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Dwelling size and usability in London: a study of floor plan data using machine learning

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ABSTRACT
Based on a dataset of dwelling unit plans ($n = 2283$) with detailed dimensions derived from open-access plan data using machine learning, this paper analyses the size and usability of dwellings in London. Half of London's housing stock was built before the Second World War but has been extensively modified. Due to greater pressure on the housing market and problems with dwelling size, London was the first local authority in England to reintroduce space standards for all housing sectors in 2011. Providing a first comprehensive analysis of space standards and dwelling size in London at room level and across all built periods, the data shows that 61% of London homes fail the recommended minimum dwelling sizes of the London Housing Design Guide (2010), 51% a bedroom standard and 88% at least one of the dimensional requirements. The paper quantifies the extent to which homes fail both recent and historical space standards and discusses their effectiveness in relation to dwelling usability and issues of design.

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Dwelling size; space standards; machine learning; floor plans

Introduction: dwelling size as an indicator of housing quality

Since the report on housing by the Tudor Walters Committee (LGB, 1918), housing quality has been largely understood from a planning perspective in terms of dwelling usability and measured against space standards that prescribe dwelling and room sizes needed to accommodate essential domestic activities (Park, 2017; Clifford & Ferm, 2021). The usability and availability of domestic space have a direct impact on the health and wellbeing of occupants (Usbourne, 2018; Kearns, 2022) and the long-term flexibility and adaptability of housing (HATC 2006) as COVID-19 lockdowns have also demonstrated (Brown et al., 2020; Tinson & Clair, 2020). The lockdowns have revealed fundamental failures in spatial equity and dwelling usability, raising questions about the effectiveness of space standards after more than 110 years but also how the usability criteria that inform them might have changed. While many studies have analysed housing in relation to space standards, the critical issues of usability and effectiveness are often overlooked, yet fundamental to providing better evidence on how space standards might improve housing quality. This paper focuses on these issues by analysing housing in London in relation to changing space standards and transformations in housing production and building stock.

The *Tudor Walters Report* proposed the first comprehensive space standards that, like many that followed, were primarily aimed at public housing. In anticipation of a post-First World War housing shortage, the report set out the standards to which new housing should be developed (LGB, 1918). These space standards were reviewed over the following decades by the Dudley Committee (CHAC, 1944; MoH, 1949) and Parker Morris Committee (MHLG, 1961), with increases in recommended dwelling size reflecting shifts in housing policy, demand and need. The last mandatory national standard for new council housing, the Parker Morris standards, was abolished in 1980 alongside large scale, state-led public housing programmes.

In 2011, the Greater London Authority (GLA) formally reintroduced space standards for housing developments on public land or with a public subsidy through the *London Housing Design Guide* (Mayor of London, 2010), hereafter called the London Standards. The principles of the London Standards were later adopted by the Nationally Described Space Standard (NDSS) in 2015 (DCLG, 2015), but with reduced requirements (Table 1). Despite this, the NDSS was still around 10% larger than the Parker Morris

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Table 1. Comparison of minimum room sizes and dimensions in the Nationally Described Space Standards (2015, technical requirements) and the *London Housing Design Guide* (2010, desirable standards).

	London Standards (Desirable areas)	NDSS (Technical requirements)
Double/twin bedroom	12 m^2 first bedroom (min 2.75 m width)	11.5 m^2 (min 2.75 m for first, then 2.55 m width)
Single bedroom	8 m^2	7.5 m^2 (min 2.15 m width)
Built-in storage	1.5 m^2 for 2 person, then +0.5 m^2 per additional occupant (min 2 m high)	1.5 m^2 for 2 person, then +0.5 m^2 per additional bedroom (height of 0.9–1.5 m counted 50% and under stairs as 1 m^2)
Ceiling heights	min 2.5 m (rooms with pitched roof: min ceiling height in min 60%).	min 2.3 m (min. 75% of GIA)
Min combined living room, dining room and kitchen areas	23 m^2 for 2 persons, then +2 m^2 per additional occupant; min room width of 2.8 m in 2–3 person dwelling and min 3.2 m for 4 < person	N/A
Bathroom/WCs	Dwellings for 5-person min 1 bathroom/WC + 1 WC	N/A
Study/work	area for desk, chair and filing cabinet or bookshelf	N/A
Private open space	5 m^2 for 2 persons, then extra 1 m^2 per additional occupant (min width and depth of 1.5 m).	N/A
Circulation	5% circulation allowance for flats, 19 m^2 of staircase and hallway space for two-storey dwellings (these include Lifetime Home accessibility requirements)	N/A

Standards (Park, 2017; Kearns, 2022). The NDSS are the first national minimum requirements that in principle apply to all housing sectors. However, they are only a recommended statutory guidance, with local authorities that adopt them enforcing compliance through the local planning system and not as mandatory building regulation as in most other European countries (Ozer & Jacoby, 2022).

Gross Internal Areas (GIAs) recommended in space standards are set according to the maximum occupancy that dwellings are designed for (measured in bedspaces) and the number of storeys in a dwelling (Table S1). Minimum GIAs are calculated by adding up all secondary 'desirable' areas (London Standards) or 'technical requirements' (NDSS) for living rooms, bedrooms, storage space, circulation areas and bathrooms or WCs. These areas or requirements are based on the dimensions of typical furniture needed, activity zones (to use and move the furniture and permit daily activities), and access or circulation areas. The London Standards, for example, provide a detailed schedule of required furniture and activity zones as well as exemplary furnished layouts for each room to show how its requirements can be met and recommend the submission of this information (Figure 1). While this is largely based on generalizations and assumptions about the daily activities of a household (Mukhtia, 2020), it provides an immediate measure to assess the usability of dwellings.

This paper analyses a new large floor plan dataset derived from housing in London in terms of dwelling and room sizes and compares them to both the London Standards and historical space standards in use at the time of their construction. The study questions to what extent dwellings are usable as defined by different standards and the effectiveness of space standards until now. Combined, both questions are essential to the definition and design control of decent housing.

A focus on London was chosen as dwelling size and quality has been under greater pressure than in other regions due to higher construction, land and housing costs (Edwards, 2016). According to the *Housing in London* reports, in 2017 the average dwelling size was 87 m^2 and household size 2.5 persons, equating to 35 m^2 per person (an increase on the 31 m^2 in 2001), which compares to 91.5 m^2, 2.4 persons, and 39 m^2 per person in the rest of England (GLA, 2021). In response to market pressures and continuing shrinking of space (Goodchild & Furbey, 1986; Karn & Sheridan, 1994; Drury & Somers, 2010) the GLA was the first to return to the use of space standards. The impact of this, however, has not been fully studied so far.

Since the abolishment of space standards in public-sector housing in the early 1980s, housing quality and dwelling size have become a growing concern, resulting in a series of studies that compare housing against different space standards. Research showed that in the 1980s and 1990s, in the absence of official housing standards, the average size of new dwellings in England noticeably shrank (Goodchild & Furbey, 1986; Karn & Sheridan, 1994). A shared conclusion of these studies was a significant lack of space in England's housing compared to space standards. However, a major problem of research into dwelling size is the trade-offs between detail, accuracy and sample size.

Earlier research was particularly interested in new-built homes, analysing small and specific samples of floor plans from typical housing developments, and included room by room discussions. More recently, studies have utilized dwelling size data from developers (Leishman et al., 2004) and large-scale open data on usable floor areas provided by Energy Performance Certificates (EPCs) and the English Housing Survey (EHS) (Morgan & Cruickshank, 2014; Hubbard et al., 2021).

