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Atrium Daylight Penetration in Dense Apartment Blocks. A case of Roysambu Nairobi, Kenya.

By Etta Madete

A thesis submitted in partial fulfillment of the requirements for the Award of the Degree of Master of Architecture in the Faculty of the Built Environment and Design at the Department of Architecture, University of Nairobi.

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Declaration

This project report is my original work and has not been presented for the award of a degree in any other University or any institution of higher learning. No part or whole of this work may be reproduced or transmitted in any other form without the prior permission of the author and / or the University of Nairobi.

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Dedicated to my family,

whose spirit, sustenance, support and love I am forever indebted.

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Operational Definition of Terms-

Atrium: An open-roofed entrance hall or central court in a development, typically distinguished from a courtyard because it has three or more enclosing surfaces (Britannica, 2021).

Daylight- the combination of all light received from the sky as direct light from the sun and indirect light from the diffused daylight scattered in the atmosphere and reflected light from the ground and surrounding objects (Koenigsberger, 1975).

Daylighting- the illumination of interior spaces in buildings by natural light (direct and indirect light) by using properly designed windows and / or skylights (Koenigsberger, 1975).

Daylight Factor- the ratio of the illuminance due to daylight at a point on the indoors working plane, to the simultaneous outdoor illuminance on a horizontal plane from an unobstructed overcast sky (Koenigsberger, 1975).

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ABSTRACT

In dense urban neighbourhoods the main source of daylight to the internal spaces is the atrium, however, these are not designed, or sized to consider daylight penetration along all its floors. Adequate daylight in residential spaces has proved to have physiological and psychological benefits, improves air quality, reduces damp rising, reduces energy consuming effects of using artificial lighting during the day, reduces operational costs and improves rental value. The study looked at existing literature on atrium design for daylight penetration in dense apartment blocks to identify parameters, then used the case study research method to conduct data collection, analysis, and BIM simulation on 50 x 100 ft plots in the Roysambu neighbourhood in Kenya.

The study identified three atrium types namely the I- shaped, O-shaped, and U-shaped atriums. Daylight penetration is most effective in U – shaped atriums shared between neighbouring plots because each development benefits from shared daylight access. This is the recommended typology for dense urban apartments. In addition, the study identified daylight obstructions namely stairs, hanging lines, vehicles (on ground floor) and opaque railing materials. As well as opportunities for daylight optimisation namely, large window sizes, light coloured wall finishes and glazed internal partitions, ensuring residential units on ground floor are replaced with commercial functions, having single banked, single space units with minimal internal partitions, and having a dedicated, and secure laundry area to prevent hanging lines in the atrium.

The recommendations from the study were used to form policy and design guidelines for effective atriums for daylighting in dense apartments.

1. INTRODUCTION

1.1 Background of The Study

According to the UN (UN Stats, 2020), 1.6 billion people live in substandard housing and one billion people currently live in urban slums. This figure is projected to increase to two billion by 2050. In Kenya, the government's Vision 2030's Big Four Agenda (GOK, Big Four Agenda, 2021) includes affordable housing, affordable healthcare, food security, and manufacturing as key goals. Despite this effort, the private sector is the highest provider of affordable housing in Kenya, whose dominant market solution for affordable housing has been a five to seven-storey apartment block on a 50 x 100 ft (1/8th acre). In such dense urban neighbourhoods, the main source of daylight to the internal spaces is the atrium; however, these are not designed or sized to consider adequate daylight penetration along all its floors. These impact the health and wellbeing of the residents as well as the energy use of each household due to the increased reliance on artificial lighting. Yet, Nairobi, Kenya benefits from an average of 12 hours of sunlight every day which can be harnessed (Climatedata, Accessed 2021).

The policies that frame Kenya's sustainability goals include the Kenyan constitution, Article 42; the right to a healthy and clean environment for every Kenyan citizen. As well as Section 43 (1) (b) grants that every person has the right to "accessible and adequate housing and reasonable standard of sanitation (GOK, 2010). Additionally, Vision 2030 outlines the goals to be a nation that has a clean, secure, and sustainable environment. Other relevant policies include the Climate Change Act, 2016, the National Climate Change Framework Policy 2016, Kenya's National

Climate Change Action Plan 2018-2022, The Built Environment Bill 2017, the Housing Bill 2017, and the Paris Climate Agreement of 2015, which Kenya is a signatory (GOK, 2017).

Green building rating tools such as LEED-US (Leadership in Energy and Environmental Design), BREEAM-UK (Building Research Establishment Environmental Assessment Methodology) and as the Kenyan Building code have specifications about daylight requirements, in relation to window sizes, and the space required outside a window. None of this addresses the specific options available for six-storey atrium housing on 50 x 100 ft plots which is the primary vehicle for providing affordable housing to the urban population in Kenya (GOK, 2020). This research studied atriums in dense urban apartment blocks to outline guidelines for effective daylight penetration.

Figure 1 Density informal low-income housing in Nairobi. Source; Author 2021

1.2 Problem Statement

Currently, six-storey apartments in 50 x 100 ft plots are the majority of affordable housing in Kenya being provided by the private sector. The cost of construction of the project is a significant factor in affordability and developers aim to maximise the number of units permissible according to the law. This has led to high densities and congestion we see coming up in Nairobi which, as shown in figure 2, and has led to poor daylighting conditions in many of the homes. Each new building is designed to borrow light from incorrectly sized atriums, narrow street canyons, and from adjacent plots, which will inevitably get built on in the future and block the main source of daylight.

In dense urban neighbourhoods such as Roysambu, shown in figure 3, the primary source of light is the atrium which are not designed or sized to consider daylight penetration along all its floors. Yet, access to adequate daylight in residential spaces has proved to have physiological and psychological benefits due to its ability to ensure a healthy circadian rhythm (sleep /wake cycles), improve mood, improve concentration, reduce eye strain, provide essential vitamin D, reduce depression, ensure hormonal balances, reduce molding, and increase productivity (Johnsen, 2010). Natural daylight also reduces the operational costs of a building and has a positive effect on the rental value of a space. To meet both global and Kenyan climate change targets and the growing demand for affordable urban housing, whilst ensuring these are good for the users' wellbeing, it is necessary to develop realistic design guidelines for effective atrium daylight penetration in dense apartment blocks, specifically 50 x 100 ft plots.

Figure 2 High densities driven by market forces, high land prices and demand for low-cost houses have reduced energy efficiencies in many neighbourhoods. Source; Author 2021, Thika, Kenya

Figure 3 High densities in low-income housing in Nairobi, Kenya. Source; Author 2021.

1.3 Research Objectives

- To establish existing knowledge on atrium design for daylight penetration in dense apartment blocks.
- To assess daylight penetration from the atriums of apartment blocks in Roysambu-Nairobi.
- To make recommendations on the design of atriums for dense apartment blocks for effective daylight penetration.

1.4 Research Questions

- What is the existing knowledge on atrium design for daylight penetration in apartment blocks?
- What is the status of daylight penetration of atriums in apartment blocks in Roysambu-Nairobi?
- How should atrium design for dense apartment blocks such a Roysambu be effective for daylight penetration?

1.5 Justification of the Study

The dominant affordable housing in Nairobi is five to seven storeys walk-up apartments on eighth-acre plots (50 x 100 ft) with atriums as their main source of lighting. However, these are not designed or sized to consider daylight penetration along all its floors. Adequate daylight in residential spaces has proved to have physiological and psychological benefits, improves air quality, reduces damp rising and molding, reduces energy-consuming effects of using artificial lighting during the day, reduces operational costs, and improves rental value.

