with the limited street front and the buildings that are restricted from three sides have precluded those types from being densified in certain ways (Figure 13). It is characteristic that the most popular operations (221 in total) are extensions [04], entrance spaces [06] and sheds [05], all of which have taken place in the open space at the front of the houses, between the building and the street. The last remark concerns the outliers, which mainly depict the truncated plots of the second *cité* as a result of the street alignment.

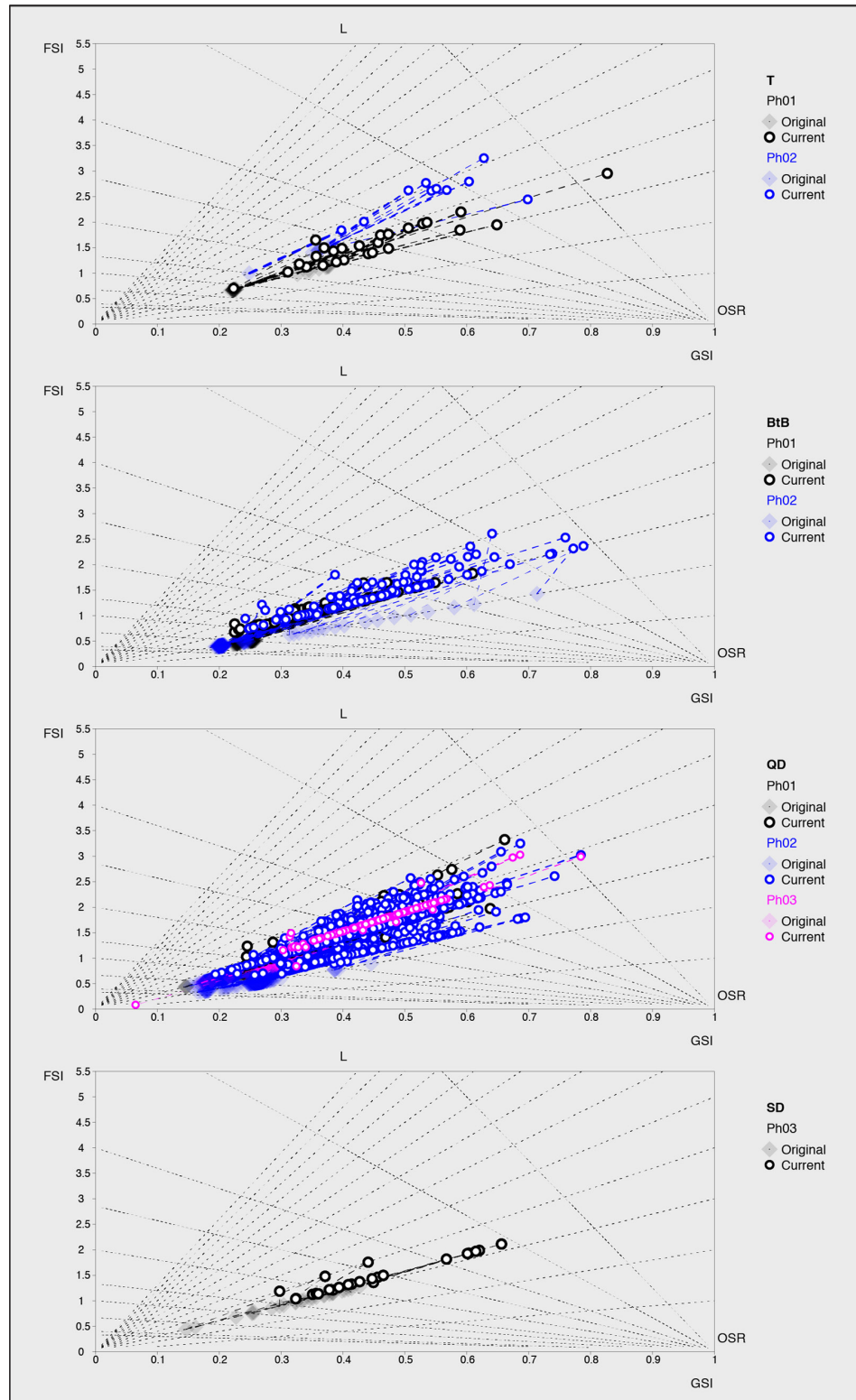


Figure 12: Spacemate charts for four building typologies—(top to bottom) terraced (T), back-to-back (BtB), quarter-detached (QD) and semi-detached (SD)—highlighting in different symbols the original and current states and in different colours the development phases. Lines are used to trace the movement between the dots, and their width represents the total number of changes observed. Ph01 = Phase 1; Ph02 = Phase 2; and Ph 03 = Phase 3. Source: Base diagram and formula by Berghauser Pont & Haupt (2010).