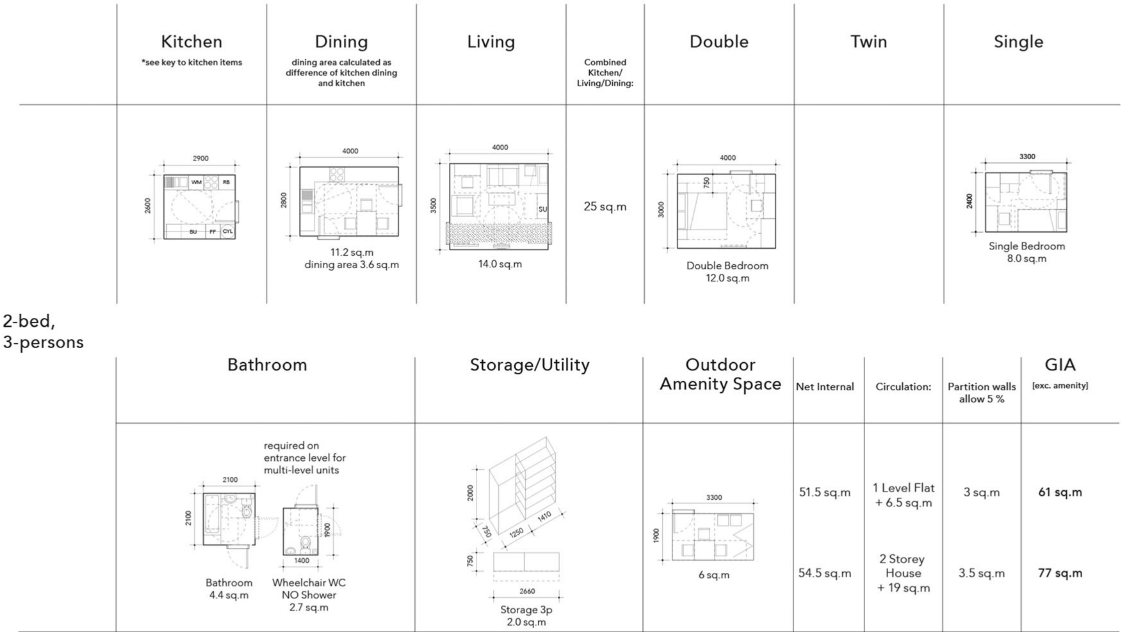

Figure 1. Example of standard room layouts and details of GIA calculation for two-bed three-person dwellings. Excerpt from: *London Housing Design Guide (2010)*, Appendix 1-Space Standards.

However, GIAs stated in EPCs and the EHS provide limited information at room level and are in part estimates based on the dwelling width and depth.

Studying housing built in the early 1990s, Karn and Sheridan (1994) found that 68% of dwellings supplied by housing associations and 53% of private-sector housing were below the Parker Morris standard. Likewise, Drury and Somers (2010) established that 75% of one-bedroom flats and 91% of two-bedroom flats built in London in the late 2000s were below the Housing and Communities Agency standards. In addition, having analysed new-built homes in England by eight major housebuilders, a study by the Royal Institute of British Architects (RIBA, 2011) concluded that the average one-bedroom flat from the early 2010s was 4 m² and the average three-bedroom house, 8 m² short of the recommended dwelling sizes in the London Standards. A follow-on study in 2015, when the Nationally Described Space Standard (NDSS) was introduced, found that the average size of new three-bedroom dwellings had increased but was in many places still significantly below the new standards – only dwellings in London remained well above the standard despite a slight drop in size since 2011 (RIBA, 2015).

Morgan and Cruickshank (2014) used data from the EHS of 2012 to estimate that of 16,047 surveyed homes, 55% fail the minimum dwelling floor area recommendations of the London Standards, which is reduced to 21% if accounting for dwelling under-occupancy. However, there are methodological problems in comparing London Standards to an existing housing stock as captured by the EHS. While the EHS collects household data, it does not verify the maximum level of occupancy dwellings are designed for, which is needed to reliably determine applicable space standards. In addition, GIAs in the EHS are measured differently from those in the London Standards.

Another large-scale study by the Local Authority Building Control (2018) sampled around 10,000 houses from the 1930s to 2010s to determine changes in dwelling size for each decade. Analysing dwelling plans from property websites including Rightmove and Zoopla, it found that the average three-bedroom family house had shrunk from 83.3 m² in the 1970s to 67.8 m² in the 2010s, with average bedroom areas reducing from 15.3 m² in the 1930s to 13.4 m² in the 2010s but living rooms becoming larger. While these calculations include floor areas for living rooms, kitchens, bedrooms and bathrooms, they problematically exclude those for hallways, stairs and storage (as these are not indicated on the plans), which can significantly differ between dwelling types and over time and affect dwelling size.

What the different studies on dwelling size and space standards highlight are that findings are difficult to quantify and are sometimes contradictory, as no reliable large-scale data on this exists that can be directly consulted. Studies so far also lack a detailed assessment of the extent of the lack of space and usability. Especially studies on housing built in the past and changes made to them are missing, as the focus has been on how housing meets newly introduced space standards. Yet, London's housing stock is old and has been extensively subdivided or enlarged, with half dating to pre-Second World War according to the Valuation Office Agency (VOA, 2010).

To reliably compare a large number of existing dwellings in their size to current and historical space standards creates two challenges. First, accurate usable floor area data at both dwelling and room levels are needed for a full comparison to the dimensional requirements and usability criteria found in statutory guidance or design guides. Second, the number of usable bedspaces must be established to determine potential maximum occupancy rates and applicable floor area standards to avoid under- or over-reporting of failure rates. This study collected room-level data to analyse the various aspects of dwelling size and usability and determine occupancy rates based on minimum use criteria to overcome limitations found in previous studies.

Methods

To overcome issues of dwelling size data reliability and comparability to space standards found in previous studies, a large new dataset was created by extracting dimensional information at dwelling and room levels from architectural floor plans using machine learning-based algorithms. Due to regional differences in housing sizes and markets (RIBA, 2015), floor plans were only collected from one region, inner London, to ensure that data are compatible.

The sample contained 2283 unique dwelling unit plans including housing from all built periods. While most existing studies of dwelling size have focused on recent space standards and new-built dwellings (RIBA, 2011, 2015), this dataset permits analysing how dwelling usability and compliance with standards have changed over time. Comparing older dwellings to both current floor area recommendations and those in use when originally built, provides insights into how or why some might fail current space standards.

Sampling

The selection of floor plans used a two-stage process and a purposive sampling method at the Lower Layer Super Output Area (LSOA) level, which are standardized statistical geographical areas with an average population of 1500 people or 650 households (MHCLG, 2019). A random sampling that would have reduced selection bias was not possible, as property addresses and floor plans could not be sufficiently matched at the scale necessary for this study.