The case study research method was chosen as it is most effective in understanding and evaluating the ‘why ‘and ‘how’ of unique circumstances such as those found in dense urban neighbourhoods through data collection and analysis of the context of the typical urban block, the atrium form, size, functional and architectural characteristics. The block was then drawn and recreated with certain assumptions to provide quantitative data for statistical analysis and digital daylight simulation.

The practical approach was important in identifying, documenting, and analysing the real-life situation on the ground because the market rarely follows building code regulations. As such, the conclusions would prove useful and practical guidelines for future developments tackling the recurrent problem of designing for daylight on a 50 x 100 ft plot. In addition, the government can have realistic guidelines to inform policies, regulations, and enforcement criteria which will benefit the growing population of people living in these spaces.

1.6 Significance of the Study

The study established that the market has developed multiple solutions to atrium designs in dense apartment blocks while still trying to meet minimum regulations, maximise profit and rental income. Atriums in low-income neighbourhoods are used for multiple activities, including parking, clothes hanging, and storage, hence minimizing the daylight penetration into the space.

The study was supported by theory in that the well index and sky view factor calculations. As well index increases, the daylight factor decreases. The closer the sky view factor is to one, the better the daylight penetration. The study identified three atrium types in the case study neighbourhood: the I- shaped, O-shaped block, and the U-shaped atriums. The U-shaped shared atrium typology is the most effective for daylight penetration. It maximises lettable space, minimises corridor space, and is improved when U – shaped atriums are shared between neighbouring plots because each development benefits from shared daylight access.

The study identified key obstructions within atriums that were detrimental to effective daylight penetration, namely: stairs, hanging lines, vehicles (on the ground floor), and opaque railing materials. The study identified critical opportunities for optimisation of daylight penetration namely, large window sizes, light coloured wall finishes, and having internal partitions fitted with glazing. The study identified key functional considerations for optimising atrium daylight penetration, namely residential units on the ground floor should be replaced with more commercial functions in dense urban neighbourhoods as they have the lowest daylight penetration, having single banked, single space units (such as studios) with minimal internal partitions, and each development having a dedicated, and secure laundry area to prevent hanging lines in the atrium. The guidelines described above-formed policy recommendations on the optimum length, width, and area of atriums and relevant functional characteristics for future housing developments above four stories in 50 x 100 ft plots.

1.7 Scope and Limitations of the Study

The geographical scope of this study is limited to the Roysambu neighbourhood in Nairobi, Kenya. The location was chosen because of the high densities which are representative of the typical atrium walk-up apartment block in Nairobi, Kenya. As well as its population growth parameters, and neighbourhood block featuring four roads on each side and typical apartment blocks. The study takes a cross-sectional study during the year 2021 for data collection and analysis. The year of study was during the COVID- 19 pandemic, which created unique circumstances in the study region.

The theoretical scope of the study is environmental science bound by the study of daylighting, which is the natural light coming directly from the sun and reflected by water and dust. The study is also theoretically bound by housing in 50 X 100 ft plots provided by the private sector because it is currently the prevalent form of housing being supplied to the market and will continue to do so, given the growing housing crises.

1.8 Organisation of the Study

Chapter One – Introduction; This chapter gives the background of the study. It begins with the history and evolution of the apartment block and daylighting issues in the urban context. The research problem which is the current lack of daylighting consideration in dense urban housing, and the requisite research questions and objectives are articulated. Lastly, the chapter expounds on the justification and significance of atrium design for effective daylighting in affordable housing. The chapter concludes with the organisation of the study and the definitions of key terms.

Chapter Two – Literature Review; This chapter gives the theoretical framework for the study through the analysis of past and ongoing research on daylighting through atriums in dense urban neighbourhoods. The first part of the review will begin by looking at apartment block design, atrium design, and daylighting from historical approaches to the present day. Then the factors and variables affecting effective daylighting in urban apartments were identified and used to create a framework that was used in fieldwork data collection, documentation, and analysis.

Chapter Three – Research Methods; This chapter discusses the research methodology that will be used in the field, including data collection, analysis, and presentation. The investigation uses the case study research method with a mixed method of quantitative and quantitative data collection and analysis to understand effective atrium design for dense urban housing. Secondary data for this investigation were collected and analysed from existing literature, internet sources, and academic journals. Primary data was collected and analysed through observation, sketches, and daylighting simulation analysis of apartment blocks in Roysambu, Nairobi, Kenya. Primary data collection methods included observation, interviews, and climatic data recordings presented in written narrative, sketches, photographs, architectural drawings, graphs, charts, and tables.

Chapter Four – Findings and analysis; This chapter analyses and presents primary data collected from Roysambu, Nairobi, Kenya, through sketches, photographs, architectural drawings, graphs, charts, and tables. The case study region was chosen because of the high densities, that represent the typical atrium walk-up apartment block in Nairobi Kenya. As well as its population growth parameters and neighbourhood block featuring four roads on each side and typical apartment blocks.

Chapter Five – Conclusions and Recommendations; The concluding chapter of the investigation provides conclusions of each chapter of the study as well as looks like the conclusions and recommendations from each research objective. Additionally, making recommendations for further study and global sustainable development.

2 LITERATURE REVIEW

2.1 History

Apartments

The word apartment was developed in the 1800s and comes from the root Latin word, ‘appartare,’ meaning ‘to separate.’ It is defined as self-contained housing units but part of a larger development or a building with several residential units as shown in figures 4 and 5. The concept started in Roman Empire to accommodate the less wealthy population who could not afford to live in a standalone house. They were traditionally called insulas, translated to island, because they were far away from the aristocrats and had shops on the ground floor with rooms upstairs. The historical building codes restricted them to a maximum of five to six storeys height to reduce fire risk. The higher the apartment, the cheaper it was to rent. As early as the 10th century, the Puebloan people in the Americas had multi-room dwellings with over 900 rooms (Britannica, 2021).


Figure 4 Roman Insula. Source: Wikipedia commons & Figure 5 1840 tenement housing in Glasgow. Source Heatherwood.com, 2021.

In the 16th century, in the Yemeni city of Shibam, as shown in figure 6, developed five to eleven storey apartments made from mud bricks, with over 500 apartment units per block. In the desert climates, this was very efficient as the clustered buildings shaded each other from the high heat, enabled efficient water supply, and sewage systems. The Haka people of China used enclosed high-rise units to house their large population, and create highly defensible spaces (Britannica, 2021).

The apartment as we know it today first appeared in Paris in the 18th century and in New York the 'Railroad' flats came out in the 1830's named due to their narrow rooms, arranged end to end. In the 20th century, after the invention of the elevator, taller apartments began being developed, with centralized services, for efficiency (Britannica, 2021). From then on, apartments became popular as they can offer an efficient footprint to offset the high costs of land in urban areas.

Figure 6 Yemeni 16th century apartments made from mud brick. Source; (Goran, 2021).

2.2 Daylighting

Daylight is the natural light coming directly from the sun and reflected by water and dust. It has daily and seasonal variations in quantity, intensity, quality, and colour rendering (Sok, 2017). Daylight can transform a space to be more uplifting and enjoyable for the users (Johnsen, 2010). Effective daylighting in buildings requires a balance between light distribution, solar gains, views out, views in, privacy, spatial configurations, internal finishes, and the buildings' shading devices. Apart from its obvious uses in aiding in a visual tasks such as working, seeing, orientation, it is important to consider the physio-psychological aspects such as its ability to enhance natural metabolic rhythms propagate positive psychological stimulation and entrain our circadian rhythms, (our biological clock determining our sleep/wake cycles) as well as prevent damp and moulding. A disrupted circadian system causes long-term health problems and exposure to daylight during the day and no light during the night helps resolve that (Peter Boyce, 2003).

