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COMPARATIVE SIMULATION OF CIRCULATION DENSITY AND POTENTIAL AIRBORNE EXPOSURE IN CO-HOUSING AND SOCIAL HOUSING TYPOLOGIES

Birlikte Yaşam (Co-Housing) ve Sosyal Konut Tipolojilerinde Dolaşım Yoğunluğu ve Potansiyel Havadan Maruz Kalmanın Karşılaştırmalı Simülasyonu

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ABSTRACT

This study investigates how co-housing typologies influence circulation density and relative airborne exposure conditions among non-kin occupants. Using conceptual assumptions derived from the Wells–Riley framework, the study evaluates relative airborne exposure potential in densely occupied shared environments. A concentric circulation model was developed based on Hillier's (2007) theory of spatial behavior and simulated using AnyLogic software. Input parameters were derived from empirical data and spatial configurations of existing social-housing layouts. The model analyzes circulation typologies and occupant density (persons/m²) to evaluate relative airborne exposure potential based on spatial concentration patterns. Results provide a comparative spatial framework for assessing density-related airborne exposure conditions in co-housing designs under pandemic conditions such as COVID-19.

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ÖZ

Bu çalışma, akraba olmayan kullanıcılar arasında ortak konut tipolojilerinin dolaşım yoğunluğu ve göreli havadan maruziyet koşulları üzerindeki etkilerini incelemektedir. Wells–Riley çerçevesinden türetilen kavramsal varsayımlar kullanılarak, yoğun kullanılan ortak mekânlardaki göreli havadan maruziyet potansiyeli değerlendirilmektedir. Hillier'in (2007) mekânsal davranış teorisine dayalı olarak eşmerkezli bir dolaşım modeli geliştirilmiş ve AnyLogic yazılımı kullanılarak simüle edilmiştir. Girdi parametreleri, ampirik verilerden ve mevcut sosyal konut düzenlerinin mekânsal konfigürasyonlarından türetilmiştir. Model, mekânsal yoğunlaşma örüntülerine dayalı olarak göreli havadan maruziyet potansiyelini değerlendirmek amacıyla dolaşım tipolojilerini ve kullanıcı yoğunluğunu (kişi/m²) analiz etmektedir. Sonuçlar, COVID-19 gibi pandemi koşullarında ortak konut tasarımlarındaki yoğunluk temelli havadan maruziyet koşullarını değerlendirmek için karşılaştırmalı bir mekânsal çerçeve sunmaktadır.

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RESEARCH ARTICLE / ARAŞTIRMA MAKALESİ

1. INTRODUCTION

1.1. Historical Evolution and Contemporary Objectives of Co-Housing

Co-housing refers to a residential model that combines private living units with shared communal facilities and collective social interaction. Although its contemporary form became widespread in Denmark during the 1960s, collective living models have historically emerged in response to social, economic, and spatial challenges (Scotthanson & Scotthanson, 2004; Vestbro, 2010).

Contemporary co-housing developments are increasingly associated with affordability, sustainability, and community-oriented living. Shared facilities, compact spatial organization, and collective circulation systems support social interaction and efficient land use (Hagbert et al., 2020; Baas, 2021). However, the COVID-19 pandemic also highlighted the potential vulnerability of densely shared indoor environments to airborne disease transmission. The global scale of the pandemic, which resulted in hundreds of millions of confirmed cases worldwide, further emphasized the importance of understanding transmission risks in shared indoor environments (Worldometer, 2025). In this context, circulation intensity and occupant density within co-housing environments have become important topics for architectural and public-health-oriented spatial research

1.2. Transmission Mechanisms of COVID-19 and Implications for Indoor Environments

COVID-19 emphasized the importance of indoor environmental conditions in the transmission of airborne diseases. Aerosolized virus-containing particles may remain suspended in enclosed environments for extended periods, particularly in spaces with limited ventilation and high occupant density (Ehsanifar, 2021; Chan et al., 2011).

The Wells–Riley framework provides a conceptual basis for understanding airborne exposure risk in enclosed environments. According to this framework, spaces with insufficient ventilation and concentrated occupancy may increase the probability of airborne exposure due to prolonged aerosol accumulation.

In residential buildings containing shared circulation systems and communal spaces, occupant density and movement patterns become critical spatial variables affecting potential airborne exposure conditions. Therefore, this study investigates how different residential typologies—

specifically co-housing and conventional social housing—affect circulation density and spatial exposure potential through a comparative simulation-based approach.

Accordingly, the primary objective of this study is to compare the spatial resilience of co-housing and conventional social housing typologies against airborne disease transmission through circulation density analysis. To achieve this, a concentric circulation model based on spatial syntax theory is developed and simulated using the AnyLogic platform. The study aims to quantify crowd density distributions and identify spatial risk concentrations associated with different residential configurations.

2. METHOD

2.1 Methodological Framework

This study develops a comparative spatial simulation framework to evaluate how circulation density and spatial configuration influence relative airborne exposure potential in co-housing and conventional social housing environments. The methodological workflow consists of sequential stages integrating spatial data preparation, concentric circulation modeling, occupant behavior simulation, and density-based exposure interpretation.

Initially, international housing standards, planning guidelines, and co-housing literature were reviewed to establish generalized residential area requirements for both housing typologies. Residential unit sizes, communal-use spaces, and circulation-area ratios were calculated to create comparable spatial configurations under equivalent resident populations.

Following the spatial preparation stage, concentric circulation layouts were developed based on spatial syntax principles to standardize circulation permeability, accessibility, and movement comparability across different residential typologies. The concentric organization enabled the evaluation of circulation overlap and shared occupancy conditions under controlled spatial conditions. The concentric circulation model was intentionally developed as an abstract and standardized spatial framework rather than a direct representation of a specific architectural housing typology. The purpose of this abstraction was to minimize configurational variability and establish equivalent circulation conditions for comparative simulation analysis.

Concentric geometry was selected because it enables comparable accessibility, circulation distance, and spatial permeability across all residential units relative to shared-use areas. Unlike irregular or asymmetrical residential layouts, the concentric organization reduces spatial bias caused by unequal corridor depth, fragmented circulation paths, or disconnected communal zones.

This controlled spatial configuration allows the study to isolate circulation-density effects independently from architectural irregularities specific to individual building plans. Therefore, the concentric model functions primarily as a comparative analytical framework for evaluating circulation concentration and occupant overlap under standardized spatial conditions.

Occupant behavior and circulation dynamics were then simulated using the AnyLogic Pedestrian Library through agent-based modeling techniques. Pedestrian agents representing residents moved between predefined spatial destinations according to occupancy probabilities and indoor space-use behavior patterns derived from residential behavior studies. Density accumulation was calculated dynamically throughout the simulation process using persons per square meter (persons/m²) as the primary spatial indicator.

The resulting density maps were interpreted through the conceptual assumptions of the Wells–Riley framework. Rather than directly calculating epidemiological infection probability, the study evaluates how circulation concentration, prolonged occupant overlap, and shared-use areas may contribute to relative airborne exposure conditions within enclosed residential environments. Recent studies have further expanded the Wells–Riley framework for probabilistic indoor airborne exposure estimation under varying occupancy conditions (Xenakis, 2023).

The methodological workflow of the study is summarized below:

1. Spatial data collection and area calculations;
2. Development of concentric circulation layouts;
3. Definition of occupant movement behavior;
4. Agent-based simulation using AnyLogic;
5. Generation of density concentration maps;
6. Interpretation through the Wells–Riley framework;
7. Comparative spatial exposure assessment.