The first selection criteria for LSOAs were property type (detached, semi-detached, terraced, flat), built period and bedroom numbers to reflect the variety of housing and urban developments in London. Due to housing being produced in England at scale using standardized layouts and construction methods, some building typologies (such as tower-block, slab-block, terraced house, or semi-detached houses) are dominant in specific periods. For example, terraced houses made up 87% of all housing in England in 1911 (Muthesius, 1982). Terraced and semi-detached houses were mostly built before 1939, housing estates with repetitive blocks of flats and maisonettes from 1945 to 1982, and flats in large mixed housing developments after 1983. Using council tax statistics (VOA, 2018), LSOAs with a minimum of 60% of their properties completed in the same built period were identified. However, while built periods and building typologies in principle correspond, many older houses have been converted or altered, changing their property type classification. According to the VOA (2010), 20% of dwellings in these boroughs were converted from dwellings built before 1939. To capture this change in property type and dwelling size in the sample, the number of bedrooms was used as an additional criterion. For every selected LSOA, the predominant building typology and level of repetition were verified using Google Maps satellite images and historical ordnance survey maps from the 1840s to the 1990s, while ensuring that the overall selection of LSOAs contained all typical London building typologies (Table S2).

The second selection stage was based on the availability of scaled floor plans for these LSOAs. Local planning departments hold archival information on planning applications, including scaled existing and proposed floor plans. While the record-keeping is inconsistent between boroughs and difficult to access and review at scale, all provide online access to digitized planning applications at least lodged since the 2000s, and some as far back as the 1980s. From these, plans for dwellings built after 1982 and before 1939 could be collected (as many older houses require planning permissions for their conversion or alteration). But this lacked sufficient information for dwellings built between 1945 and 1982, with plans for this period collected from Rightmove, the UK's largest online real estate website with an archive of past online property listings.

The two-stage process resulted in a final selection of 108 out of 2046 LSOAs in 14 London boroughs, and the collection of 4210 dwelling unit plans (with multi-storey units only counted as one dwelling unit plan). 1482 floor plans were sourced from the boroughs' online planning archive and 1310 from Rightmove. For 27 LSOAs with properties built since the 1980s, only type plans (typical unit plans that are repeated in larger housing developments) were analysed. These 1418 type plans represent more than 70% of all dwellings in these LSOAs, equivalent to 14,400 actual dwelling units. In the analysis, the repetition of each type plan or, likewise, the common repetition of terraced housing plans, however, was not further considered, as the exact repetition of each plan was difficult to verify.

All usable floor areas indicated in the measured plans were assumed to comply at least with the minimum height of 1.5 m except for under stairways, which follows the VOA's method of calculating usable GIAs (VOA, 2012) and is equivalent to those used in both planning applications and property plans.

Data conversion

The collected floor plans were processed using algorithms provided by the PropTech companies Archilogic and Archilyse (2035 dwelling units) and XCYDE (1088 dwelling units) to extract dimensional and geometric data. The algorithms were based on an image-recognition process to detect architectural components (walls, windows and doors) and scale bars in raster image files (JPEG or PDF) of floor plans and vectorize and scale them. Data collected included net floor area, geometry, corner points, number of windows and doors, kitchen and bathroom elements, and staircases.

From the 4210 plans, 1575 had to be eliminated at this data extraction stage due to not being fully readable to the algorithm (due to missing scale information and inconsistent drawing styles), leaving 2635 plans. The accuracy of the derived data was verified by manually comparing 30 randomly selected floor plans from each data batch by Archilogic/Archilyse and XCYDE to the original floor plan. They were compared to room dimensions rather than to stated floor areas, as estate agent plans can overstate dwelling size when rooms are measured at their widest points (Spec, 2019). Derived dimensions showed acceptable divergence from the original plans for the analysis. For 75% of the compared rooms, the difference was less than 0.3 m² per room (average 0.19 m²), equating to an over- or under-estimation of around 2%. In comparison, Hubbard et al. (2021) found around 8% of over- or under-estimation of property sizes in EPCs, the most readily available dwelling size data in the UK.

For the remaining 25%, the difference was 1–2 m² per room, due to incorrect scaling of the original plans (due to missing or incorrect scale bars), resulting in exceptionally large or small dwellings in comparison to other samples with the same number of rooms from the same LSOA. These plans were classed as outliers and removed from the data analysis, leaving a total of 2283 dwelling unit plans for comprehensive study (Table S3).

The data conversion was followed by the identification of rooms ('kitchens', 'bedrooms', 'storage' spaces, 'bathrooms' and 'circulation') needed for detailed comparison to space standards that use the same classification. The labelling followed a decision tree to determine room uses according to furniture, features and dimensions (Figure 2). A 'room' was defined as a space bounded and separated from others by walls and connected by doors. Rooms not linked by doors, such as connected living and dining areas or an entrance area open to a living room, were thus labelled as one room. Built-in storage was also classified as a 'room'.

Bathrooms (and WCs) and kitchens were labelled first by detecting typical furniture elements. Kitchens were further labelled as 'habitable' (living-in kitchen) or 'non-habitable' (working kitchen). 14 m² was hereby used as the threshold for habitable kitchens, based on a manual comparison of kitchen sizes, types and unit usability in a smaller sample of dwellings ($n = 471$).

In dwellings without a habitable kitchen (combined kitchen-dining), the largest remaining habitable room in the dwelling was labelled as a 'living' room. Further assessing rooms in terms of their dimensions and compactness ratio (the room area compared to the area derived from its maximum width and depth), large compact rooms were labelled as a 'double' or 'single' bedroom. Rooms not meeting the double or single bedroom criteria were labelled as circulation (corridor) or storage space (including utility rooms), depending on their size and number of doors. Storage spaces opening to bedrooms were considered built-in storage and added to the bedroom area, and stairs not within a habitable room were labelled as vertical circulation.

To determine whether a room is a double or single bedroom, room dimensions were assessed against the basic furniture and activity zones needed for their use: beds, bedside tables, wardrobes and activity zone for dressing (Figure 3). This intentionally disregarded the more extensive requirements for a chest of drawers, desk and wheelchair turning circle in the London Standards to establish a baseline definition of bedroom usability that could be applied to housing from all periods.

Based on this definition, the maximum number of usable bedspaces in a dwelling (counted as two for a double or twin room and one for a single) were calculated to avoid misrepresenting compliance. In new-built housing, this is frequently done during planning by declaring bedrooms below the prescribed double bedroom size as singles or small singles as studies,