Figure 13: Isometrics of the 3D model of Cité Ouvrière before and after the densification. Each snapshot corresponds to a different building type: terraced (T) (first row), back-to-back (BtB) (second row) and quarter-detached (QD) (third row).

The QD typologies have experienced the most intense densification process. The calculations note a remarkable increase of the FSI (at times three-fold) and a considerable increase of the GSI (at times two-fold) (**Figure 12**). The houses have accommodated a high number of extensions [04]—including additions of entrance porches—sheds [05], plot chamfers [08] and extrusions [03]. All typological variations have accommodated at least two physical transformations, with the smallest QD2 type receiving the most (on average 3.4). The extent of this growth becomes evident from the spread of the current spatial fingerprints to various different positions between the $L = 3$ and 5 lines. From the five outliers, the one at the bottom-left corner of the chart corresponds to a currently empty plot and two others refer to truncated plots.

The evolution of QD houses has benefitted the compactness (or GSI) of the original built forms and boosted the amount of built programme (or FSI) mainly by adding more floors (one or two) and consuming the open space at the front, lateral and cross sides (**Figure 14**). From a total of 2470 volumes added in QD types, 1101 are located on the front zone, 577 on top of the building, 511 besides and 258 on the diagonal part. Essentially, the positioning of the building on the squared plot provides two additional areas—the besides and cross—where physical adaptations can potentially take place.

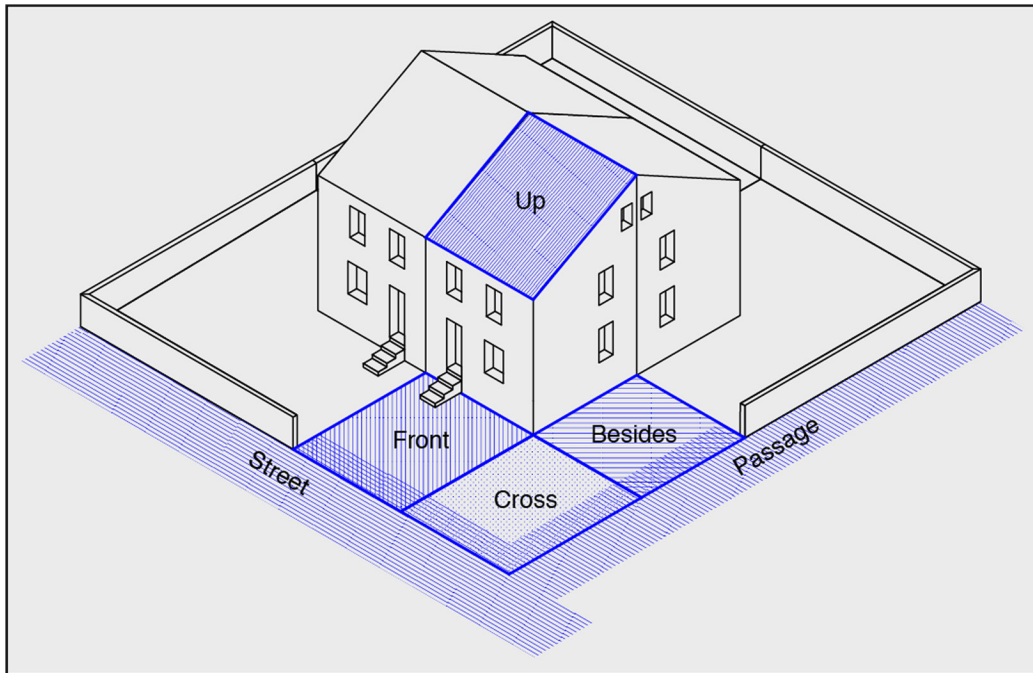


Figure 14: Plot zones in a squared plot of a quarter-detached (QD) building, where extensions can potentially take place.

This configuration has further repercussions. First, it expands the topologically feasible arrangements within the plot in relation to other building-plot compounds, alleviating the pressure on the open space in front of the house. Second, there is twice as much plot width in direct contact with the street, increasing the amount of space which is immediately accessible and visible from it. Third, the added volumes, especially those besides the principal building, can accommodate openings and separate entrances, and possibly one or two unobstructed facades overlooking the garden and the street (especially in corner plots). This way the light in the interior of the house is maximised and the depth of the rooms from the entrance decreases. Fourth, certain types of changes such as join [01], subdivide [02] or extend [04], depending on their physical dimensions, lead to typological mutations. From the original QD types, 426, or 57%, have already mutated to different types: 368 have turned into BtB, 33 have become 'L'-shape, 17 are SD, seven T and one detached.