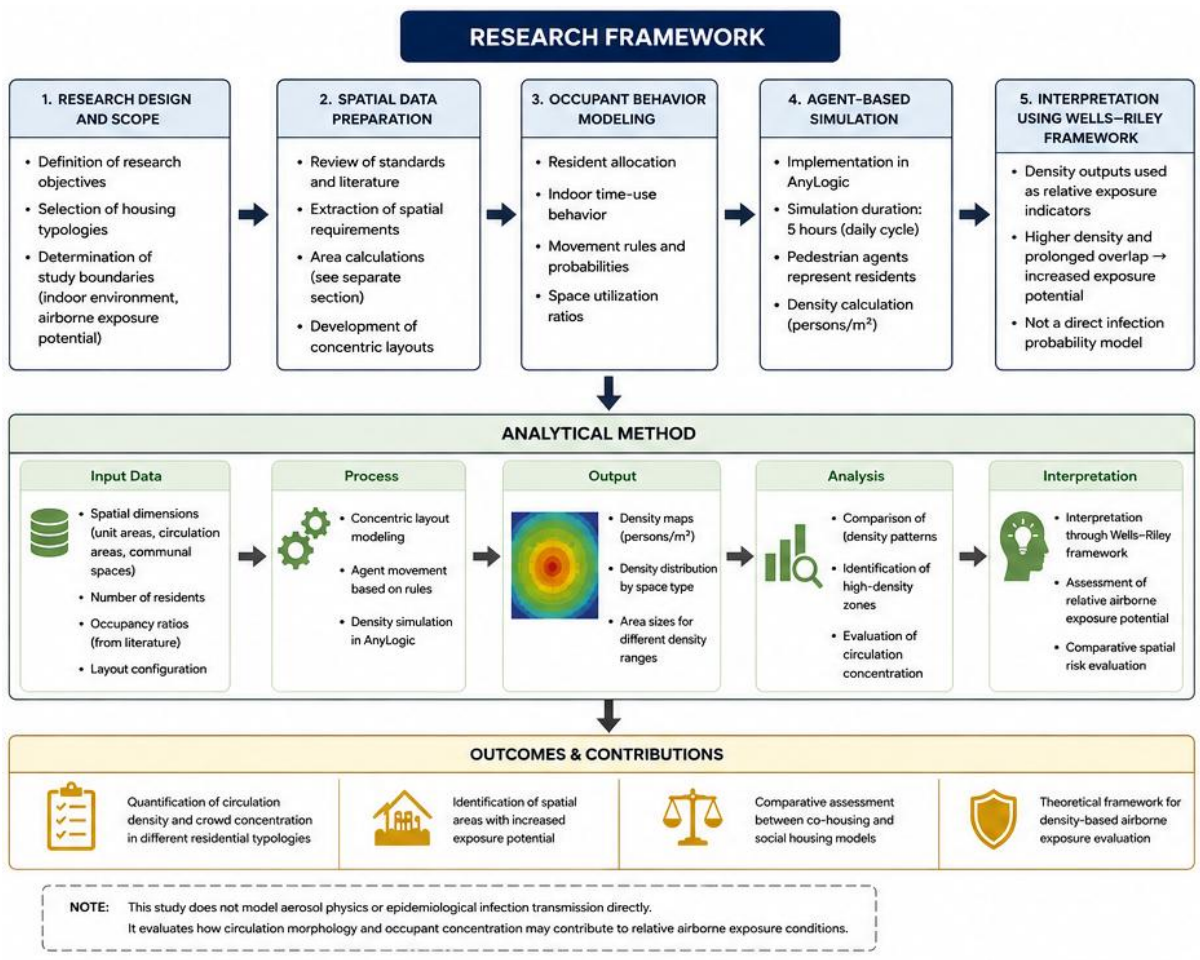

Figure 1. Research methodology framework.

Şekil 1. *Araştırma metodolojisi çerçevesi.*

2.2 Simulation Framework

Spatial dimensions and residential area calculations were derived from international housing standards and co-housing planning guidelines. Residential unit sizes, communal-use areas, and circulation spaces were generalized to establish standardized residential configurations for comparative simulation scenarios.

For social housing typologies, dwelling-unit dimensions were categorized according to representative residential standards. In co-housing typologies, smaller private units were integrated with additional communal spaces such as shared kitchens, lounges, and collective-use facilities. Circulation spaces including corridors, stairs, and access routes were calculated as approximately 30% of the total usable area.

A standardized resident population of 100 occupants was used in all simulations to establish equivalent comparison conditions between different residential typologies.

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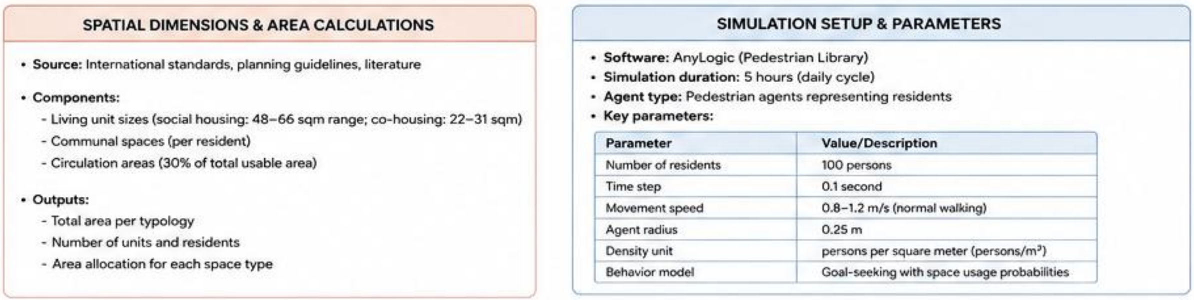
Occupancy ratios and indoor movement distributions were adapted from residential behavior studies to define movement probabilities and space-utilization behavior.

The simulation framework was implemented using the AnyLogic Pedestrian Library. Pedestrian agents representing residents moved between predefined destinations according to behavioral probabilities and circulation rules. Simulations were conducted over a five-hour daily cycle to evaluate density accumulation and circulation concentration during indoor occupancy periods.

Key simulation parameters included simulation duration, movement speed, agent radius, density calculations, and time-step intervals. Density outputs were calculated dynamically as persons per square meter (persons/m²), generating spatial density maps representing circulation overlap and occupant concentration.



SPATIAL DIMENSIONS & AREA CALCULATIONS

- **Source:** International standards, planning guidelines, literature
- **Components:**
  - Living unit sizes (social housing: 48–66 sqm range; co-housing: 22–31 sqm)
  - Communal spaces (per resident)
  - Circulation areas (30% of total usable area)
- **Outputs:**
  - Total area per typology
  - Number of units and residents
  - Area allocation for each space type

SIMULATION SETUP & PARAMETERS

- **Software:** AnyLogic (Pedestrian Library)
- **Simulation duration:** 5 hours (daily cycle)
- **Agent type:** Pedestrian agents representing residents
- **Key parameters:**

Parameter	Value/Description
Number of residents	100 persons
Time step	0.1 second
Movement speed	0.8–1.2 m/s (normal walking)
Agent radius	0.25 m
Density unit	persons per square meter (persons/m²)
Behavior model	Goal-seeking with space usage probabilities

Figure 2. Spatial dimensions and area calculation framework, and simulation setup and key parameters.

Şekil 2. *Mekânsal boyutlar ve alan hesaplama çerçevesi,ve simülasyon kurulumu ve temel parametreler.*

The agent-based simulation framework was configured using the AnyLogic Pedestrian Library under standardized behavioral and environmental conditions. Pedestrian agents were assigned probabilistic movement behaviors derived from residential indoor occupancy studies and shared-space utilization patterns.

Each resident agent was programmed to move between private living units, circulation corridors, and communal-use spaces according to predefined stochastic transition probabilities. Destination selection was determined through weighted random distributions reflecting daily residential movement tendencies.

Movement speed parameters were standardized between 1.0–1.4 m/s to represent typical indoor pedestrian behavior under non-emergency residential conditions. Agent body radius was defined as 0.25 m to maintain realistic interpersonal spacing and collision avoidance behavior within circulation routes.

The simulation environment utilized dynamic density calculation functions embedded within the AnyLogic Pedestrian Library. Spatial density accumulation was continuously calculated as persons per square meter (persons/m²) at discrete simulation intervals throughout the five-hour occupancy cycle.

Time-step intervals were maintained under fixed simulation resolution to ensure stable pedestrian-flow computation and consistent density-map generation across all housing typologies.

To minimize configurational variability, all residential scenarios were simulated under equivalent assumptions regarding:

- resident population size,
- circulation accessibility,
- movement duration,
- occupant activity schedules,
- and shared-space usage probability.

This controlled simulation structure enabled the comparative evaluation of circulation-density concentration independently from behavioral or environmental variability.

2.3 Assumptions, Analytical Method, and Limitations

Simulation outputs were comparatively analyzed according to density distribution patterns and circulation concentration levels observed within different residential typologies. Density maps generated through AnyLogic simulations were classified according to persons-per-square-meter ranges representing different exposure-density conditions.

Areas characterized by increased pedestrian concentration, repeated circulation overlap, and prolonged shared occupancy were interpreted as zones with elevated relative airborne exposure potential. The analytical comparison focused on identifying high-density circulation zones and evaluating how communal-space integration influences circulation concentration patterns.

The Wells–Riley framework was employed conceptually to interpret density-related airborne exposure conditions. However, the model was not directly implemented as a quanta-based epidemiological infection equation. Variables including aerosol dispersion, ventilation performance, HVAC systems, pathogen decay, mask usage, and biological transmission mechanisms were not explicitly simulated.

Several simplifying assumptions were adopted to establish a controlled comparative framework. All residential typologies were evaluated under equivalent ventilation assumptions, similar movement behaviour, equal simulation durations, and standardized circulation conditions. The concentric circulation model was selected to minimize configurational variability and improve comparability between residential typologies.

Although the concentric circulation geometry inevitably simplifies real residential morphologies, the abstraction improves methodological control by enabling equivalent spatial comparison between different housing typologies. Therefore, the model should be interpreted as a generalized analytical framework rather than a direct architectural prototype.