The key factors that need to be considered are the quantity of light, quality of light, distribution of light, well index and sky view factor. Different spaces and their respective uses also have different lighting requirements. (Johnsen, 2010). The design must also avoid the undesirable side effects of daylight, such as heat gain, and glare. For spatial design, the window size and location, the glass type, reflectance, interior finishes, and partitions all play a role in the quality and quantity of daylight in the space (Ander, 2016). In Germany, this requirement is in their building code and states that buildings should receive 1 hour of direct sunlight in winter (Mueller, 2013).

History

Until 1940, daylight was the primary way of lighting a building and goes back to caveman times, forming crude openings in the earliest shelters (Torcellini, 2002). However, with the invention of artificial light, it is being neglected in the design process.

In 1189 Roman building law termed the ‘Rights to lights’, required that if a window had access to 20 years of uninterrupted daylight, this access would become permanent. New York 1916 Zoning law required that after a certain height, towers step back from a diagonal at the centre of the street to allow for adequate daylight penetration of the urban block as shown in figure 7. In Japan, there is a requirement that residential apartments need to have at least four hours of direct sunlight every day (Altomonte, 2008).

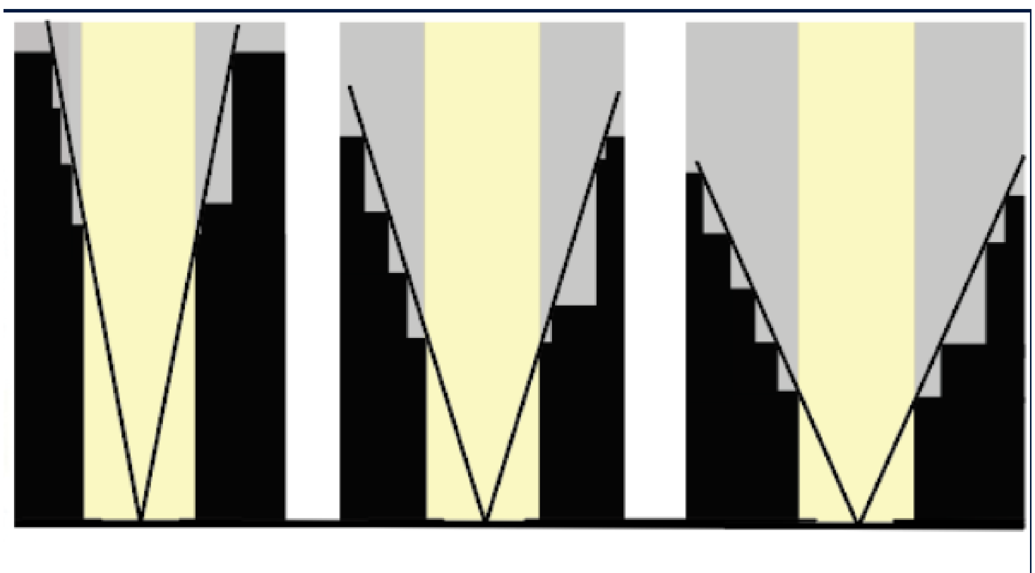


Figure 7 New York 1916 Zoning law required that after a certain height, towers step back from a diagonal at the centre of the street to allow for adequate daylight penetration of the urban block. Source: https://old.skyscraper.org/zoning/, 2021.

Daylight and well being

The World Health Organization defines health as the state of complete physical, mental, and social well-being and not just the absence of disease and infirmity and help is important to people's productivity, Psychologically, being able to see effectively, understand, and interact with the environment around you while performing a task affects your motivation and ability to complete the task. Additionally, having openings with views gives the occupants visual relief and stimulation adding to their motivation and satisfaction (Peter Boyce, 2003). In higher latitudes during the sunlight deprived winter months, Seasonal Affective Disorder (SAD) develops. SAD is a depression triggered by a biochemical imbalance in the brain due to shorter daylight hours and is characterised by lethargy, drowsiness, low concentration, and anxiety (Sok, 2017). Daylight enhances our moods, morale, reduces fatigue, stress, and eye strain (Torcellini, 2002).

Physiologically, a healthy circadian rhythm controls our sleep/ wake cycles, our hormonal rhythms and hence our alertness and concentration levels and are negatively affected in artificially lit urban environments. The hormonal balances of serotonin, dopamine (pleasure hormone), cortisol (stress hormone), melatonin (sleep hormone) are also negatively affected without regular access to daylight (Altomonte, 2008). Ultra-violet irradiation from sun exposure of the skin is important and the easiest way to enhance the production of vitamin D and a lack of sunlight causes Vitamin D deficiency which is linked to rickets and cancer (Peter Boyce, 2003). Being able to move your field of vision to near field objects outside a window provides muscle relief to the eyes and the eye works best when it receives the full spectrum of light like the one from daylight. Compared to artificial sources like florescent which only work with the yellow-green part of the spectrum.

Daylight availability

Daylight sources depend on the latitude of a building's location and the immediate surrounding conditions such as neighbouring buildings, trees, shrubs, obstructions, the climate of a region, the seasonal variations, and the probability of sunlight penetration through the sky. In the tropics, daylight levels are high and consistent throughout the year compared to higher latitudes where daylight levels vary through seasons (Johnsen, 2010).

Nairobi, Kenya, lies approximately 1,669 M above sea level and is classified as a subtropical highland climate under the Koppen climate classification. Temperatures an average temperature of 19.0 °C and annual rainfall of 869 mm. Days can reach highs of 24 °C and nights can reach lows of 9 °C with a 73% relative humidity (Climatedata, Accessed 2021). The average hours of sunshine range from four hours twenty minutes in the cold months of July to nine hours thirty minutes in the hot months of February. The days are typically 12 hours long with the difference between the shortest and longest day being less than ten minutes. There is a 58% average of 2,525 hours of sunlight out of a possible 4,383 total days in a year, as shown in table 1 below.

Table 1 Daylight and sunlight data for Nairobi, Kenya. Source; http://www.nairobi.climatemps.com/sunlight.php, Accessed July 2021.

	Jul	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**
Average Sunlight Hours per day	4:17	4:23	6:0 0	7:05	7:04	8:15	9:05	9:27	8:42	7:2	6:00	5:44
Average Daylight hours per day	12	12	12	12	12	12	12	12	12	12	12	12
% Sunny daylight hours	36	37	50	59	59	68	75	78	73	59	50	48
% Cloudy hours	64	63	50	41	41	32	25	22	27	41	50	52
Sun altitude(deg.) at noon on 21st day	68.2	76.6	87.4	79.8	71.1	67.9	71.2	80.2	87.6	76.8	68.5	65.3

Daylight measurement

Daylight Factor (DF) is the most used method for calculating daylight quantity in a room. It quantifies the amount of diffuse daylight at points within a space under an overcast-sky condition, at work plan height of 0.85M above the floor as shown in figure 8. The higher the DF, the higher the daylight penetration. A DF of 2% is adequate for normal tasks, but artificial lighting will be required for detailed work. In a room with a DF of 5%, no additional artificial lighting is required, (Yao, 2019).