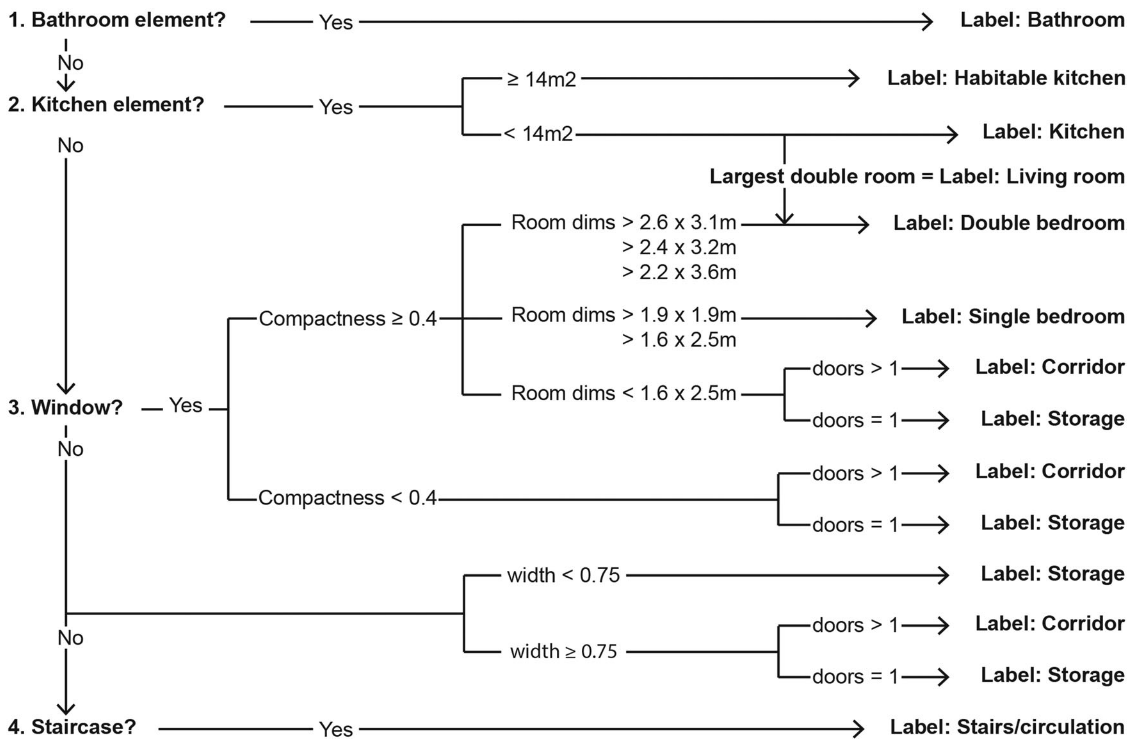

Figure 2. Decision tree for room labelling.

even though they are likely to be later marketed and used differently. A bedroom definition based on usable bedspaces also accounts for dwellings designed to different bedroom standards, with rooms as small as 4.5 m^2 considered single bedrooms in the 1990s by the National House Building Council (NHBC) standards (Karn & Sheridan, 1994). It further acknowledges that so-called box rooms, common in older terraced housing, now often serve as bedrooms.

Method of analysis

In the first part of the analysis, dwellings were categorized according to the number of storeys, bedrooms and bedspaces (Table S4), and compared to primary and desirable criteria of London Standards (Tables 1 and S1) to establish compliance rates. This comparison is given in Table S5. Although the London Standards were replaced by the *Housing Supplementary Planning Guidance* (2016) that adopted the (NDSS) in 2015 and the *Approved Document M: Access to and Use of Buildings, Volume 1: Dwellings* (2015 Edition) of the Building Regulations, they are used for the comparison and analysis in this paper. The reasons for this are twofold. First, the London Standards provide extensive good practice guidance with detailed requirements and calculation of space standards unlike the NDSS, which was based on them but has marginally smaller standards for larger dwellings. Second, the proposed *London Plan Guidance: Housing Design Standards* (2022 draft

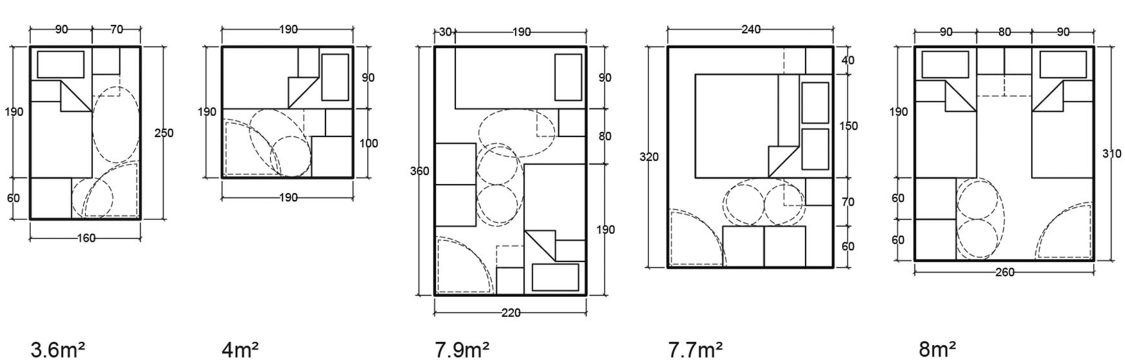

Figure 3. Minimum bedroom dimensions. Derived from a dimension- and furniture-based assessment of usability.

version for consultation), which maintains the key design guidance from the London Standards, encourages that new homes exceed the NDSS by at least 5%, equating to larger dwellings sizes than were recommended by the old London Standards.

In addition to overall rates of failure, the degrees of failure and excess were analysed for each primary and desirable criteria described in the London Standards (Tables S6–S9). All comparisons were also grouped by built year and provider and described in the results.

For those built between 1945 and 1982, additional comparisons to the space standards in use during this period were made (Figure 4, Table S10). These were only made for two- and three-bedroom dwellings, as these were the dwelling types that space standards prescribed. For these comparisons, space recommendations for bedrooms, living rooms and kitchens were collated for each period from national housing reports, design guides, or statutory guidance (Table S4). Where room sizes were not specified as space standards, exemplary layout plans in the documents were measured, including the smallest and largest room examples. All supplementary tables (Tables S1–S11) can be found online.

Results

Overview of the sample

Consistent with the sampling approach, the plan data contained dwellings from all built periods found in council tax statistics. Twenty-one per cent of dwellings were built before 1939, 34% between 1945 and 1982, and 44% after 1983 (Table S4). The sample was skewed toward newer dwellings, as 51% of housing in London was built before 1939, 24% between 1945 and 1982 and 23% after 1983 (VOA, 2018).

Most of the analysed dwellings consisted of one- (25%), two- (41%) and three-bedroom (21%) dwellings. The numbers of studio flats (3%) and four- (9%) and five-bedroom (2%) dwellings were comparatively small. This distribution was consistent with the inner-London housing stock characteristics of 24% one-bedroom, 41% two-bedroom, 21% three-bedroom, and 9% four-bedroom dwellings as reported by VOA (2018).

In this study, the number of dwelling storeys rather than property types were used in the classification to be consistent with how space standards are applied (referred to as dwelling types). Most dwellings were only one-storey (67%), followed by two-storey (29%) and a small portion of three-storey units (4%). It was impossible to directly compare this to council tax statistics, as they include under ‘flats’ both single storey and multi-storey flats (maisonettes). But, according to the VOA (2018), 75% of dwellings in inner London were ‘flats’ and 23% are houses, thus roughly corresponding to the distribution found in the sample.

Significantly, one- and two-bedroom dwellings were predominantly one-storey dwellings (97% and 78%, respectively), with more than half of them being completed since 1983 (52% and 54%), followed by those completed before 1944 (13% and 14%). In contrast, three- and four-bedroom dwellings were mostly multi-storey dwellings (60% and 80%) and built before 1982 (69% and 77%). This distribution reflected general changes in dwelling types over time. There was no public data linking the number of bedrooms, property types and property built periods to compare. However, previous studies reported that more flats than houses or maisonettes have been built in London over the past decades, with three- and four-bedroom flats uncommon after the 1990s (Karn & Sheridan, 1994; Drury & Somers, 2010; Roberts-Hughes, 2011). In the analysis and interpretation of results, the dependencies between built year, number of storeys and number of bedrooms were further considered.

Comparison to London Standards

When comparing the plan data to the space standards in the London Standards, 39% of dwellings met the recommended minimum GIAs. In addition, storage space requirements, which are considered a high priority, were met by 41% (Table S5).