Therefore, the findings should be interpreted as comparative spatial-density assessments rather than deterministic epidemiological infection predictions. The study primarily evaluates how circulation morphology and occupancy concentration may contribute to relative airborne exposure conditions within enclosed residential environments.

OTHER ITEMS TO STRENGTHEN THE METHOD SECTION		
1	Justification of choices	Explain why the concentric model was chosen and why 100 residents were used as a standard case.
2	Assumptions	List all key assumptions (e.g., equal ventilation in all spaces, similar behavior among residents, no mask effect, etc.).
3	Limitations	Clarify the limitations of the model (no aerosol physics, no ventilation simulation, simplified behavior).
4	Sensitivity / Robustness (optional)	If possible, mention that different scenarios (unit sizes, occupancy ratios) were tested.
5	Validation (if any)	Describe any validation or reasonableness check of the model (e.g., comparison with observed density patterns in literature).
6	Data sources	Provide clear references for all numerical data (standards, occupancy ratios, movement parameters).

Figure 3. Additional methodological considerations.

Şekil 3. *Ek metodolojik hususlar.*

3. GENERALIZED SPATIAL DIMENSIONS AND CHARACTERISTICS OF SOCIAL HOUSING AND CO-HOUSING

Spatial requirements and typologies for social housing and co-housing developments are typically established by architects, designers, and real estate professionals with an emphasis on optimizing occupant comfort, rather than minimizing or excessively expanding residential areas (Gensler, 2012; Elbir, 2023). These spatial parameters are influenced by various factors including user demographics, design objectives, and financial constraints. Although municipal regulations and standardized housing policies provide baseline guidelines, spatial configurations vary substantially, necessitating a systematic itemization and classification of spatial features to enable precise characterization of these housing typologies (Aalbers, 2015).

Co-housing typologies are implemented in both urban and rural contexts, with distinct spatial characteristics reflecting their environmental settings. Rural co-housing frequently comprises dispersed, cluster-based dwellings with shared common areas, typically consisting of a limited number of residential units. In contrast, urban co-housing developments, particularly those located in city centers, tend to be high-density structures incorporating numerous units, often ranging from studio apartments to clustered flats (Levinson, 2003; Darling, 2017).

Urban co-housing environments are frequently associated in the literature with compact living arrangements and shared green spaces that may support social interaction and resident well-being (Giorgi et al., 2021). However, such environmental and psychological effects were not directly evaluated within the scope of the present simulation framework, which primarily focuses on circulation density and spatial exposure potential. However, urban co-housing typically exhibits higher population density and stronger social connectivity compared to rural counterparts, underscoring the importance of assessing their role in airborne disease transmission, such as COVID-19.

To analyze social and co-housing spatial characteristics, housing units are schematized to include circulation zones, shared common areas, and private living units, as depicted in Figure 2 (Gensler, 2012).

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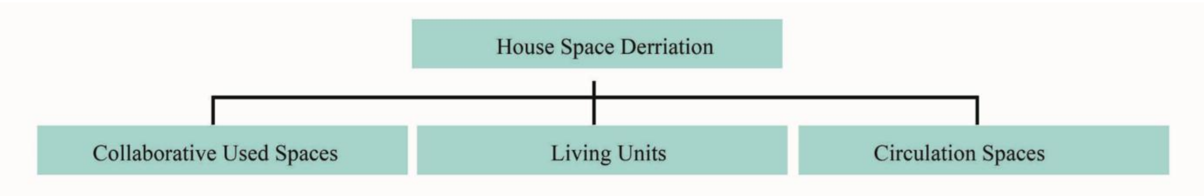


Figure 4. Schematization of co-houses' and basic social houses' space using.

Şekil 4. *Ortak konutlar ve temel sosyal konut birimlerinde mekân kullanımının şematik gösterimi.*

Various governmental guidelines and design manuals define minimum habitable space standards, often codified within construction legislation to ensure adequate living conditions for households. For example, European social housing regulations specify minimum floor areas ranging from 43 sqm to 70 sqm, varying by country (Table 1) (Keleş, 1996). The countries presented in Table 1 were selected according to the availability of comparable regulatory data concerning minimum social housing space standards and their relevance within established European social housing frameworks. These examples were intended to provide a representative cross-section of welfare-oriented housing policies rather than a statistically exhaustive sample of all European countries. Consequently, the table serves as a generalized reference framework for deriving standardized residential area ranges utilized in the comparative simulation model. While these figures represent regulatory minima, actual housing constructions generally meet or exceed these thresholds. To generalize minimum space requirements across heterogeneous data, standard deviation is applied to derive a statistically robust range of typical minimum floor areas.

Table 1. Representative minimum social housing unit space standards in selected European countries.

Tablo 1. *Seçilmiş Avrupa ülkelerinde temsilî sosyal konut minimum alan standartları.*

Countries	Published Year	Minimum Space Areas (sqm)
Austria	1956	55 sqm
Finland	1955	50-55 sqm
France	1955	56 sqm
Holland	1956	58 sqm
Norwegian	1956	70 sqm
Sweden	1956	60-70 sqm
Hungary	1956	43 sqm

The selected countries provide a representative reference framework for comparing European minimum social-housing standards.

Standard deviation was used to generalize representative residential space ranges derived from heterogeneous national housing standards.

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N} (x_i - \mu)^2}$$

Standard deviation (σ), a statistical measure of data dispersion from the mean (μ), quantifies the variation among minimum space values reported by different countries (National Library of Medicine, 2025). Utilizing this approach, the mean minimum floor area across the countries surveyed is approximately 57.07 sqm, with a standard deviation of 8.71 sqm. Consequently, typical minimum social housing floor areas can be generalized to range between approximately 48 sqm and 66 sqm.

Further spatial requirements for social housing are derived from the Department for Communities and Local Government's 2013 guidebook, which outlines that residential indoor environments comprise basic and ancillary sub-spaces. Basic spaces include living, sleeping, dining, washing, toilet, and storage areas, while ancillary or side spaces encompass elements such as balconies and sunshades. In multi-story residential buildings, additional circulation areas—such as stairwells, lifts, and corridors—are included. Notably, traditional social housing designs generally do not incorporate collaborative shared spaces (Department for Communities and Local Government, 2013).

Based on this framework, minimum floor space requirements per dwelling unit range between 48 sqm and 66 sqm, with an additional 9 sqm allocated per additional occupant, divided as 6.5 sqm for basic spaces and 2.5 sqm for ancillary spaces. Given the average household size of approximately 2.3 persons in the European Union, typical social housing units require between 60 sqm and 78 sqm to accommodate occupants comfortably (European Commission Eurostat, 2025).

In contrast, co-housing developments, which include both private living units and shared communal spaces, are governed by distinct spatial standards. The Glasgow City Council's *Large-Scale Co-Living Planning Guidance* (2024) specifies minimum private unit sizes of 31 sqm, with an allowance to reduce to 22 sqm in cases of retrofitting existing structures. These self-contained units typically incorporate integrated kitchenettes, living, and sleeping areas.

Communal facilities in co-housing schemes include shared kitchens, dining areas, and laundry rooms, as outlined in Table 2. Additionally, shared sanitary facilities must be provided adjacent to these spaces. To foster community interaction, an additional 5 sqm per resident is recommended for shared spaces, including semi-open gardens or terraces, with communal outdoor areas not less than 40 sqm (Glasgow City Council, 2017). Thus, large-scale, multi-story co-housing buildings should allocate approximately 6 sqm per resident to communal amenities (Table 3).

Table 2. Supporting spaces of international co-housing buildings facilities given all residents (Glasgow City Council, 2017).

Tablo 2. *Uluslararası Ortak Konut Yapılarında Tüm Sakinlere Sunulan Destekleyici Alanlar (City Development Plan 2017, 2024).*

Communal Facilities	İs it involved in 1 sqm of 'supporting' spaces?	Other definition
Kitchen	Yes	At least 5 cooking stations per kitchen
Dining space	Yes	0.5 sqm per resident
Laundry rooms (included in circulation spaces)	No	1 washer and dryer for each 10 residents

Table 3. Lifestyle and external spaces of international co-housing buildings facilities given all residents (City Development Plan 2017, 2024).