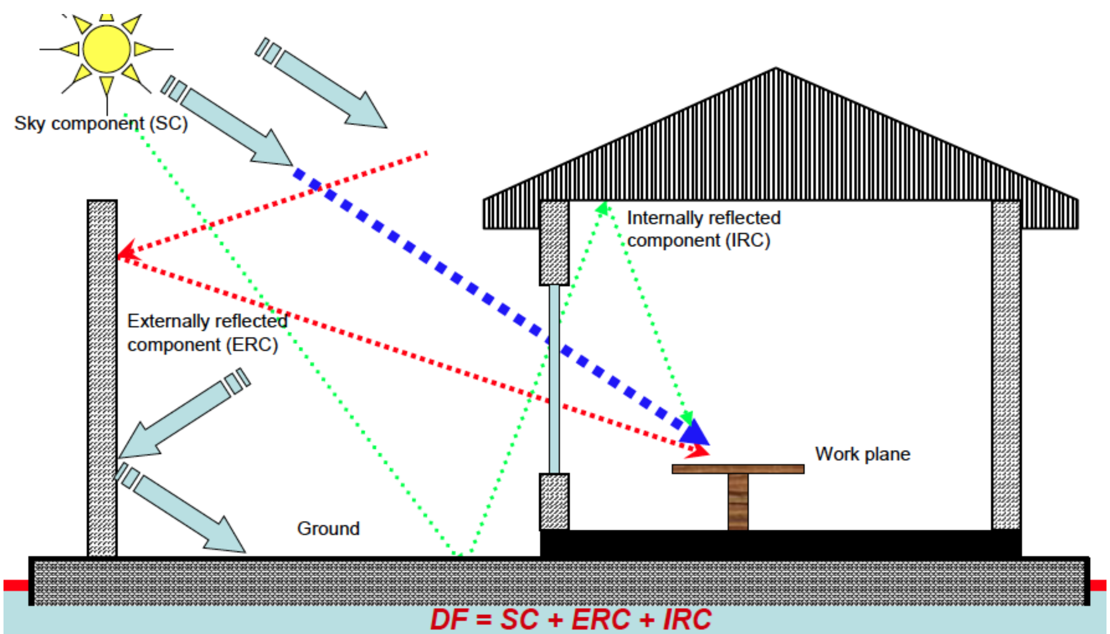


Figure 8 Key terms in daylight factor calculations. Source; google images

Global daylight provision standards

The global daylighting standard guide is the European-EN 17037, which looks at four criteria: daylighting, views, access, and glare. The daylighting criteria require a minimum of 300 lux of natural light, over 50% of the space for more than half of the daylight hours available in the year. The views criteria require that building occupants have unobstructed and naturally coloured exterior views. The access criteria require users to be exposed to direct sunlight. The glare criteria requires that the daylight glare probability (DGP) is calculated and used to determine whether anti-glare provisions are required.

Green building rating tools such as LEED-US (Leadership in Energy and Environmental Design), BREEAM-UK (Building Research Establishment Environmental Assessment Methodology), and DGNB (Deutsche Gesellschaft für nachhaltiges Bauen) typically use Daylight factor as the key criteria in their assessment for daylight. As well as parameters of views out and glare control as shown in table 2 below.

Table 2 Standards, regulation, and rules for daylight provision in buildings. Source: Velux and Designing buildings Wiki adapted by Author, Accessed 2021.

Green building rating tool		**Requirements**
BREEAM- Building Research Establishment Environmental Assessment Methodology	General	80% of floor area has daylight factor of 2% or more 80% of working plane should receive direct light from the sun
	Kitchens	DF > 2%
	Living rooms, dining rooms, studies	DF > 1.5%

LEED- Leadership in Energy and Environmental Design	General	In clear sky conditions illuminance levels of minimum 270 lux and maximum 5400 lux and minimum DF of 2
DGNB- (Deutsche Gesellschaft für nachhaltiges Bauen)	General	50% of the usable area throughout a building has a DF of; > 3% very good > 2% medium > 1% slight < 1% none
Illuminating Engineering Society (IESNA RP-5-99)	General	2%- Poorly lit DF- No need for daytime Artificial lighting >5%
CIBSE-Chartered Institution of Building Service Engineers	General	2%-5% - needs artificial light DF- No need for daytime Artificial lighting >5%
British Standard for lighting in Buildings (BS 8206 Part 2),	General	2%-minimum DF- No need for daytime Artificial lighting >5%

Kenyan Building code regulations

The Kenyan Draft Building code for 2020 gives daylight regulations to ensure every space in a building has lighting and ventilation for the health and safety of the occupants for the use it was designed for. Every room must have at least one fenestration for light and ventilation and that all fenestrations must be at least 10% of the floor area of the room (but less than 0.2 M2). The open space outside a window of any room must be at least 2.4M (GOK, 2020).

2.3 The Atrium

History

In c.80-15 BCE Marcus Terentius Varro and Vitruvius named the ‘hollow of the house found in typical housing typologies as-Cavum Aedium. It is also defined as the waiting room or open area inside the house wall that everyone can use. In De Arcitectura book 6.3, Vitruvius further details the various configurations an atrium could take; Tuscan, Corinthian, tetrastyle- depending on the column configuration and roof support system as shown in figure 9 and figure 10. All had a compluvium an opening to the sky at the centre for light and ventilation, and an impluvium (water pool) that captures rainwater to the storage (Heatherwood, 2021).

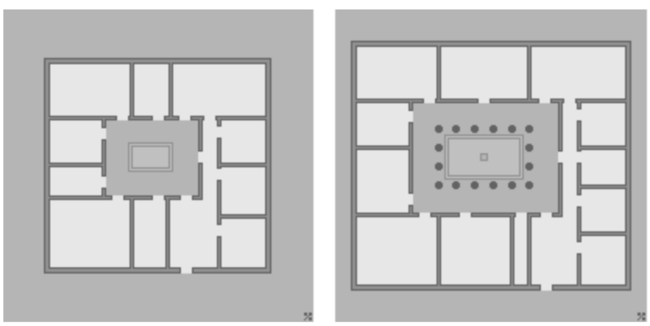


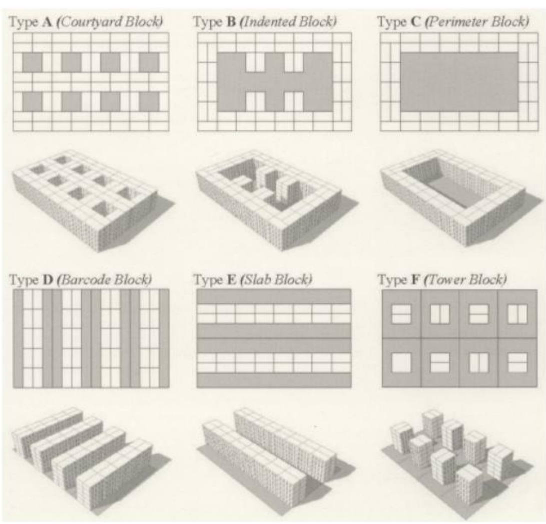
Figure 9 Variations in Roman atriums. Source; www. khanacademy.com

Figure 10 Roman atrium featuring a water feature for communal use. Source; www.hisour.com

Atriums have always had three key considerations in apartment design: the architectural, the environmental, and the economic. In Roman times this open internal space turned the building inward away from the street (Heatherwood, 2021). In the early 20th century as modern architecture and the industrial revolution took over the built environment, explorations by protagonists Frank Lloyd Wright in the Larkin Building (1903), and Guggenheim (1959) museum, Johnson Wax Head Quarters (1936) all featured this covered top light central space (Paramits, 2014).