The last chart concerns the evolution of the 27 SD houses (**Figure 12**) built during the last period of the Cité (Phase 3) in the triangular block at its north-west side. All have different original spatial fingerprints on the Spacemate chart due to the very nature of the block layout, which makes each plot geometrically distinctive, especially in terms of its depth. Over the years they have experienced a mild densification, which can be entirely attributed to changes at the ground level [05] and few alterations at the roof structure [07], such as the installation of dormer windows. Almost all dots have moved along the $L = 3$ line, which basically translates into an absence of vertical growth. The truth is that these types were already big when constructed, so no dramatic changes have been observed.

5.2.3. The effect on the neighbourhood as a whole

By superimposing the current spatial fingerprints of all types, the overall built density performance of Cité Ouvrière is made visible (**Figure 15**). Hierarchical cluster analysis⁸ is used to detect three clusters, indicative of different degrees of densification (**Figure 16**): *low* (cluster 1: FSI = 1, GSI = 0.3, OSR = 0.5–1.0) representing houses that have not received many changes or whose changes have kept the ratio between the four morphological variables almost unchanged; *moderate* (cluster 2: FSI = 1.63, GSI = 0.46, OSR = 0.15–0.75) reflecting the course of the majority of the houses, which have intensified their built area and increased their compactness; and *high* (cluster 3: FSI = 2.72, GSI = 0.71, OSR = 0.10–0.15) grouping the most densified cases—or outliers—that fall outside the Spacemate boundaries defined by the current building regulations.