Tablo 3. *Uluslararası ortak konut yapılarında tüm sakinlere sunulan yaşam tarzı unsurları ve dış mekân alanları (City Development Plan 2017, 2024).*

Communal Facilities	Required / Optional	İs it involved in 5 sqm of 'lifestyle and external' communal spaces?	Other definition
İnternational communal space, such as a games room, cinema, library	Required	Yes	
Living room (lounges)	Required	Yes	
Other recreational and work spaces used without charge	Optional	Yes	
Any spaces used with extra charge	Optional	Yes	
External communal space	Required	No	1 sqm is required per resident, and an external

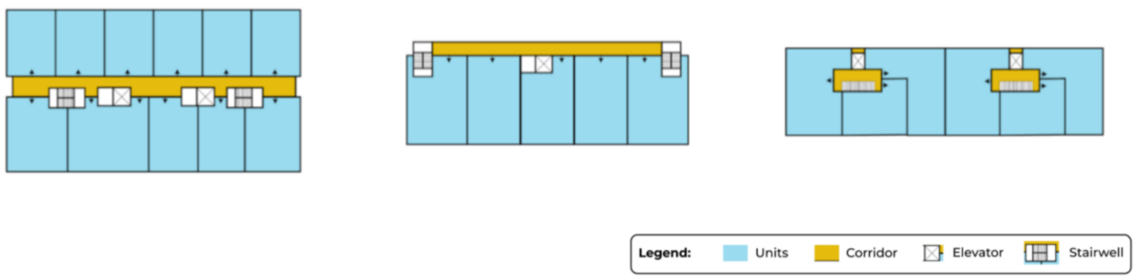
	space can not be lower than 40 sqm

Circulation spaces—comprising corridors, lifts, and stairwells—are an essential component in both social and co-housing buildings. Architectural design literature identifies three primary circulation typologies in multi-story buildings: double-loaded, single-loaded, and point-block access configurations (Table 4). Double-loaded corridors, prevalent in North American residential buildings, accommodate two rows of units along a central corridor, maximizing unit density. Single-loaded corridors serve units on one side only, while point-block access, common in European contexts, clusters units around a central core, promoting compactness (Happy Cities, 2022).

Table 4. Major circulation manners which are always used in house buildings (Happy Cities, 2022).

Tablo 4. *Konut yapılarında yaygın olarak kullanılan başlıca dolaşım türleri (Happy Cities, 2022).*

Double-loaded manner	Single-loaded manner	Point-block access manner



Due to limited region-specific data on circulation area proportions in European housing, this study references the U.S. General Services Administration's Public Buildings Service (2012) guidelines, which indicate circulation spaces comprise approximately 25–40% of total usable floor area. Accordingly, a conservative estimate of 30% circulation space is applied to both social and co-housing building typologies for subsequent spatial calculations.

The resultant spatial requirements for social housing and co-housing buildings, integrating private units, communal areas, and circulation spaces, are summarized in Table 5. These values form the basis for developing concentric layout models used in the exposure potential simulation presented in the following section.

Table 5. Spaces' area calculation with the accordance of 100 residents.

Tablo 5. *100 Kişilik nüfusa göre mekân alanı hesaplaması.*

	Social housing buildings' unit space area calculation						Co-house buildings' unit space area calculation			
	Living units			Circulation spaces			Living units		Collaborative use spaces	Circulation spaces
	With the lower standard deviation	With the standard deviation	With the upper standard deviation							
For the minimum unit of living	48 sqm	57 sqm	66 sqm	30% of living units			**22 sqm per resident (low)**	31 sqm per resident (ideal)	6 sqm per resident	30% of living units and collaborative space
For the average unit of living (2.3 residents per unit)	60 sqm	69 sqm	78 sqm							
In a sample of 100 people	2640 sqm	3036 sqm	3432 sqm	792 sqm(with lower)	910 sqm (with standard)	1030 sqm(with upper)	2200-3100 sqm		600 sqm	840-1110 sqm
Total building area (with the circulation)	3432 sqm	3946 sqm	4462 sqm				3640-4810 sqm			
	For 44 living units-100 persons						**100 persons-100 units**			

4. DEVELOPMENT OF A QUANTIFIABLE CONCENTRIC LAYOUT FOR MEASURING RESIDENTIAL CIRCULATION

Circulation systems organize movement between spatial units and play a significant role in shaping occupant interaction patterns within residential environments. In this study, circulation organization is analyzed as a spatial variable affecting density concentration and movement overlap

Previous architectural studies have shown that spatial configuration influences movement behavior and accessibility patterns within buildings (Hillier, 2007; Natapov et al., 2015). Based on this approach, the present study adopts a simplified concentric circulation framework to standardize movement conditions across residential typologies.

To operationalize spatial configuration analysis, the framework of space syntax is applied, as exemplified in Figure 5. Despite three architectural plans (a, b, c) sharing identical physical subspaces—each containing nine subunits—their distinct syntactic arrangements illustrate how configuration impacts spatial use and user movement.

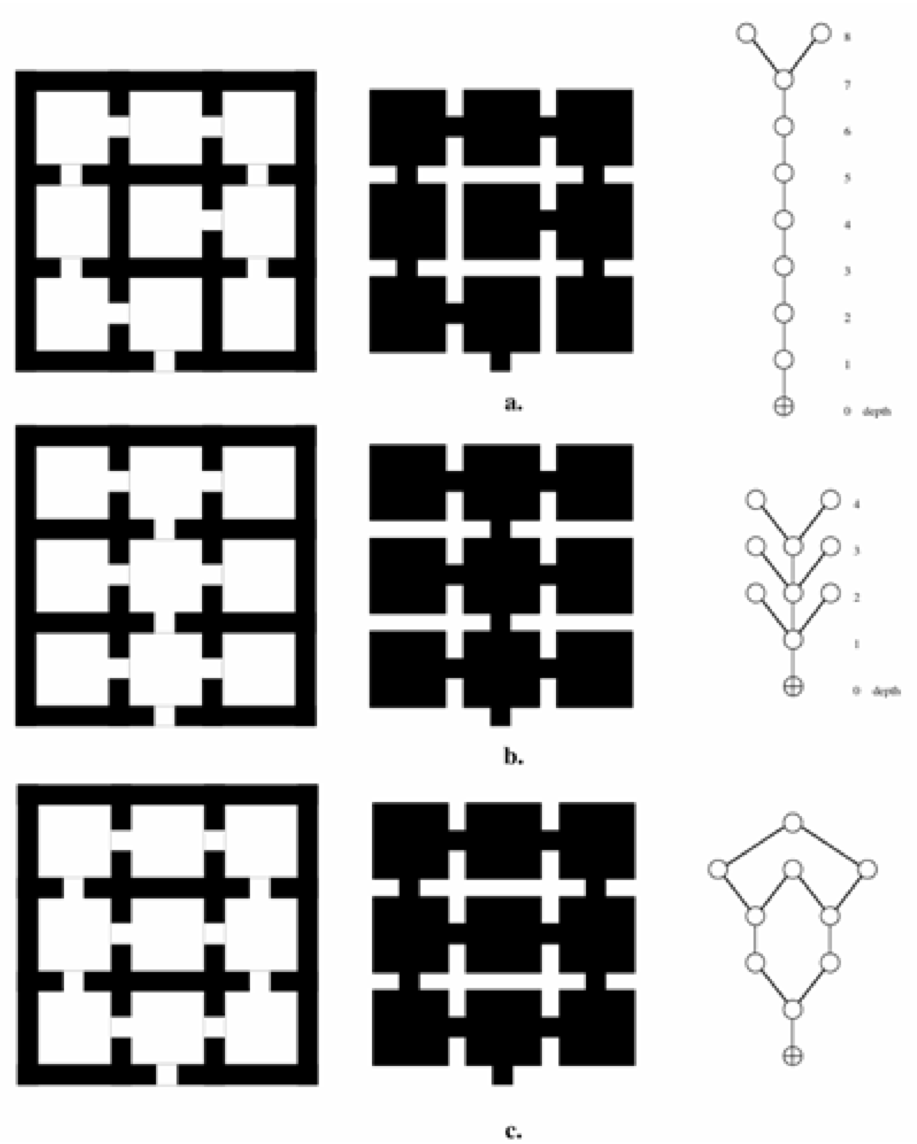


Figure 5. Different configurating of space and different permability of space (Hillier, 2007).

Şekil 5. *Farklı mekânsal konfigürasyonlar ve mekân geçirgenliğinin çeşitli düzeyleri (Hillier, 2007).*

Spatial syntaxes, characterized by distinct configurational patterns, significantly influence individual movement behaviors and spatial usage preferences. Architectural space syntaxes within residential buildings vary widely, reflecting diverse design strategies and functional priorities. However, when quantifying and comparing circulation crowd dynamics within social housing and co-housing environments, no single universal syntax pattern or uniform wayfinding capacity can be assumed across different layouts. To standardize the analysis and control for wayfinding variables, the circular space syntax—frequently cited in architectural research (Hillier, 2007; Natapov et al., 2015)—is adopted as the representative model for this study.