The London Standards also recommended ‘desirable’ floor areas for key rooms. (1) Dwellings for more than one occupant should have at least one bedroom to the double/twin bedroom standard of 12 m^2, which was achieved by 63% of dwellings. (2) All bedrooms should at least comply with the single bedroom standard of 8 m^2, which was met by 70% of dwellings. All single and double/twin standards were met by 49% of dwellings. (3) Living, kitchen and dining spaces to have a minimum combined area proportional to the number of occupants, which was achieved by 54% of dwellings. While 32% of dwellings satisfied these three desirable criteria, only a mere 12% met all floor-area-related requirements of the London Standards.[1]

However, when broken down into dwelling types (number of floors and rooms), built year, and provider, there were significant differences in the rates of compliance with the London Standards, which are detailed in the following.

Dwelling size

London Standards prescribe GIAs that start with 37 m^2 for one-storey, one-bedroom dwellings for one person

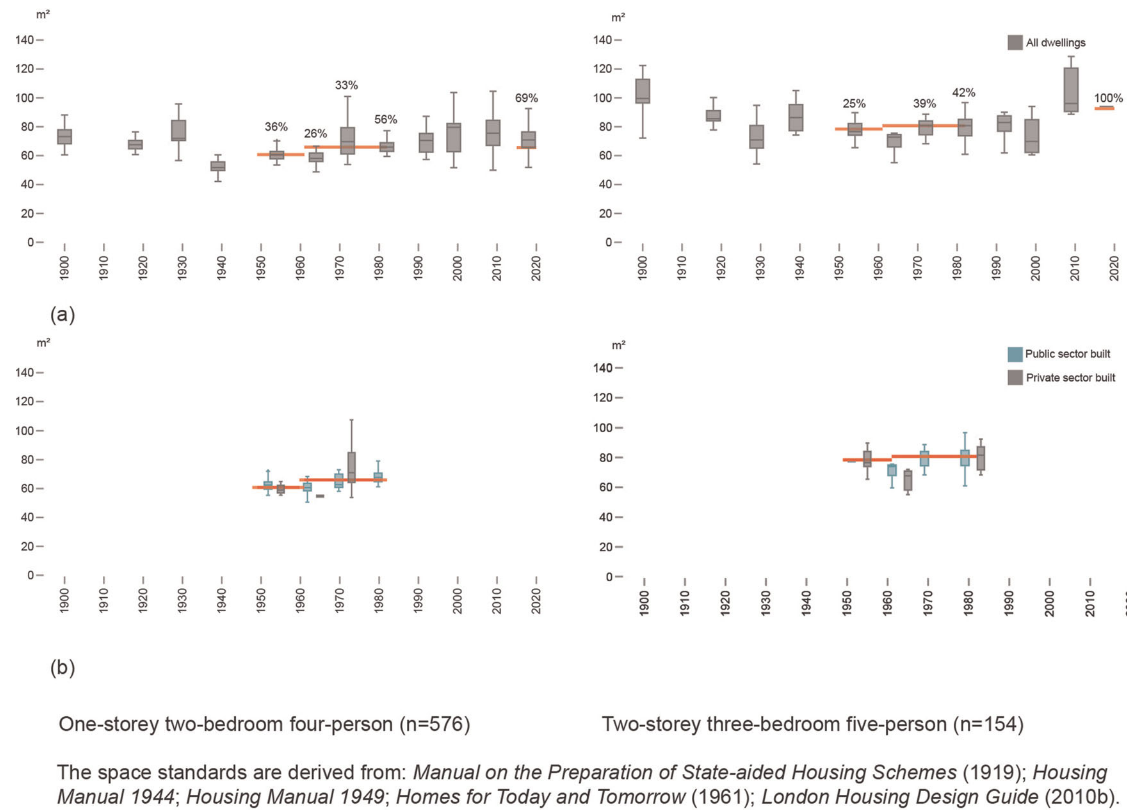

Figure 4. 2B4P and 3B5P dwellings compared to historical space standards.

(minimum permitted dwelling size) and increase with the additional number of floors, bedrooms and bedspaces. 61% of dwellings failed the recommended minimum GIAs. Overall, 22% of dwellings were up to 10%, 31% of dwellings were between 10% and 25%, and 8% of dwellings were more than 25% smaller than the prescribed GIAs (Table S6).

Critically, 63% of studios were below the required 37 m² standard, with 22% being up to 10% (33.3–37 m²), 27% between 10 and 25% (27.8–33.3 m²), and a significant 14%, more than 25% below (<27.8 m²). In addition, 10% of one-bedroom dwellings were also below 37 m².

Based on the calculated maximum bedspaces (equitable to maximum occupancy rates), the average floor area per bedspace in London was 19 m² (19.7 m² for private-sector and 17.8 m² for public-sector housing).

Dwelling size, built year and historical space standards

Space standards were nationally in use for public housing in 1919–1921 (Tudor Walters standards), 1944–1981 (*Housing Manuals 1944 and 1949*, and Parker Morris standards), and since 2015 (NDSS), with London-wide standards in place since 2011. Most historical space standards or dwelling size recommendations were for two-storey, three-bedroom family dwellings and some for one-storey, two-bedroom dwellings. Comparing the size of these dwelling types and different built periods to space standards in use at the time, many dwellings were found to be smaller than the space standards (Figure 4(a)). A general correspondence between dwelling size and space standards was, however, interestingly evident for housing built by both the public and private sectors (Figure 4(b)).

Compared to the *Housing Manual 1949*, 37% of one-storey, two-bedroom, four-person dwellings built in the period 1945–1964 were above the minimum dwelling size of 65 m² (700 ft²). In two-storey, three-bedroom, five-person dwellings, even lower numbers met the recommended 83.6 m² (900ft²) – 25% of dwellings completed in 1945–1954, and no dwellings in 1955–1964 (Figure 5).

When the Parker Morris standard was in use, a noticeable higher proportion of dwellings met the recommendations. Sixty per cent of one-storey, two-bedroom, four-person units completed in 1965–1972 and 55% in 1973–1982 were larger than the recommended 66.9 m² (720 ft²). For two-storey, three-bedroom, five-person units completed in 1965–1972, this dropped to