Urban building form and Daylight

The Chartered Institution of Building Services Engineers (CIBSE) defines atriums as, "an interior space enclosed by building walls that permit the entry of daylight" (Jie Li, 2019). As shown in figure 11, 12 and 13, density was the main driver of the design of the apartments and was dependant on the plot size and the required volume of construction to produce the rental yield. Daylight penetration would be a secondary consideration.



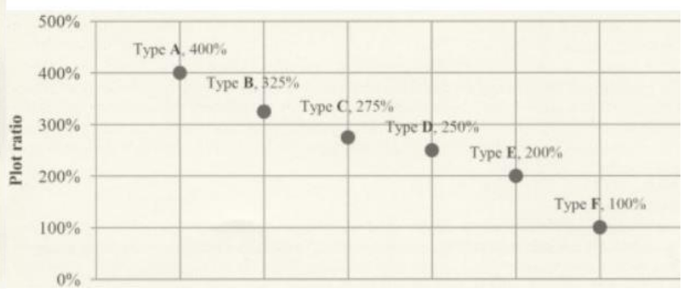


Figure 11 Six traditional urban building types and their corresponding plot ratios. Source; Jstor, 2021

Figure 12 Plot ratio in relation to building density per unit area. Source; Jstor, 2021

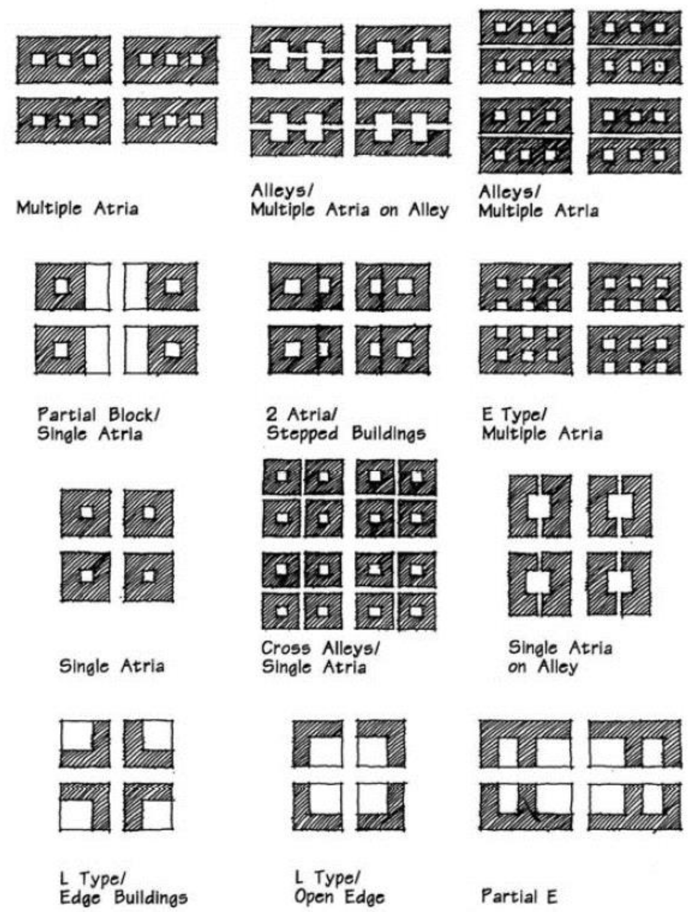


Figure 13 Urban atrium types. Source; (Decay, 2010)

Calculating an atriums effectiveness for daylight penetration

In dense apartment blocks the atrium is the main source of light. To optimise daylight performance of atrium building the key considerations, namely the typical sky conditions, roof fenestration system- (Not applicable in the Kenyan context), atrium geometry, volume and shape, surfaces of enclosing walls and of the adjacent spaces, window size and position on enclosing surfaces, building regulations - Plot ratio (PR) and ground coverage (GC) (Yao, 2019).

Well index has been identified as the key determinant typing atrium design with daylight penetration and as Well index increases, Daylight factor decreases. As such for this study the geometrical properties shown in figure 14 below are the key quantitative factors. The calculation for Well index comes from its plan aspect ratio and section aspect ratio as described below and shown in figure 15 (Ran Yi, 2009). The closer an atriums PAR (Plan Aspect Ratio=W/L) is to 1(square) the better the daylight performance. The circle is the most efficient shape of an atrium, followed by a square (Northern, 2008). An atriums SAR is its Section Aspect Ratio and measures the height vs. its width (SAR= H/W). Low SAR means the atrium is shallow and has, therefore a high daylight penetration. A high SAR means it is very deep and has low daylight penetration.

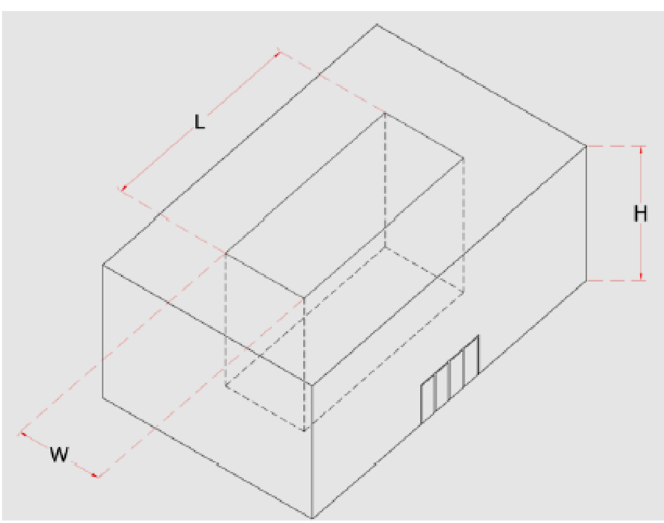


Figure 14 Geometric properties of an Atrium. Source; (Mahlanbani, 2019)

$$\mathrm{WI} = \frac{H(W+L)}{2WL} = \frac{1}{2}\frac{H}{W}\left(1+\frac{W}{L}\right) = 0.5\mathrm{SAR}(1+\mathrm{PAR})$$

Figure 15 Formula for Well index- which determines the geometric effectiveness of atriums for daylight penetration. Source (Mahlanbani, 2019)

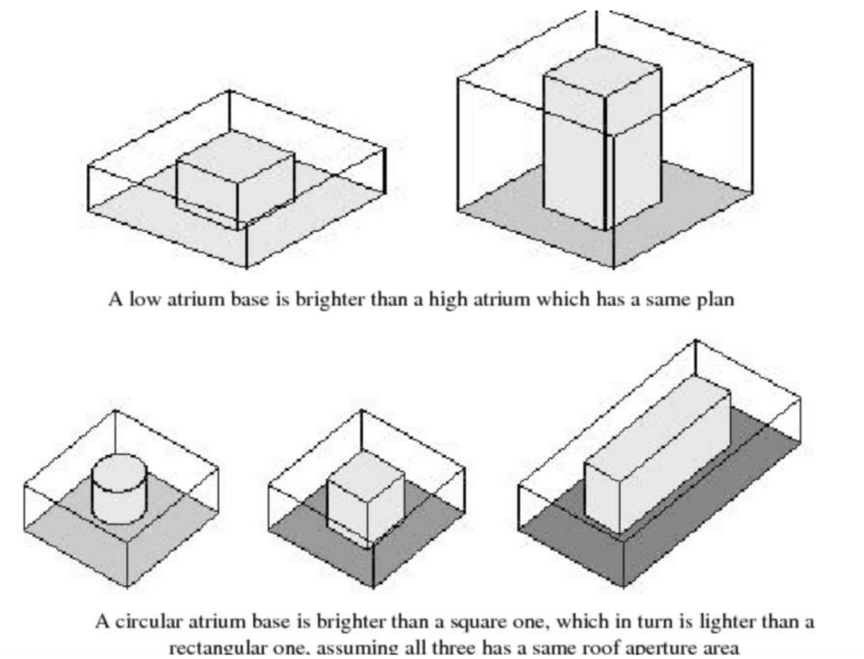


Figure 16 How atrium geometry affects daylight penetration. Source; (Julitta Yunus, 2010)