Unlike linear or angular configurations such as 'L', 'I', 'U', or rectangular syntaxes, the circular space syntax is characterized by equidistant side spaces radiating from a central common area. This arrangement ensures that all users access their respective destinations via a shared circulation corridor, with all points being equidistant from the central communal zone. The central common use area, positioned at the core of the concentric syntax, functions as the primary node or embarkation point for movement within the system (Figure 6) (Natapov, Kuliga, Dalton, & Hölscher, 2015; Natapov, Kuliga, & Dalton, 2019).

The concentric circulation model was selected to standardize spatial permeability, route accessibility, and wayfinding conditions across different residential typologies. Rather than representing a specific architectural form, the model functions as an abstract comparative framework that minimizes configurational variability and enables controlled comparison of circulation density patterns. This approach allows the analysis to focus primarily on movement concentration and spatial interaction potential.

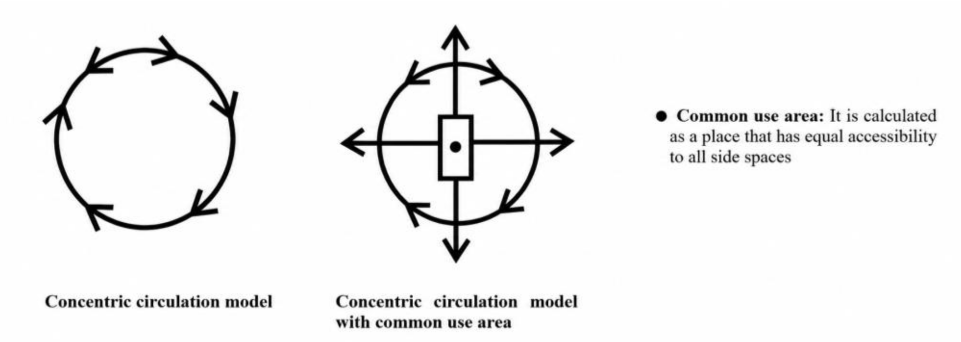


Figure 6. Abstract concentric circulation framework developed for controlled comparative simulation analysis.

Şekil 6. *Kontrollü karşılaştırmalı simülasyon analizi için geliştirilen özet eşmerkezli dolaşım çerçevesi.*

5. MEASURING CROWD DYNAMICS OVER CONCENTRIC LAYOUT VIA 'ANYLOGIC' SIMULATION

In this section, crowd movement and density within prospective layouts—developed based on predefined space types and quantities—are analyzed using the AnyLogic simulation software. AnyLogic offers a comprehensive platform to model and visualize human flow, illustrating how individuals evacuate, congregate, or navigate indoor spaces over specified time intervals. The embedded agent-based IT system in AnyLogic is designed to emulate both individual and group behavioral tendencies with high fidelity (Scherer et al., 2018).

Accordingly, the AnyLogic simulations focused on spatial movement dynamics, pedestrian density accumulation, and occupant interaction intensity across circulation networks. The resulting density maps were interpreted through the theoretical assumptions of the Wells–Riley framework, where increased occupant concentration, prolonged shared occupancy, and repeated circulation overlap are associated with elevated airborne exposure potential.

To maintain methodological consistency, all residential typologies were simulated under equivalent assumptions regarding resident population, movement duration, and circulation accessibility. This controlled comparative framework enables the evaluation of how different architectural configurations influence density-based airborne exposure potential.

The simulation relies on input data describing spatial parameters (such as area and typology) alongside occupant distribution and dwell time within these spaces. Prior to simulation, the layout's components—including spatial widths, types, and the number of occupants directed along different circulation paths—are encoded to ensure accurate representation of movement patterns.

Based on the parameters outlined in Table 5, each social housing unit is modeled assuming an average household size of 2.3 individuals, with unit sizes set at 60 sqm, 69 sqm, and 78 sqm to reflect the range of space provisions. Conversely, co-housing units are modeled with unit sizes of 22 sqm and 31 sqm. Considering that an average co-housing building footprint spans approximately 5,000 sqm (Glasgow City Council, 2017), an initial occupancy estimate is approximately 100 residents. However, given the necessity for co-housing cooperatives to foster balanced community dynamics that support both social interaction and individual privacy (UK Cohousing Network, 2025), the number of living units is adjusted to 40 to better facilitate effective neighborly relations.

A population size of 100 residents was selected to establish a standardized comparative framework between housing typologies and to maintain simulation manageability within comparable spatial scales. This population size also reflects occupancy ranges commonly observed in medium-scale collective residential developments.

Accordingly, a co-housing building with 40 residents requires a total of 240 sqm of communal space. In addition to this, active circulation corridor areas are calculated at 336 sqm and 444 sqm for co-housing layouts. For social housing buildings, circulation areas are computed corresponding to three standard deviation scenarios: 157 sqm (lower deviation), 364 sqm (mean deviation), and 412 sqm (upper deviation). The resulting layouts generated with these spatial parameters are illustrated in Figures 7 and 8.

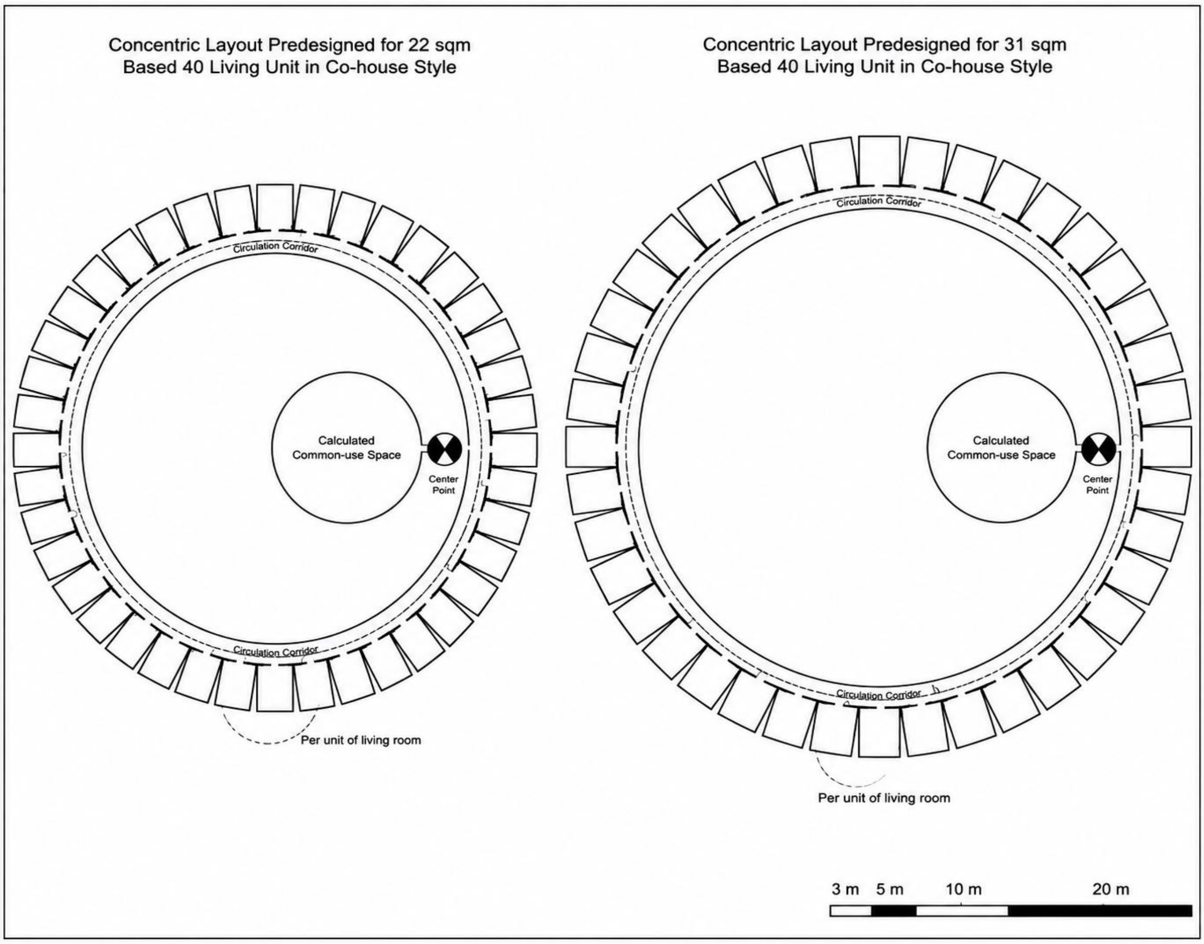


Figure 7. Concentric layouts developed for the average co-housing model, including 22 sqm and 31 sqm living-unit configurations.