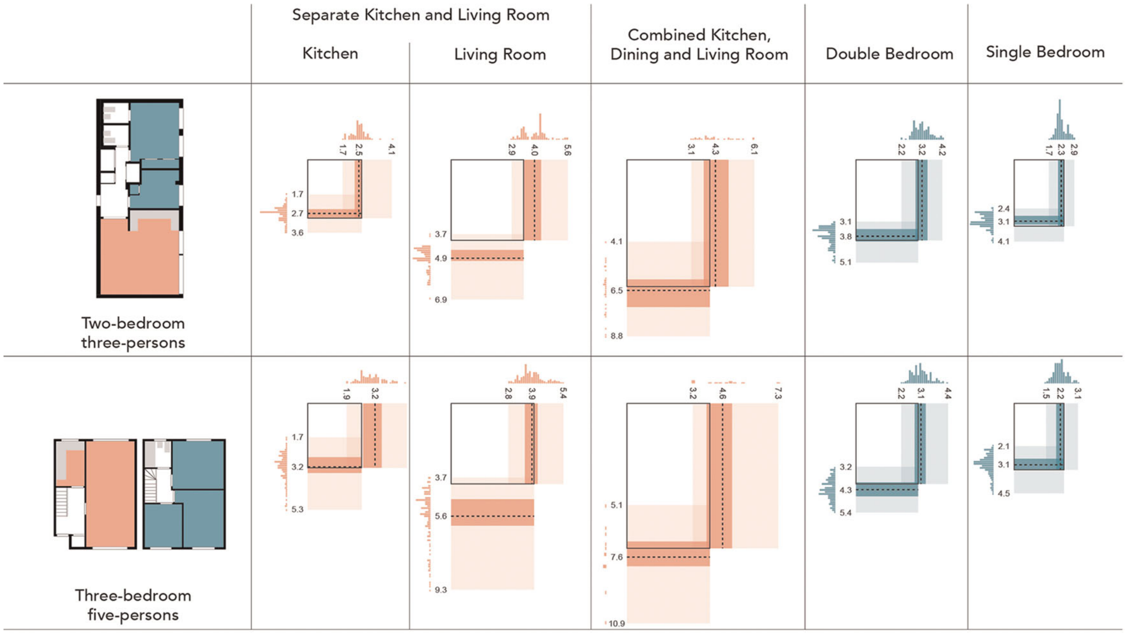

Figure 5. Distribution and range of room sizes in one-storey, two-bedroom, three-persons and two-storey, three-bedrooms, five-persons dwellings compared to rooms given in the *London Housing Design Guide* (2010), Appendix 1-Space Standards.

39% and rose for 1973–1982 to 42% of dwellings that are smaller than the recommended 81.7 m² (880 ft²).

Analysis at room level

Bedrooms

According to London Standards, the largest bedroom must be a minimum of 12 m². Thirty-seven per cent of dwellings failed this criterion, with 16% having a main bedroom in the 11–12 m² band, 16% in the 9–11 m² band and another 5% being smaller than 9 m² (Table S7). A similar failure rate was observed for the smallest bedrooms, as the smallest bedroom was below the single room standard of 8 m² in 34% of dwellings with more than one bedroom. Thirteen per cent of these were in the 7–8 m² band, another 10% were in the 6–7 m² band and 11% were smaller than 6 m² (Table S8).

There was generally a direct relationship between GIAs and room sizes. Fifty-three per cent of dwellings that failed to meet the expected GIA also had substandard main bedrooms (while in dwellings that met the GIAs, this was on only 12%). Similarly, 41% of dwellings failing the GIA also failed the single bedroom standard (compared to 17% in dwellings meeting the GIA).

Substandard bedroom sizes were more common in three- and four-bedroom dwellings, with the average size of the smallest bedroom decreasing from 10.1 m² in two-bedroom to 7.6 m² in four-bedroom dwellings. A similar trend of non-compliance with minimum room sizes in larger units was also observed when comparing one-storey and two-storey dwellings. Two-storey dwellings had a noticeable lower rate of compliance with the single room standard (50%) than one-storey dwellings (79%).

In the two periods before 1918 and between 1973 and 1999, a significantly higher proportion of the smallest bedrooms was below the single room standard of 8 m². In comparison, only 7% of dwellings from 2000 to 2018 had rooms smaller than 8 m², with the smallest bedrooms averaging 11.2 m², suggesting an overall increase in dwelling size.

In addition to floor area, the London Standards recommended a minimum width of 2.75 m for double and twin bedrooms to ensure their usability. 85% of main bedrooms met this. When compared to the 2.55 m minimum requirement in the NDSS, this rate increased to 95% for doubles, and for singles (minimum width of 2.15 m) it was the same at 85%. This indicates that despite high numbers of bedrooms failing minimum floor areas, most met the minimum recommended widths needed to fit and use bedroom furniture, thus, were usable (Figure 5).

Living, kitchen and dining areas

The minimum combined size for living, kitchen and dining areas recommended by the London Standards was 21.4 for one-person units and 29.1 m² for five-person units (Table S1). Overall, only 54% of dwellings meet these standards (Table S5). Twenty per cent of living areas were up to 10%, another 20%, between 10% and 25%, and 6%, more than 25% below (Table S9).

Kitchen, dining and living areas came in different combinations: separate rooms, combined living-kitchens, or dining-kitchens and separate living rooms. 36% of analysed dwellings had a combined kitchen and living space (living-kitchen) and 64% provided them as separate rooms. Proportionally more layouts with living-kitchens (61%) met the living area standards compared to separate rooms (48%). While it is common to integrate the main circulation with living areas, the method used in this study did not account separately for the circulation area in these cases. When excluding dwellings with integrated living-kitchens and circulation from the calculations (25%), the compliance rate dropped to 55%. For further comparison, while only 18% of dwellings built before 2000 had living-kitchens this rose to 91% for dwellings built after 2000.

As expected, the rate of compliance was lower in dwellings that failed overall GIA standards. Seventy-two per cent of substandard one-bedroom and 74% of substandard two-bedroom dwellings also failed the living area standards, compared to 15% of one-bedroom and 9% of two-bedroom dwellings that met the GIAs.

Compliance rates with living area standards did not noticeably differ for dwellings with different numbers of floors and bedrooms (Table S5). However, the lowest compliance rates were found in dwellings built between 1930 and 1964, with the average size of living area in three-bedroom dwellings just 26.4 m^2. Compliance rates were higher for the period before 1918 and after 2000, with the average living area in three-bedroom dwellings much larger at 37.5 and 38.7 m^2, respectively.

Storage and circulation

Overall, 41% of dwellings met the storage standards, which include storage and utility rooms, built-in storage, and storage under staircases (Table S5). London Standards prescribed a minimum storage space requirement that increases with the number of occupants. When analysed, the average storage space increased with the number of bedrooms from 1.5 m^2 in one-bedroom to 3 m^2 in four-bedroom dwellings. However, in the analysis, the compliance rates with storage standards decreased with the number of rooms from 49% in one-bedroom dwellings to 17% in five-bedroom dwellings, with no significant difference between those satisfying and failing to satisfy overall GIAs.

The compliance rates were highest in 1965–1972 at 66% and 1973–1982 at 64%. This period was followed by a drop in 1983–1992 to 41% and had the lowest compliance rate of 18% in 1993–1999. Most recent dwellings built in 2000–2018 have a compliance rate of 44%.

London Standards did not directly prescribe minimum circulation areas. However, a 5% circulation allowance was used for one-storey dwellings and a 19 m^2 staircase and hallway space for two-storey dwellings (which includes Lifetime Home accessibility standards, Table S1). Only 23% of dwellings sampled had circulation areas above these (Table S5). In 27% of one-storey and 12% of two-storey dwellings, circulation areas were higher than those calculated in the London Standards. While 51% of dwellings that met the overall GIAs also met these circulation areas, this dropped to 11% in dwellings that were below recommended GIAs.

Discussion

Housing space shortage in London

Average dwelling sizes in the UK are reported as the smallest in Europe (Evans & Hartwich, 2005; Gallent et al., 2010). This study found that 61% of dwellings fail the London Standards. This is higher than that previously estimated by comparable studies, for instance, based on representative data from housing across England, Morgan and Cruickshank (2014) calculate that up to 55% fail the London Standards.