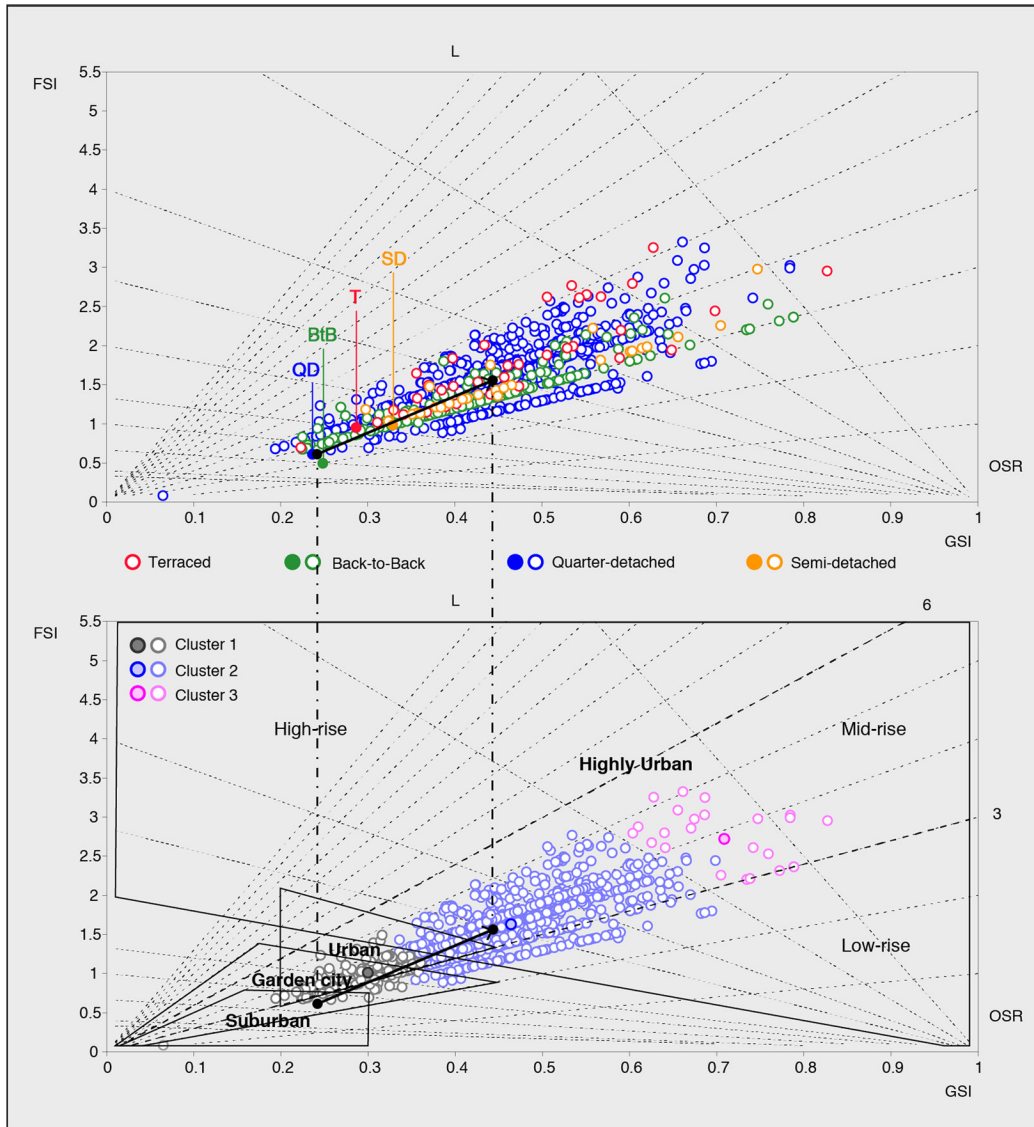


Figure 15: (top) Spacemate chart mapping all the house types of Cité Ouvrière (represented as dots) in terms of their current density. (bottom) The same dots clustered in three groups according to their degree of densification. Overlaid on top are four benchmark areas with different degrees of urbanisation as defined by Berghauser Pont & Haupt (2004: 76–77). The black arrow indicates the shift of the density average for the entire scheme over time.

Source: Base diagram and formula by Berghauser Pont & Haupt (2010).

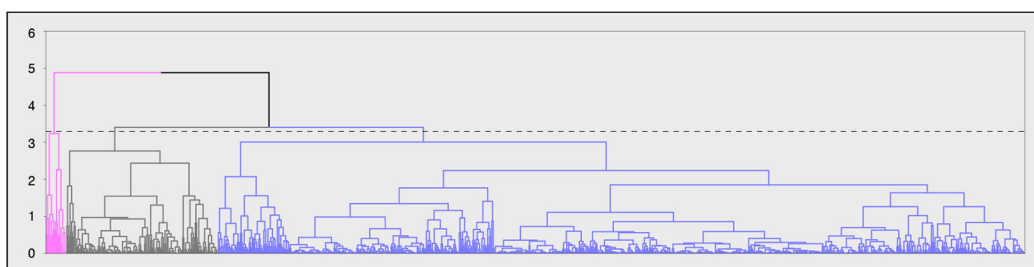


Figure 16: Dendrogram of the hierarchical clustering and the cut-point at 3.3 resulting in three clusters.

The bottom chart also demarcates four reference areas with different degrees of urbanisation (highly urban, urban, garden city and suburban) as these were defined in Spacemate by Berghauser Pont & Haupt (2004) based on combinations of FSI, GSI, OSR and L values. The authors consider urban environment:

an environment with a mix of functions, with good connectivity and collective open spaces within the building blocks

and a suburban one:

an environment consisting of mainly (attached) single-family houses, private gardens and employment opportunities within the residences. (Berghauser Pont & Haupt 2009: 180).

Indeed, Cité Ouvrière was designed to be a low-rise suburban development (below three floors) with low density (GSI = 0.24, FSI = 0.61) and generous gardens (OSR = 1.33). Within 165 years and owing to numerous, individual and bottom-up transformations, the settlement has turned into a more compact and intense built environment by means of consuming open space in all its three dimensions. Cité has densified its ground coverage (GSI) by 84%, increased its land intensity (FSI) by 155% and decreased open space (OSR) by 70%. According to Berghauser Pont & Haupt (2004), it is this ratio between non-built and built space and the pressure that the latter puts on the former that reveal the degree of urbanisation in an area. And in the case of Cité Ouvrière, it can be argued that the scheme 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 a highly urban area (OSR < 0.5) for its most part.

6. CONCLUSIONS

This study identified two mechanisms of morphological growth: intensification and land union or subdivision. The first describes the volumetric increase of buildings, which consumes the available open space of plots (also infills). The second mechanism concerns plots, and their potential to merge or subdivide. The effect of the two mechanisms on the built density is reciprocal. With a fixed building footprint, plot area growth decreases density, while a growing building in a fixed plot increases it. The degree of growth was found to be conditioned by a set of three constraints:

- the socioeconomic constraints established by national or local authorities, the industrialists and the households
- the legal constraints of building regulations
- the physical constraints imposed by the original design, particularly the uneconomically high ratio of road area to built area, the size and shape of plots and buildings, and the configuration of the buildings in the plot

Physical constraints and their relations are of interest here, should useful lessons be extracted for architects and planners. It is concluded that the original street layout imposed spatial constraints to land development and plots' size, which in turn influenced the nature and extent of subsequent building growth by the need for accessibility, natural daylighting and ventilation.