Şekil 7. *Hesaplanan ortalama ortak konut yapısı için tasarlanan konsantrik dairesel düzenler: düşük yaşam birimi alan gereksinimi için 22 m² ve yüksek yaşam birimi alan gereksinimi için 31 m² dahil.*

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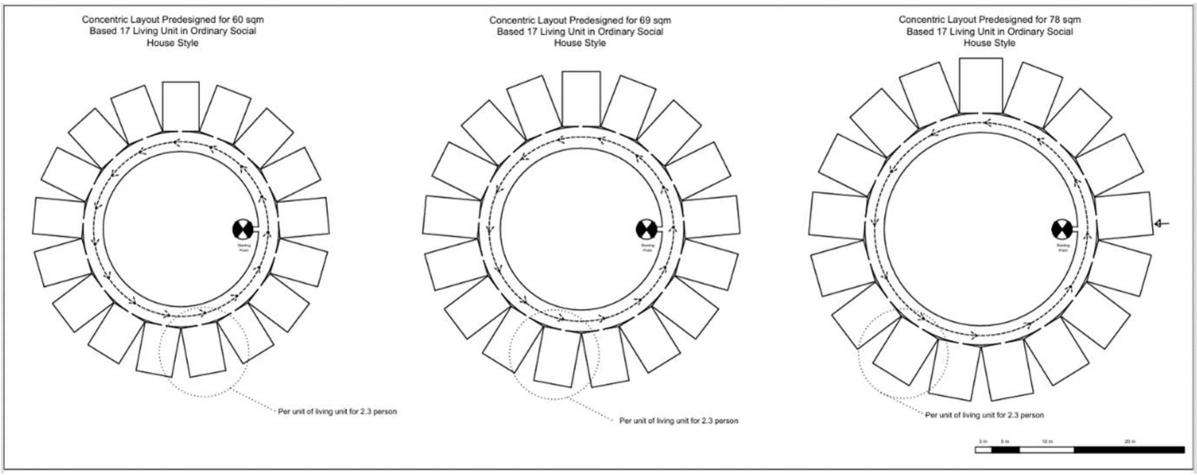

Figure 8. Concentric layouts developed for the average social housing model, including 60 sqm low-deviation units, 69 sqm medium-deviation units, and 78 sqm upper-deviation units.

Şekil 8. *Hesaplanan ortalama sosyal konut yapısı için tasarlanan konsantrik dairesel düzenler: düşük sapmalı yaşam birimleri için 60 m², orta sapmalı yaşam birimleri için 69 m² ve yüksek sapmalı yaşam birimleri için 78 m² alan gereksinimlerini içermektedir.*

The prepared layouts, developed with varying design requirements, exhibit notable differences. Initially, the co-housing layout includes 40 living units, whereas the average calculated social housing layout consists of 17 units. Due to the variation in the spatial dimensions of living units arranged around the circulation area, the corresponding widths and lengths of circulation paths adjust accordingly.

The methodological workflow of the study consists of four sequential stages:

1. Definition of generalized residential spatial typologies based on social housing and co-housing standards;
2. Construction of concentric circulation layouts derived from spatial syntax theory;
3. Agent-based simulation of resident movement and density accumulation using AnyLogic;
4. Interpretation of density concentration maps through the conceptual assumptions of the Wells–Riley airborne exposure framework.

Through this workflow, the study does not directly simulate aerosol physics or infection transmission mechanics. Instead, it evaluates how architectural circulation organization may contribute to relative airborne exposure conditions through density concentration and shared spatial occupancy.

6. RESULTS

6.1. Residential Crowd in Co-housing and Conventional Social Housing

This section presents the density-distribution results obtained from the AnyLogic simulations. The analysis focuses on circulation concentration, occupant overlap, and spatial-density patterns observed across different residential typologies.

Resident movement frequencies were estimated based on household time-use patterns reported by Khajehzadeh and Vale (2015). According to these findings, approximately 31% of indoor occupancy time was allocated to common-use spaces within the simulation framework.

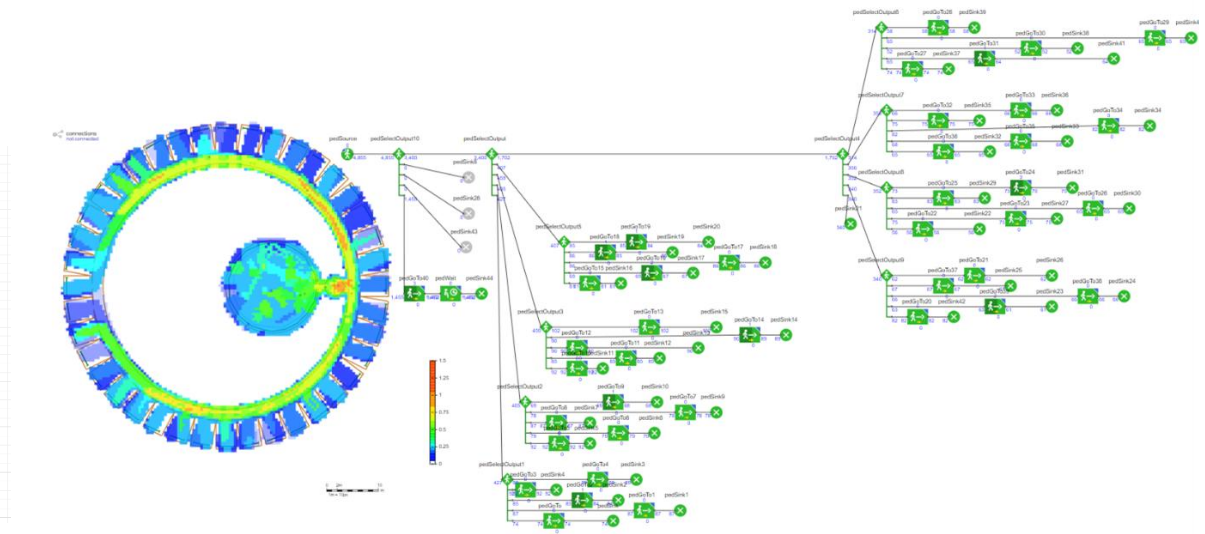

Figure 9. Density map of the 22 sqm co-housing layout.

Şekil 9. *22 m² ortak konut yerleşiminin yoğunluk haritası.*

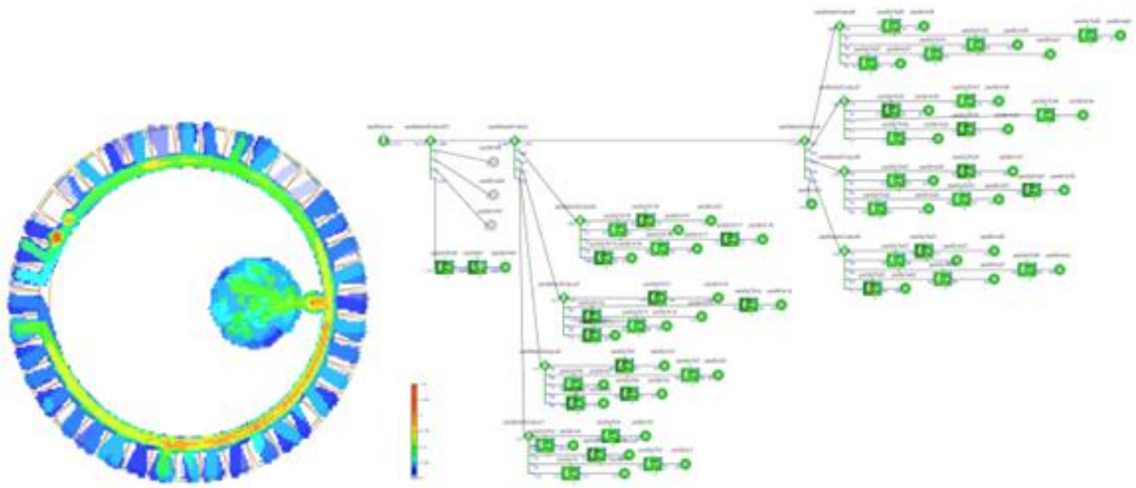

Figure 10. Density map of the 31 sqm co-housing layout.

Şekil 10. *31 m² ortak konut yerleşiminin yoğunluk haritası.*

The occupancy maps for 22 sqm and 31 sqm living units were generated using the AnyLogic simulation program. The concentric layouts were simulated under the program's predefined simulation parameters over a duration of five hours per day. Within the simulation, all circulation lines in the concentric layouts were designated as walls to define spatial boundaries accurately. The density indicators on the maps utilize a color-coded scheme to represent occupant concentration: red indicates high density, ranging from 1 to 1.5 persons per square meter; orange represents moderate density between 0.75 and 1 person per square meter; and green and blue denote lower densities, with values below 0.75 persons per square meter (Mikszewski et al., 2020).

The simulation results reveal that significant density concentrations occur within the circulation spaces in both housing typologies. Although circulation areas occasionally reach densities of 0.75 to 1 person per square meter, individual living units predominantly exhibit much lower densities, typically around 0.25 persons per square meter. Similarly, commonly used shared areas demonstrate density fluctuations ranging between 0.25 and 0.5 persons per square meter.