This very high rate of failure suggests that there is a considerable lack of space in London's dwellings. Based on the maximum number of bedspaces in a dwelling, the average floor area per bedspace is 19 m^2. In comparison, the average space per person is 35 m^2, when considering actual occupancy levels (GLA, 2021). This indicates high levels of under-occupation that are partially explained by a market preference for dwellings with smaller but more rooms (Leishman et al., 2004), shrinking household sizes, and differences in dwelling types in inner and outer London. Although problems with dwelling or room sizes can be compensated by high under-occupancy rates as found by Morgan and Cruickshank (2014), they suggest significant issues in rental and subsidized housing that tend to be built to the lowest permissible standards while having the highest levels of full occupancy. For example, according to the GLA, in the period 2015–2017, the average floor area per person for all Londoners was 33 m^2, but 41 m^2 for owner-occupants and 26 m^2 for social housing tenants (GLA, 2021). This social divide is exacerbated by the highest rates of overcrowding (9%) and lowest rates of under-occupancy (10%) in housing for social rent compared to 1% and 52%, respectively, in owner-occupied homes (MHCLG, 2019).

The inequitable distribution of housing is also evident from the wide range of dwelling sizes in London.

In one-storey and two-storey homes, the largest is often 2–2.5 times the size of the smallest dwellings with the same number of habitable rooms and storeys. However, average dwelling sizes are closer to the lower end of their ranges. This is expected as much housing tends to be standardized and designed to just meet minimum expectations, whether defined by space standards or market norms (Hooper & Nicol, 1999; Leishman et al., 2004).

Recent debate has paid much attention to dwellings such as studios and one-bedroom dwellings that are smaller than the minimum dwelling size of 37 m^2 permitted by current space standards. Substandard studios and one-bedroom dwellings were found on the increase, with EPCs for dwellings less than 37 m^2 making up over 8% of all certificates issued in 2019 (Hubbard et al., 2021). These were often enabled by permitted development rights (Ferm et al., 2020) until changes in regulations in 2021. This problem is also highlighted by this analysis showing that 63% of studios and 10% of one-bedroom dwellings are below the permitted minimum of 37 m^2. While the failure rate of studios built after 2000 is lower (50%), this is clearly a persistent problem as substandard dwellings are found within all periods.

This study further found that 58% of dwellings fail the desirable criteria – bedroom and living area sizes – of the London Standards. Most dwellings failing dwelling size standards also fail desired room sizes. For example, compliance with living area standards changes significantly between dwellings that meet overall GIAs and do not, ranging from 93% to 26% in one-bedroom dwellings. This aligns with previous research that found that living areas are the rooms developers adjust most relative to dwelling size and cost constraints (Hooper & Nicol, 1999; Leishman et al., 2004; Imrie, 2010). However, the analysis also demonstrates that space standards do not guarantee the desired usability. Twenty-seven per cent of dwellings fall short of 'desirable' room sizes despite meeting minimum dwelling sizes, suggesting that more contextual design determinants must be considered, such as site or building shape and layout inefficiency.

Beginning with the Parker Morris standards, prescribing room sizes was debated but decided against in favour of greater flexibility in provision (MHLG, 1961; Goodchild & Karn, 1997). Even the London Standards remained cautious and made room sizes desirable rather than mandatory. Moreover, previous research found that room sizes and space for furniture and activities matter to occupants more than overall dwelling size, suggesting a need to review dwelling design and internal floor area distribution (Leishman et al., 2004; Finlay et al., 2012). This is particularly important when considering accessibility requirements (Milner & Madigan, 2004; Imrie, 2010). Furthermore, the COVID-19 pandemic and stay-at-home restrictions have made the lack of space evident to many occupants, for instance, as an inability to create a desk space for work from home (Hubbard et al., 2021).

Effectiveness of space standards

As the analysis suggests, despite significant numbers of dwellings from all built periods being below the standards in use at a time, space standards are effective when consistently applied. For example, public-sector dwellings that were controlled in their size until the 1980s often produced standardized housing solutions of similar size just around the minimum space standards.

In the period that followed the abolishment of Parker Morris standards, the shortage of space, particularly at room levels, was highest. As also confirmed by Goodchild and Karn (1997), after the abolishment of the Parker Morris standards, the average double bedroom size dropped to 11.5 m^2 as overall dwelling sizes shrunk in the 1980s and 1990s. Karn and Sheridan (1994) also note that the standards established by private housebuilders and housing associations in this period were very low, with bedrooms as small as 4.5 m^2 provided as singles and 9 m^2 as doubles. Hooper and Nicol (1999) further found that the private sector removed storage spaces and decreased dwelling sizes in this period, which were first prescribed by the Parker Morris standards. While the floor plan analysis reflects these historical fluctuations in provision and size, it also highlights a persistent lack of storage space, with 59% of dwellings failing recommendations.

At the same time, even though space standards were not applied to private-sector housing until 2011 in London, the private sector overall outperformed public housing in terms of dwelling size, as also observed in the 1990s by Karn and Sheridan (1994). This points to common cultural changes in housing expectations and usability criteria that are reflected by the housing market. Since the introduction of space standards for all sectors in 2011, dwelling sizes have increased, albeit 33% of dwellings continue to fail minimum standards. This reinforces the importance of cross-sectoral space standards to make them effective and achieve the aim of improving housing quality in the sectors under the greatest economic pressure.

Despite overall substantial and sector-specific failures, the analysis shows that dwelling sizes have generally followed changes in space standards since the 1940s.

However, when interpreting the sizes of dwellings built before the 1940s, it must be considered that these dwellings are mainly terraced houses that have been extended and subdivided since their completion, with their current size no longer linked to space standards but the spatial needs or market conditions at the time they were altered. The relationship between changes in dwelling size and space standards points in various ways to changing housing design expectations and use, with some research explaining how minimum space standards are influenced by transforming social and cultural habits, advances in technology and past housing experiences (Goodchild & Furbey, 1986). For instance, the Parker Morris report paid great attention to new kitchen appliances and changing norms of spaces for children and the family, which is reflected in an increase in space standards (MHLG, 1961). Likewise, the London Standards are higher than the Parker Morris standards, as dwelling needs and market preferences have changed (Park, 2017; Mukhtia, 2020). This is evident from average dwelling sizes already rising before the introduction of the London Standards, as also found by the RIBA (2011).

Great differences in the compliance rates between different dwelling types suggest a direct relationship between built periods, associated building typologies and general housing practices. One- and two-bedroom dwellings are mostly one-storey dwellings (85%), with more than half built since 1983 (52%), while three- and four-bedroom dwellings are mostly multi-storey dwellings (69%) and built before 1982 (71%). The proportions of three- and four-bedroom dwellings failing dwelling size standards (70% and 68%) are higher than for dwellings with fewer rooms (59% for one-bedroom and 57% for two-bedroom).

Changes in housing expectations and use are particularly evident at room level across built year periods, as prescribed overall usable floor areas derive in principle from achieving 'desirable' room sizes. But when dwelling size standards change, this is not always proportional to individual room size and might relate to preferred dwelling types, layouts and changing use.

Changes to the smallest bedroom size that have occurred over time indicate how bedrooms are planned and expected to be used relate to changes in property types. Before 1918 and from 1973 to 1999, significantly more of the smallest bedrooms were below the current single bedroom standard, even though average dwelling sizes were not the lowest when compared to dwellings from periods with higher rates of compliance. Dominant until 1918, terraced houses often had so-called box rooms that are comparatively smaller than their other bedrooms and traditionally not always used for sleeping. During the 1970s, although the Parker Morris standards were in place, they did not stipulate interior dimensions to give greater flexibility in the distribution of space and dwelling layouts, noting an increasing preference for additional and smaller rooms (MHLG, 1961).