The LT method (Lighting and Thermal)

In 2000, Nick Baker and Koen Steemers further explored daylighting through their LT method (lighting and thermal where they investigated passive and non-passive zones of daylight penetration as shown in figure 17. The LT Method covers all aspects of thermal performance including heat, ventilations and loads with estimates a designer can use from preliminary geometric information. For this study, the key component to extract is their summary that a buildings passive zone is usually two times the floor to ceiling height which may be affected by internal partitions such as furniture, doors, walls, etc. This daylight zone for atriums is limited to the sky view zone and should factor in reflected light into the spaces from adjacent surfaces as shown in figure 18 and 19 (Baker, 2000).

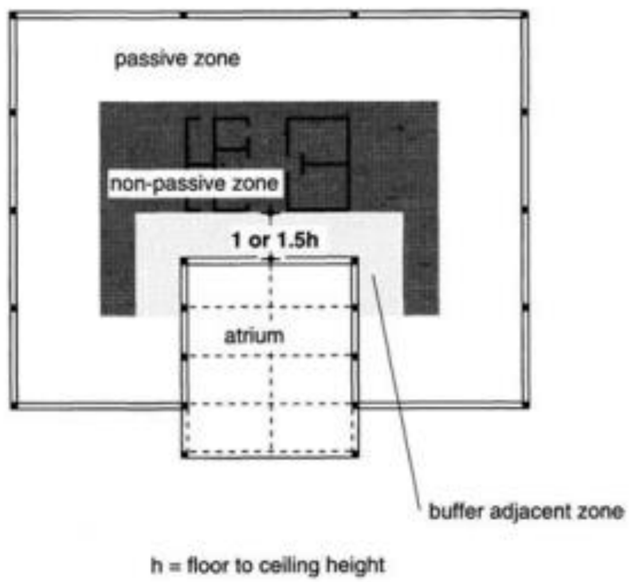


Figure 17 Passive and non- passive zone in the LT method. Source (Baker, 2000)

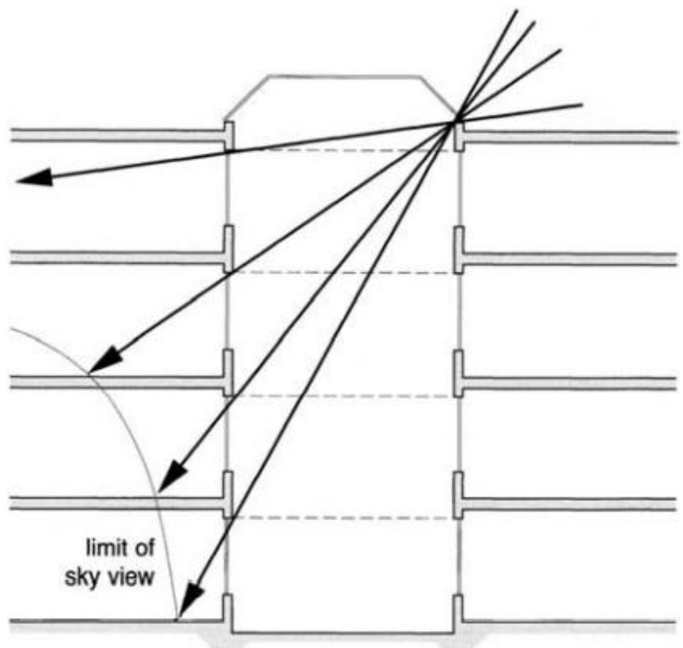


Figure 18 Sky view is key for daylight penetration of atriums. Source; (Baker, 2000)

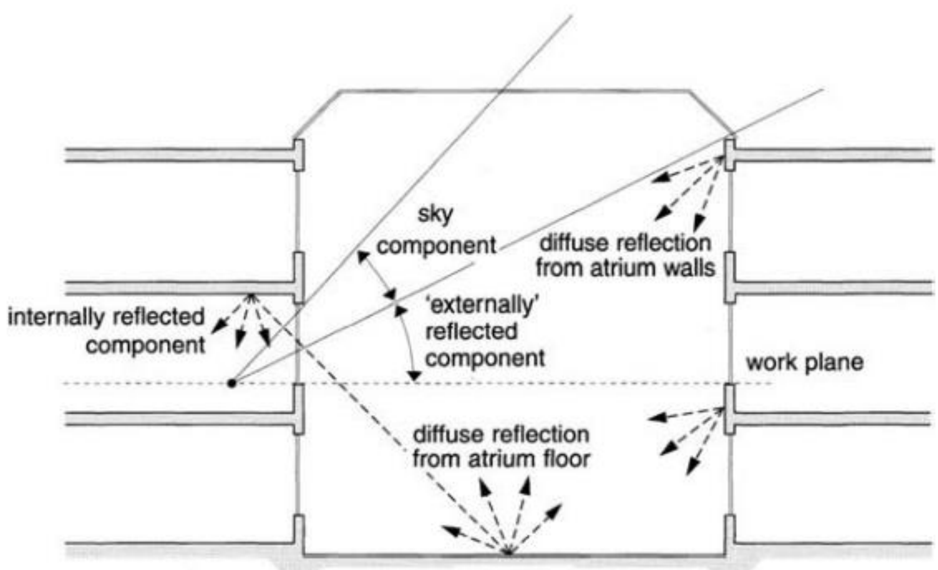


Figure 19 The multiple daylight sources within an atrium. Source; (Baker, 2000).

Sky view factor

Sky View Factor (SVF) is the ratio of sky hemisphere visible from the ground (not obstructed. by buildings, terrain, or trees. It is especially important for designing dense urban areas as it quantifies daylight access which reduces energy consumption and improves physiological and psychological health of occupants. Adversely, too much daylight and sky exposure can cause excessive heat gain, increasing the need for mechanical ventilation/ cooling and energy consumption (Golnar, Accessed, 2021). There are various methods to obtain the SVF value, the simplest for the geometric calculations of an atrium is the canyon aspect ratios as shown in figures 20 and 21 below (Golnar, Accessed, 2021). A street canyon is where the street has buildings on either side, and it affects local wind and air quality and daylight quality significantly (Steemers, 1993). When the SVF equals 0 the sky is completely covered by obstacles, a SVF above 0 means there is view of the sky.