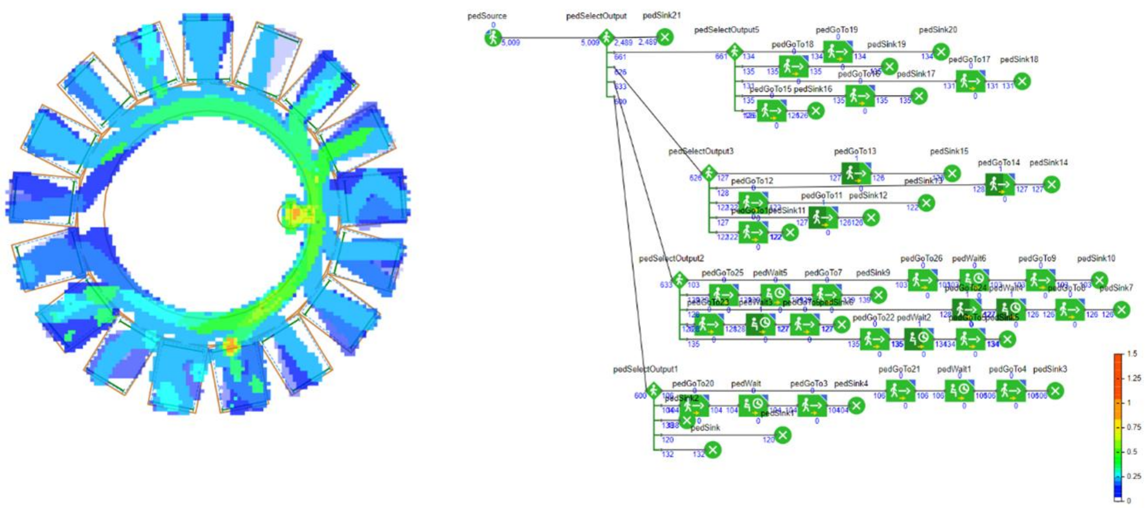

Figure 11. Density map of the 60 sqm social-housing layout.

Şekil 11. *60 m² sosyal konut yerleşiminin yoğunluk haritası.*

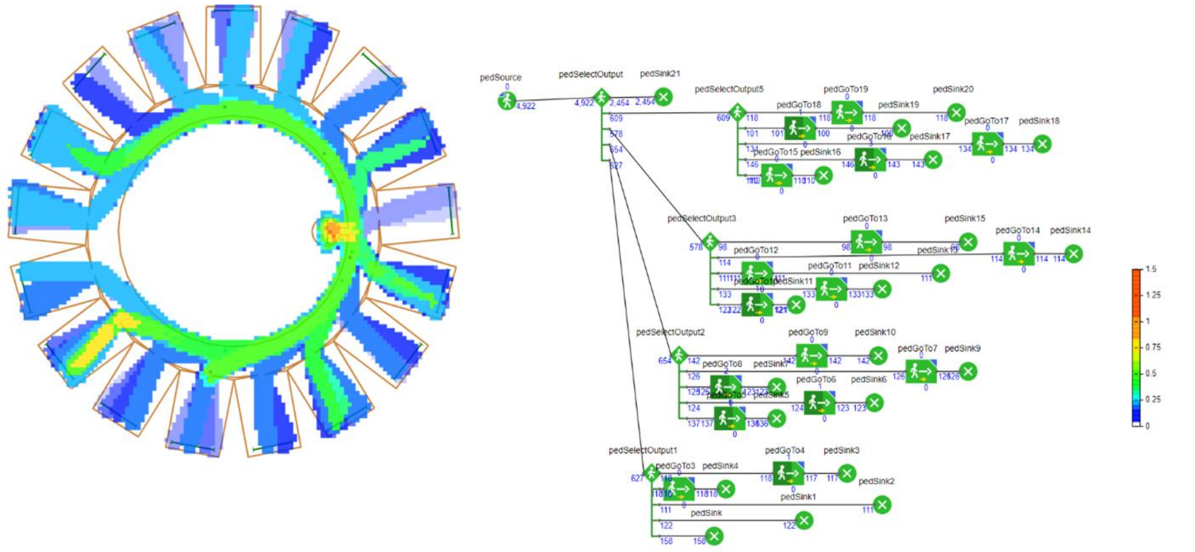

Figure 12. Density map of the 69 sqm social-housing layout.

Şekil 12. *69 metrekarelik sosyal konut yerleşim planının yoğunluk haritası.*

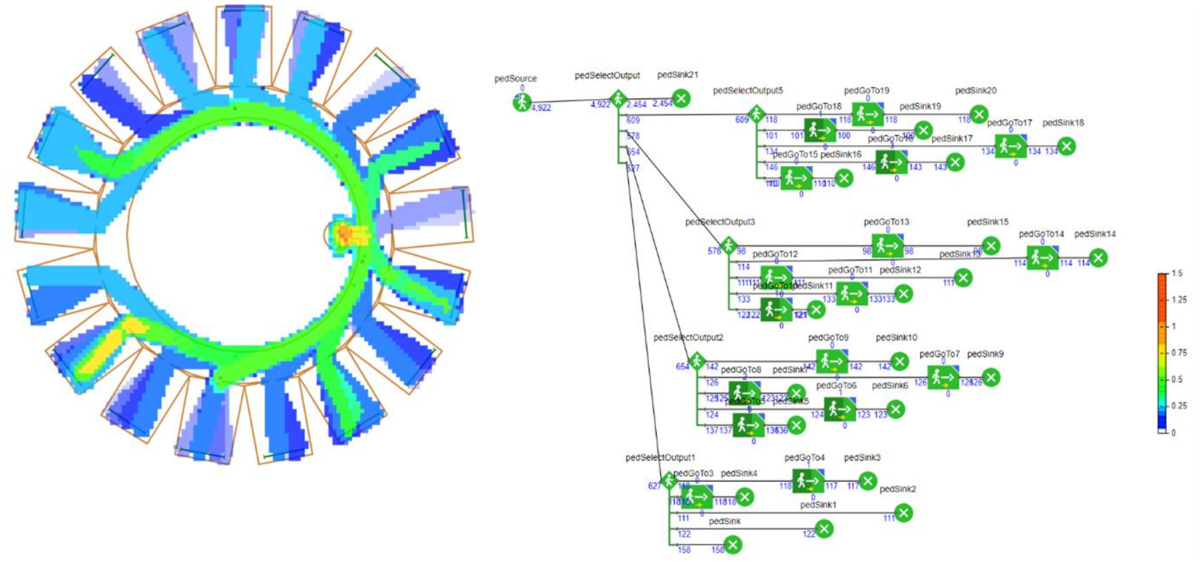

Figure 13. Density map of the 78 sqm social-housing layout.

Şekil 13. *78 metrekarelik sosyal konut yerleşim planının yoğunluk haritası.*

Contrary to the previous density maps, the layouts shown in Figures 11, 12, and 13 for the ordinary social housing do not include commonly used communal spaces. Simulations for this housing type consistently demonstrated similar results across the three cases. Circulation spaces typically exhibit moderate densities around 0.5 persons per square meter, while most living units show lower densities, approximately 0.25 persons per square meter. However, in a few isolated areas within circulation spaces, density levels rise to between 0.75 and 1 person per square meter.

6.2. Comparing Co-Housing and Normal Social Housing Residential Crowds

When comparing the two housing styles based on density map analyses, despite both being calculated with the same number of residents and similar proportions of circulation spaces derived from literature, the co-housing layout displays more localized density accumulation patterns than the ordinary social housing layout. This is largely due to the inclusion of additional communal spaces in co-housing designs, which contribute to extra areas of crowding and limit direct comparison. Nevertheless, neither co-housing living units nor ordinary social housing units exceed densities of 0.5 persons per square meter in private spaces.

While density variations are observed across different spatial categories within both housing types, overall risk quantification becomes clearer when reviewing the data presented in Figure 14 and Table 6. The co-housing models, with living units sized at 22 sqm and 31 sqm, show a notable proportion of high-density exposure areas—defined as spaces with densities of 1 to 1.5 persons per square meter—as well as moderately high-density exposure zones with densities of 0.75 to 1 person per square meter. The revised density-map interpretation indicates that high-density exposure zones remain spatially limited across all housing typologies. However, co-housing configurations still demonstrate relatively higher concentrations of moderately high-density exposure areas, particularly within circulation corridors and communal-use zones.