While bedroom sizes have remained relatively similar in size over time, living areas reflect significant changes in expectations and use. Dwellings built before 1918 and after 2000 are the largest compared to other periods. The large living areas in the older housing stock (largely terraced houses) are mainly due to rear extensions that were added more recently. In dwellings built since 2000, living, dining and kitchen areas are frequently combined. Although this has been conventionally a means of reducing areas needed for circulation and walls, newer dwellings have the largest combined living areas, even when subtracting integrated circulation areas. Hand and Shove (2004) identified a cultural change in the understanding of the kitchen beyond cooking and eating that includes leisure and socialization as an important driver of changes in preferred dwelling layout. These larger and combined layouts in new dwellings and home extensions can be thus understood through changes in social expectations and use.

The analysis highlights that many dwellings have smaller circulation areas than those used to calculate space standards. While the average circulation space in two-storey dwellings is 12.2 m^2, the London Standards are based on 19 m^2, sufficient to meet the Lifetime Home standards. This suggests that circulation areas smaller than those recommended, significantly contribute to high rates of two-storey dwellings failing space standards. However, this does not necessarily lead to diminished dwelling usability, unless accessibility needs are a priority (Rooney et al., 2013). Nearly half of all bedrooms (45%) and two-thirds of circulation spaces (77%) in existing dwellings fall short of the current standards, and thus dwellings often cannot meet recently introduced accessibility standards.

Conclusion: future research directions

Space standards are just one indicator of dwelling usability and how home use and expectation are changing. As this study found, 61% of dwellings in London, based on the calculated maximum bedspaces, fail the recommended overall dwelling sizes of the London Standards, 51% at least one of its double- and single-bedroom standards, and 88% do not meet all its spatial and dimensional requirements at room level.

From the analysis, two important observations about the effectiveness of space standards can be made. Both

Table 2. Considerations for future research and policy related to space standards.

	Usability	Design	Effectiveness
Evidence	• Studies into socio-cultural norms, lived experience and how occupants use their homes in relation to housing preferences and needs. • Studies into housing design in relation to the quality of space and the wellbeing and health of occupants.	• Research into the understanding of adaptability and flexibility of domestic space. • Post-occupancy evaluations.	• Data on changes in housing expectations and use due to wider historical challenges (e.g. demographic change, climate change, COVID-19).
Calculation	• Data on home use, expectations and needs.	• Consideration of dwelling morphologies, plan organization, and target household composition.	• Development of assessment metrics for space standards that not only consider usability or functionality but also the social value of housing. • Greater regulation of maximum occupation rates that is consistent with space standards.
Implementation	• Assessment of usability considering design factors such as shape compactness and environmental aspects (e.g. accessibility, building orientation or location).	• Development of a wider range of exemplary or alternative plan layouts to support space standards.	• Making minimum standards mandatory for all housing sectors. • Possible applications to existing housing stock (e.g. when substantially redeveloped or subdivided); economic and policy incentives to adapt and upgrade homes.

highlight the need for a more holistic approach to regulating and analysing housing usability and needs that continue to change.

First, as space standards have so far not been consistently applied in England or London, most dwellings are below the recommended minimum usable floor area. Based on the study, in the mid-1940s to mid-1960s, the failure of dwellings to meet space standards in use at the time was a minimum of 63%. Even during the much-lauded Parker Morris standards (until 1980), failure rates were above 40% and as high as 61%. However, only 33% of dwellings built since 2010 fail space standards. It is thus evident that space standards are effective when applied across all housing sectors. However, increases in dwelling size are not always directly linkable to space standards. Market conditions, economic status and housing expectations are significant drivers, with dwelling sizes in the private housing sector overall larger than in the public sector.

Second, satisfying floor area requirements does not ensure dwelling usability at room level. Usability can be limited by inefficient space distribution, room shape, the position of windows, doors and other physical elements, or ceiling heights. Dwellings that do not meet required GIAs can still be fully usable. Usability and housing quality thus depend on more factors than dwelling size and are linked to actual occupancy rates, making space standards an insufficient measure on their own. For example, while occupants generally value room sizes, space for furniture and storage, and environmental conditions (Finlay et al., 2012), some prefer having more and smaller rooms over large rooms (Leishman et al., 2004). In addition, greater control over the distribution and dimensioning of space is needed when taking accessibility into account, which is now mandatory. The impact of space shortage on housing use and flexibility varies between dwelling types and actual occupancy levels (and implicitly between tenures). In addition, differences in the internal planning and uses of homes during various periods are an important consideration, as much of London's housing is old and new pressures on dwelling usability have emerged during COVID-19.

The room-level analysis has revealed critical differences in how floor areas are distributed, which is spatially explained by morphological differences (dwelling types and building typologies). Space standards currently do not account for differences in internal layouts that have a significant impact on overall dwelling size and usability. In future research, it is therefore important to consider dwelling morphology, plan layout and compactness together when assessing but also determining space standards. For example, layouts might simply differ from those considered in space standard calculations without compromising dwelling usability.

Following this, there is also a need to consider how design plays a role in both establishing and challenging space standards through exemplary or alternative plan layouts. This should be studied in relation to other forms of spatial reasoning and evidence as well as notions of efficiency or flexibility. These underpin sometimes contradictory meanings of housing usability and quality to different stakeholders and occupants. Especially flexibility is of great importance to occupants to an adaptation of spaces to their needs, as is the quality of space, which directly affects wellbeing and perception of space. Both flexibility and quality of space are important but lacking areas of research to contextualize space standards.

It is further apparent that many factors determining dwelling layouts are decided and designed at the building scale, such as access types and building typologies. Therefore, data at dwelling and building scales, and in some cases also the urban block, must be better integrated into the assessment of housing quality. This also means that studies of housing quality and usability should extend to 3D and contextual analyses to understand wider environmental and spatial factors such as building orientation or height restrictions.

Space standards are based on assumptions about the use of space and design expectations. However, as the analysis of different usability and dwelling size standards shows, there is a lack of studies on how occupants actually use their homes and how daily experience defines housing expectations, usability and functionality. The preferences of occupants regarding home use, space distribution and room sizes are another important area of further study.

Based on the analysis of this paper, the suggested future research has two main but interrelated objectives as indicated in Table 2. First, to enhance the effectiveness of space standards, greater policy intervention is needed, requiring a stronger evidence base, more detailed calculation and wider implementation. Second, from a user perspective, the question of usability needs to be clarified by considering wider socio-cultural and daily use-based evidence that can inform user-centred calculations and metrics to better guide the implementation of space standards. Finally, effectiveness and usability are, as this study underlines, in many ways connected to problems of planning and designing homes, as issues such as home usability, adaptation and flexibility depend on the design and layout of dwellings. Without this diverse knowledge of how occupants live in and perceive their homes in relation to the space offered and its quality and design, it is impossible to fully assess if space standards are effective and can meet changing housing needs.

Note

1. While the findings in this paper discuss the applicable London Standards, additional data regarding the NDSS are given in Table S11 for future research and national comparisons. In the NDSS, minimum dwelling sizes for single-storey dwellings are identical to the London Standards, but those for two- and three-storey buildings are generally 3 m^2 lower, returning a higher overall rate of compliance with dwelling size standards of 41% (compared to 39%).

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