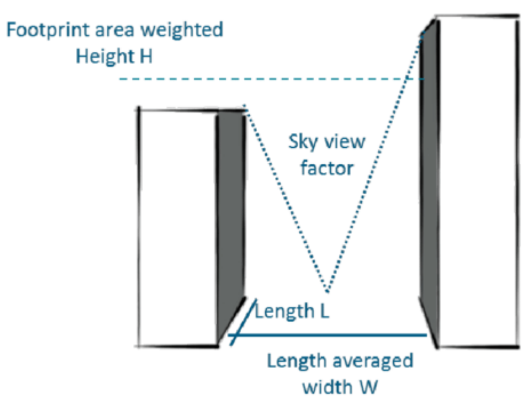


Figure 20 Street canyon design affects building daylight. Source; research gate

$$SVF_{2D} = \cos\left(\arctan\left[\frac{H}{0.5W}\right]\right)$$

Figure 21 Sky view factor-geometric calculation. Source (Golnar, Accessed, 2021)

2.4 Literature Review Conclusions

The desk study has identified key parameters to the study of daylighting atriums in dense apartment blocks. These are divided into three sections namely, the apartment building typology, atrium design, and the science of daylight in high rise buildings.

Daylight penetration- Dependent variable

Access to adequate daylight in residential spaces has been proved to have physiological and psychological benefits due to its ability to ensure a healthy circadian rhythm (sleep/wake cycles), improve mood, improve concentration, reduce eye strain, provide essential vitamin D, reduce depression, ensure hormonal balances, and increase productivity. Natural daylight also reduces operational costs of a building and has a positive effect on the rental value of a space. The tropics benefits from an average of 12 hours of sunlight every day. The unit of measurement for daylight penetration is **daylight factor (DF)** which quantifies the amount of diffuse daylight at points within a space under an overcast-sky condition.

The three factors that need to be considered **are the quantity of light, quality of light and distribution of light.** Different spaces and their respective uses also have different lighting requirements, **global green building code requirements** stipulates that 50% of all spaces should have minimum daylight factor of 2%, and that 3% is better. The factors that affect daylight in a space include**, fenestration types, materials, and size, the wall material and colour, as well as the rooms height, depth, and width. The arrangement of spaces** with each individual apartment block also plays a key role in daylight penetration, because if the user of the space adjoining the corridor / atrium feels they need more privacy, they often have **curtain or sheers** blocking the source of daylight penetration.

Apartment building typology

Since the 10th century three to six storey multi dwelling residential blocks were used to house most of the population in large villages and towns for the purposes of affordability, shared services, and developer profit maximisation for a minimised footprint. The key properties of an apartment are that they are multi-storey, multi-dwelling, and house multi-family occupant. The plurality means that they are ideal for densification and provision of housing for rising populations, as well as creating efficiencies for common services such as water supply, wastewater treatment, electricity supply, garbage collection, infrastructure, and security. In relation to massing and design the key considerations are **its location, the size of the plot, the ground coverage, plot ratio and number of floors** (without necessitating the additional cost of installing a lift).

Atrium design- Independent variable

Atriums have been used in buildings for centuries. Their main functions were for privacy from the street, creating a common meeting space that everyone had access to, which had access to natural light, ventilation, as well as for a secure defensible open space. In modern times atriums have featured across all building typologies from educational, residential, institutional, industrial, and commercial. Their main functions are to allow natural light, natural ventilation, into a deep plan building without losing out on prime real estate. Atriums in residential spaces, unlike in offices and institutional buildings, have multiple functions often not accounted for during the design stages. These include **parking, clothes hanging, outdoor cooking, social (informal meetings), extra storage, play space for children, laundry, and the circulation space (corridor and stairs).** These additional functions of the atrium space affect its daylight penetration, the quality of space and the air quality.

The design, sizing of atriums came from thought into the **architectural, economic, and environmental factors.** The key considerations for adequate daylight penetration in atriums are **the roof fenestration types, atrium geometry, wall surface material and colour, window size and position, sky conditions, building regulations (plot ratio and ground coverage), and what other functions the atrium has.**

In addition, the most effective calculations to determine the daylight penetration of an atrium which are plan aspect ratio (PAR), the section aspect ratio (SAR) and the combination of the two forming the Well Index.

- PAR= Width / Length (Closer to 1 the better)
- SAR= Height/Width (Lower the SAR the better)
- Well Index (WI)= 0.5SAR (1+PAR)- The lower the WI the higher the Daylight Factor
- Sky View Factor (SVF)=cos(atan(H/0.5*W)-Closer to 1 the better)

Building regulations

In Kenya, seven building regulations govern the sizing of atriums. The first two are in the county ordinances guide, which stipulates the **ground coverage**, which governs how much of a footprint a developer can build on a certain plot size and the **plot ratio** which governs how many stories they can build. The other four are in the building code which stipulates the **distance from an open window must be 2.4M**, also gives detailed guidelines of open zones outside a window, as well as the requirement that any multi-storey building above five levels are required to have a lift, and the total area of the openings, inclusive of frames and glazing bars, shall be at least 10% of the floor area. The seventh is the minimum subdivision of plots in municipalities in Kenya is **1/8th of an acre coming to 50 x 100ft plots (approx. 15M x 30M)**. As such most low-income, multi-dwelling apartments feature five to seven-storey atrium apartments. The Government intended for this subdivision of 50 x 100 ft plots to accommodate a single-family dwelling, but land prices and developer costs have moved towards higher densities to gain a higher rental value to cushion the rising land prices (GOK, 2020).

Variable type	**Variable**	**Code**	**Sub variable**	**Data collection method**	**Data presentation**	**Data analysis**
Daylight penetration- Dependent variable	Daylight penetration	D	Daylight Factor (DF)-quantity of light	Simulation	Tables	Comparison with green building codes
		DV2	Distribution of light	Simulation + Drawings	Daylight layouts and 3D diagrams	Measurement of total area and quantity of light and comparison with green building codes
Atrium design - Independent variable (Quantitative)	Context	IV1	IV1.1- Block design IV1.2- Sky view factor IV1.3- Relation to neighbouring buildings IV1.4- Relation to road	Observation + Measurement	Layout plans, Sections, elevations, sketches, and 3D models	Measurement of distances and qualitative analysis of key observations
	The Apartment	IV2- General	*IV2.1- Plot size* *IV2.2- Ground coverage (GC)* *IV2.3- Plot ratio (PR)* *IV2.4- Number of floors*	Observation + Measurement	Quantity tables	Qualitative analysis of key observations
		IV3- Materials	IV3.1- Wall material IV3.2- Wall finish IV3.3- Colour	Observation	Tables and images	Qualitative analysis of key observations
		IV4- Openings	*IV4.1- Size* IV4.2- Position IV4.3- % of window to floor area IV4.4- Distance outside open window IV4.5- Window blocks (i.e curtains)	Observation + Measurement	Quantity tables, elevations, and sketches	Daylight penetration and qualitative analysis of key observations
		IV5- Layout	IV5.1- Analysis of internal spatial configuration and impact on functional uses of the atrium	Observation	Layout plans, and sketches	Qualitative analysis of key observations
	Atrium	IV6- Roof	IV6.1- Roof type; open to sky or covered	Observation	Images	Qualitative analysis
		IV7- Geometry	IV7.1- PAR= Width / Length (Closer to 1 the better) IV7.2- SAR= Height/Width (Lower the SAR the better) IV7.3- Well Index (WI)=0.5SAR/(1+PAR)- The higher the WI the higher the Daylight Factor (DF)	Calculation	Quantity tables	Comparison with ideal case and qualitative analysis of key observations

3 RESEARCH METHODOLOGY

Grinell defines research as, “a structured inquiry that utilises acceptable scientific methodology to solve a problem and create new, applicable knowledge” (Grinell, 2014). This involves working systematically with methods and techniques that have been tested over time for their validity and reliability. Validity is determined by the correct method and reliability is determined by the methods ability to return comparable results when replicated (Kumar, 2005).