Table 6. Reconstructed density-based exposure areas across housing typologies derived from pixel-based spatial extraction and proportional density analysis

Tablo 6. *Yoğunluk haritalarının görsel yorumlanmasına dayalı yeniden yapılandırılmış maruziyet alanlarının konut tipolojilerine göre dağılımı.*

	Density-Based Spatial Exposure Distribution					
		Housing typologies				
	Density-Based Exposure Distribution	22 sqm Co-housing	31 sqm Co-housing	60 sqm Social Housing	69 sqm Social Housing	78 sqm Social Housing
Spatial Area Distribution (sqm	High-density exposure areas (1–1.5 people/sqm)	36 sqm	72 sqm	17 sqm	20 sqm	22 sqm
	Moderately high-density exposure areas (0.75–1 people/sqm)	182 sqm	385 sqm	137 sqm	197 sqm	268 sqm
	Moderate exposure-density areas (0.50–0.75 people/sqm)	619 sqm	673 sqm	412 sqm	434 sqm	446 sqm

Moderate-density exposure areas (0.20–0.40 people/sqm)	1492 sqm	1876 sqm	1236 sqm	1381 sqm	1517 sqm
Low-density exposure areas (0–0.25 people/sqm)	1019 sqm	1299 sqm	1064 sqm	1263 sqm	1472 sqm
No exposure-density areas (0 people/sqm)	291 sqm	505 sqm	566 sqm	651 sqm	736 sqm

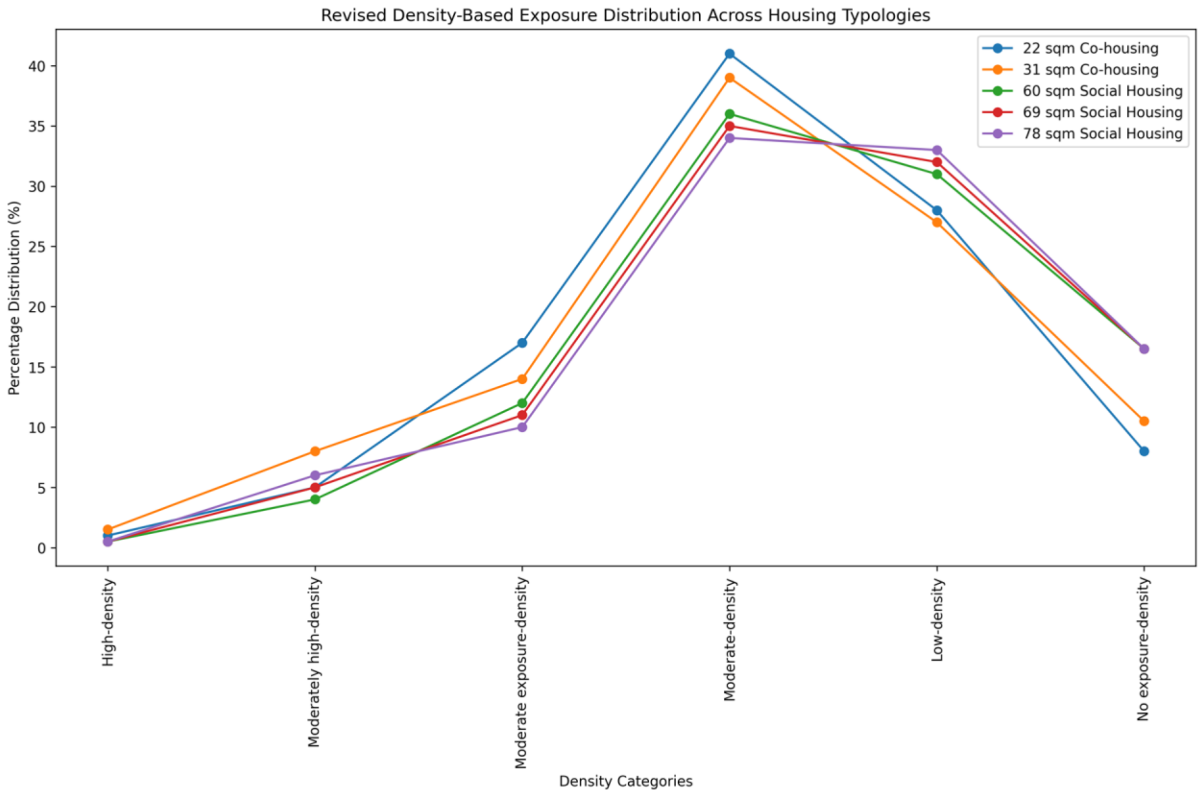

Figure 14. Reconstructed distribution of density-based exposure areas across housing typologies.

Şekil 14. *Konut tipolojilerine göre yoğunluk temelli maruziyet alanlarının dağılımı.*

In contrast, the risk-0 ratio is considerably higher in social housing developments with living units sized 60 sqm, 69 sqm, and 78 sqm compared to co-housing models, with respective ratios of 23%, 26%, and 26%. Additionally, the proportions representing low to moderate risk situations in these social housing types appear to be more unevenly distributed.

The comparison does not assume identical architectural programs between co-housing and conventional social housing typologies. Co-housing layouts inherently contain additional communal functions and shared-use spaces. Therefore, the analysis primarily evaluates how these additional communal areas influence circulation concentration and spatial exposure conditions under equivalent resident populations.

6.3. Statistical Comparison of Density Distribution

To support the pixel-based extraction of density maps, an additional proportional-density analysis was conducted using the reconstructed exposure distributions presented in Table 6. The density distributions were reconstructed through pixel-based extraction and proportional spatial analysis of the AnyLogic density maps.

$$Density\ Ratio\ = \frac{High\ Density\ Area\ +\ Moderate\ High\ Density\ Area}{Total\ Spatial\ Area}$$

The proportional comparison indicates that high-density exposure zones remain spatially limited across all residential typologies. However, co-housing configurations demonstrate stronger localized clustering tendencies within communal-use spaces and circulation corridors compared to conventional social housing layouts.

To evaluate overall spatial concentration intensity, a weighted exposure score was additionally calculated using density-category coefficients.

$$Exposure\ Score\ = \frac{(5H) + (4MH) + (3M) + (2LM) + (1L)}{Total\ Spatial\ Area}$$

where:

H = high-density exposure area

MH = moderately high-density exposure area

M = moderate-density exposure area

LM = low-moderate-density exposure area

L = low-density exposure area

The statistical comparison suggests that circulation topology and communal-space integration contribute significantly to density concentration patterns and potential airborne exposure-supporting conditions within collective residential environments.

7. DISCUSSION

The simulation findings indicate that co-housing layouts containing shared circulation systems and communal-use areas tend to generate more localized circulation density concentrations compared to conventional social housing typologies. In particular, central circulation corridors and communal spaces produce localized density accumulation zones that may increase potential airborne exposure conditions in enclosed indoor environments.

The present study should therefore be interpreted primarily as a spatial-density and circulation-risk assessment rather than a direct epidemiological transmission model. While the Wells–Riley framework traditionally incorporates variables such as ventilation rate, quanta emission, pulmonary ventilation, and exposure duration, these parameters were intentionally simplified in the current research to isolate the architectural effects of circulation organization and occupancy concentration.

This methodological simplification allows the study to focus specifically on the spatial dimension of airborne exposure potential. Several environmental and biological factors associated with airborne disease transmission, including indoor humidity conditions, VOC interactions, vegetation-related air purification effects, and aerosol physics, were beyond the scope of the present study. Previous environmental-health studies have discussed the potential role of indoor vegetation and air-quality-related parameters in influencing airborne environmental conditions (El-Tanbouly et al., 2021). Research on phytoremediation has additionally emphasized the possible contribution of plants to indoor air-quality improvement processes (Gawronski et al., 2017). The simulations focused specifically on circulation density, occupant overlap, and spatial concentration patterns within residential environments. Therefore, broader environmental-health interpretations should be considered as contextual references from existing literature rather than direct simulation outcomes.

However, the present study evaluates spatial exposure conditions primarily through circulation density and movement overlap. Variables such as ventilation performance, HVAC systems, aerosol decay, masking behavior, user health conditions, and real-time epidemiological transmission parameters were not directly simulated. Therefore, the findings should be interpreted as a comparative spatial analysis of density-related exposure potential rather than a direct infection prediction model.

Future studies may integrate computational fluid dynamics (CFD), ventilation performance analysis, and real epidemiological transmission parameters to produce more comprehensive evaluations of airborne disease propagation within collective residential environments.

The density-based spatial exposure distributions presented in Table 6 were reconstructed through pixel-based extraction and proportional spatial analysis of the AnyLogic density maps.

Color-density gradients generated by the simulation outputs were systematically categorized according to predefined density intervals (persons/m²), enabling approximate quantification of spatial concentration zones across residential typologies.

Although the procedure does not represent direct epidemiological measurement, the pixel-based spatial extraction method improves reproducibility and analytical consistency in comparative density evaluation.

Rather than representing direct pixel-based computational measurements, the distributions reflect approximate spatial proportions derived from observed color-density concentrations within the simulation outputs.

8. ACKNOWLEDGEMENTS AND DISCLOSURES

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