Effectively, the study advocates for a slow and contained densification process through a series of small changes that gradually increase the compactness of a residential area and ensure variety in the resulting environment both in terms of form and tenure. The fine-grained plot design, the piecemeal development and the financial model that allowed subsidised access to ownership maximised the neighbourhood's

resilience because they allow[ed] many people to attend directly to their needs by designing, building, and maintaining their own environment. (Moudon 1986: 188)

The building design was successful in that the houses were 'capable of being altered and were in fact altered' following the idea that

it is preferable for a house to be adapted to its occupants than for the occupants to have to adapt to their house. (Boudon 1972: 114, 117)

The densification, supported by political and socioeconomic conditions, ensured the old industrial dwellings remained fit for their purpose, maintained their value and continued to satisfy the residents' needs far beyond the operation of the factory to which they originally belonged. Furthermore, the existence of a limited set of types of changes and common building regulations established a degree of control and consistency in the process and outcome, which prevented the total degradation of the built environment; a phenomenon that is often observed in other more informal settings.

These findings expand the current understanding of physical densification and inform practitioners how the design of buildings affect their long-term resilience and potential to grow, and which non-formal factors may influence these. This is crucial insight for critical debates on energy reduction, sustainable planning, stock resilience and housing supply. Such knowledge can also benefit the sustainability agendas of cities in Europe and abroad. In Mulhouse, it has already informed the *Plan Local d'Urbanisme* (PLU), especially the propositions submitted by the *Conseil Consultatif du Patrimoine Mulhousien* (CCPM) on the conservation of the industrial heritage of Cité Ouvrière.

This study is explicitly contextual because it focuses on one particular case study and the findings are unavoidably a result of its idiosyncratic conditions, the urban form and the control of the development and management as a whole. Therefore, generalisations and direct knowledge transfers to other more central or international urban fabrics merit attention. However, its most transferable contribution is the diachronic 3D modelling and data-processing method which can help generate longitudinal simulation models that will be able to analyse and predict long-term dynamic behaviour within the domestic (and non-domestic) building stock in terms of rates of demolition and change. The approach can also be tested by other studies and applied to different contexts, while the data can be useful to both local authorities and other researchers through open schemas, such as CityGML. Finally, the findings can feed into potential interdisciplinary work that will seek to relate physical growth and change to other attributes of the built environment, such as urban economics, law, demographics, climate and transport planning.

NOTES

- ¹ Berghauser Pont and Haupt (2009: 18) explain that the plan area representations and resolutions are generic and simplified due to variations in the forms across scales; that the unbuilt space such as water and green surfaces or the streets are left unconsidered; and that the definitions and calculation methods are not consistent. They conclude, though, that 'the concept of density as such cannot be blamed for explanatory shortcomings; this is caused more by the formulation of specific definitions and their applications'.
- ² Spacematrix may also take into consideration network density (N), i.e. the amount of street network per plan area, which would result in a different diagram $FSI(N)$. While the additional variable renders the approach more comprehensive, it is not particularly relevant to the present study because no comparison is made between different neighbourhoods in the city, and streets within the Cité remain standardised in their dimensions following the original gridiron-like plan.
- ³ No facade details are mapped because they have zero volumetric cost and are thus not relevant to density studies.
- ⁴ These are houses grouped in fours, with access from roads on opposite sides.
- ⁵ The term 'affordance' was first developed by James J. Gibson (1977).
- ⁶ To simplify the calculations, regulations regarding distances from neighbouring plots and the street are not taken into consideration, even though they further limit the theoretically maximum building space based on the need to preserve daylight in all rooms.
- ⁷ Sheds [05] only contribute once to the gross floor area (GFA) because they are single-storey buildings, and thus, after the addition of sheds, the average L of the building-plot compound drops; however, the principal building still features three levels.
- ⁸ Hierarchical clustering is an agglomerative or bottom-up clustering method that begins with individual observations and successively merges them based on certain similarity measures until a meaningful number of clusters is reached. Berghauser Pont & Olsson (2017) have already tested the statistical method on 3D Spacematrix, while also considering *network density* (N), and found that it is more convincing than centroid-based clustering in distinguishing differences in both building type and street pattern. As similarity measure, the average Euclidean distance between the data points was used.

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