3.1 Research Strategy

Research strategy identifies how you will find answers to your research questions; validly, objectively, accurately, and economically (Kumar, 2005). This study uses the case study research method with both qualitative and quantitative data collection and analysis methods. Yin defines the case study research method as, “an empirical inquiry that investigates a contemporary phenomenon within its real-life context” (Yin, 2002). This method is advocated when a “why” or “how” question is being asked. The case study research approach generates an in-depth, multi-layered understanding of a complicated problem in its real-life context. (Crowe, 2011).

This study used a mixed method of qualitative and quantitative data collection and analysis. Qualitative research is the process of collecting, analysing, and interpreting non-numerical data such as text, drawings, video, and photographs. Quantitative research methods emphasise objective measurements such as statistical, calculations, mathematical measurements, or numerical analysis of the data collected (Rukwaro, 2016). In addition, the case study area was modelled using ArchiCAD and Revit software to run daylighting simulations for comparison and corroboration with the geometric calculations.

3.2 Unit of Analysis, and Variables

The unit of analysis in architectural research is the element that is being studied (Rukwaro, 2016), which in this study is the apartment block and is defined as the block as a five to seven-storey walk-up housing without a lift, on an eighth-acre plot with 50 x 100 ft (15 M x 30 M) dimensions. The atrium design is the independent variable (cause) that is affecting daylight penetration (effect). The case studies in Roysambu will study the atrium design and its effect on daylight penetration. This study took a typical block and studied the plot size, ground coverage, plot ratio, number of floors, block design, sky view factor, relation to neighbouring buildings, relation to road, wall material, wall finish, colour, size position % of the window to floor area, distance outside open window, window blocks (i.e., curtains). Analysis of internal spatial configuration and impact on functional uses of the atrium, the section aspect ratio, plan aspect ratio and the well index.

3.3 Population Sampling Strategy and Time Scope

The population was selected from a biased convenience sampling in Roysambu, Nairobi, Kenya. The biased approach in selecting Roysambu was because it is representative of typical housing units in Nairobi, Kenya for the low-income formal economic category. The author determined the suitability of the case study location and block selection during a reconnaissance visit in February 2021, together with studies of aerial photography and mapping. The selection of the block in Roysambu was because to over 90% of its buildings were completed, and each apartment block had a similar volume of construction but with different atrium types for the study.

The scope of this study was limited geographically to Roysambu neighbourhood in Nairobi, Kenya. This region was chosen because of the high densities witnessed in the area which are representative of the typical atrium walk-up apartment block in Nairobi Kenya. As well as its population growth parameters, and neighbourhood block featuring 4 roads on each side and typical apartment blocks. The study took a cross sectional study during the year 2021 for data collection and analysis. The year of study was during the COVID- 19 pandemic which created unique circumstances in the study regions.

The theoretical underpinning of the study was environmental science bound by the study of daylighting. Daylight is the natural light coming directly from the sun and reflected by water and dust. The study was theoretically bound by housing for low-income, formal apartment blocks in developing countries. This was because it was currently the prevalent form of housing being supplied to the market and will continue to do so, given the growing housing crises in Nairobi.

3.4 Data Collection and Analysis

Data collection

Primary data was collected through observations. Observations were through unstructured non-participant observation in their natural environment and were recorded using written narrative, photographs, sketching and measurements. Interviews are through non-structured interviews with users of the spaces. In addition, the measurements of each apartment block were taken and modelled, and a Building Information Model (BIM) was used to simulate the daylight factor effects across the different atrium levels. Secondary data collection; was be collected and analysed from existing literature, the internet, documents, and journals. Research assistants assisted with data collection in the field, through measurements, photo taking, and inputting into software for the author to analyse and detail.

Ethical considerations for the study included not subjecting harm to occupants, and participants in any way, prioritising respect for the dignity of the premises and occupants, obtaining consent where required, avoidance of any deception or exaggeration about the aims and objectives of the research, and maintaining honesty and transparency through the research process.

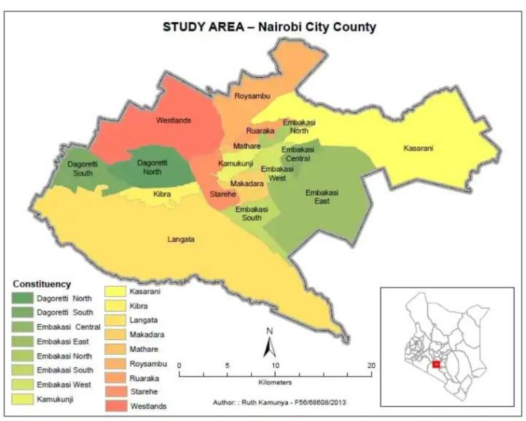
Data analysis

Both quantitative and qualitative data were collected in this study. Quantitative data went through statistical analysis to generate graphs and charts from the data after which comparisons and conclusions, and recommendations were drawn. Data was generated using the REVIT BIM software for computational analysis to generate graphs and plans with daylight factor considerations. Qualitative data from observations and interviews were analysed through written narrative and analytical sketches.

4 FINDINGS AND ANALYSIS

4.1 Context-Roysambu, Nairobi, Kenya

Roysambu is a neighbourhood in Nairobi City County and is one of seventeen constituencies in the capital city, as shown in figure 22 and figure 23. The name ‘Roysambu comes from the colonial title which was ’Royal Suburbs,’ however, the local community in Nairobi pronounced it as Roy-Sabu which eventually became the name “Roysambu.” The Roysambu sub-county has five wards including Roysambu, Zimmerman, Githurai 44, Kahawa and Kahawa West. These were originally Jewish Coffee farms owned by a man called Joreth who later sub-divided the land and sold (Mwake, 2019). The population is densely populated with approximately 4,000 people per square kilometer (GOK, 2021). The neighbourhood has multiple higher learning institutions which include Kenyatta University (KU), and United States International University Africa (USIUA).



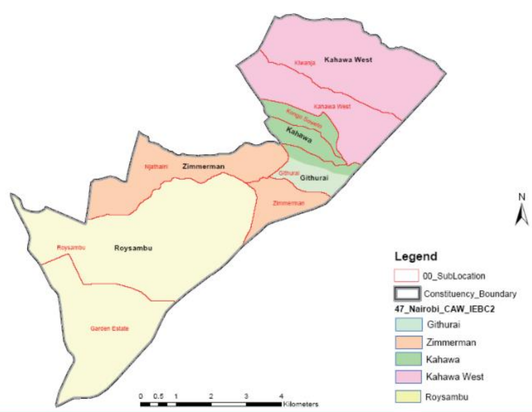


Figure 22 Roysambu in Nairobi County. Source; GOK, 2021.

Figure 23 Roysambu constituency and Wards. Study is located in Roysambu sub-ward. Source; GOK, 2021

The case study block is in Roysambu, along Lumumba drive, and is a recently densified neighbourhood that is typical of privately owned residential areas which are over the years sub-divided and sold in eighth-acre parcels. Figure 24 shows the chronological map view of Roysambu neighbourhood, as it has densified through the past 18 years which has led to the substantial loss of green areas as well as development without daylight consideration is evident.

Figure 24 Densification of Roysambu neighbourhood. Source: Author adapted from google maps, 2021.

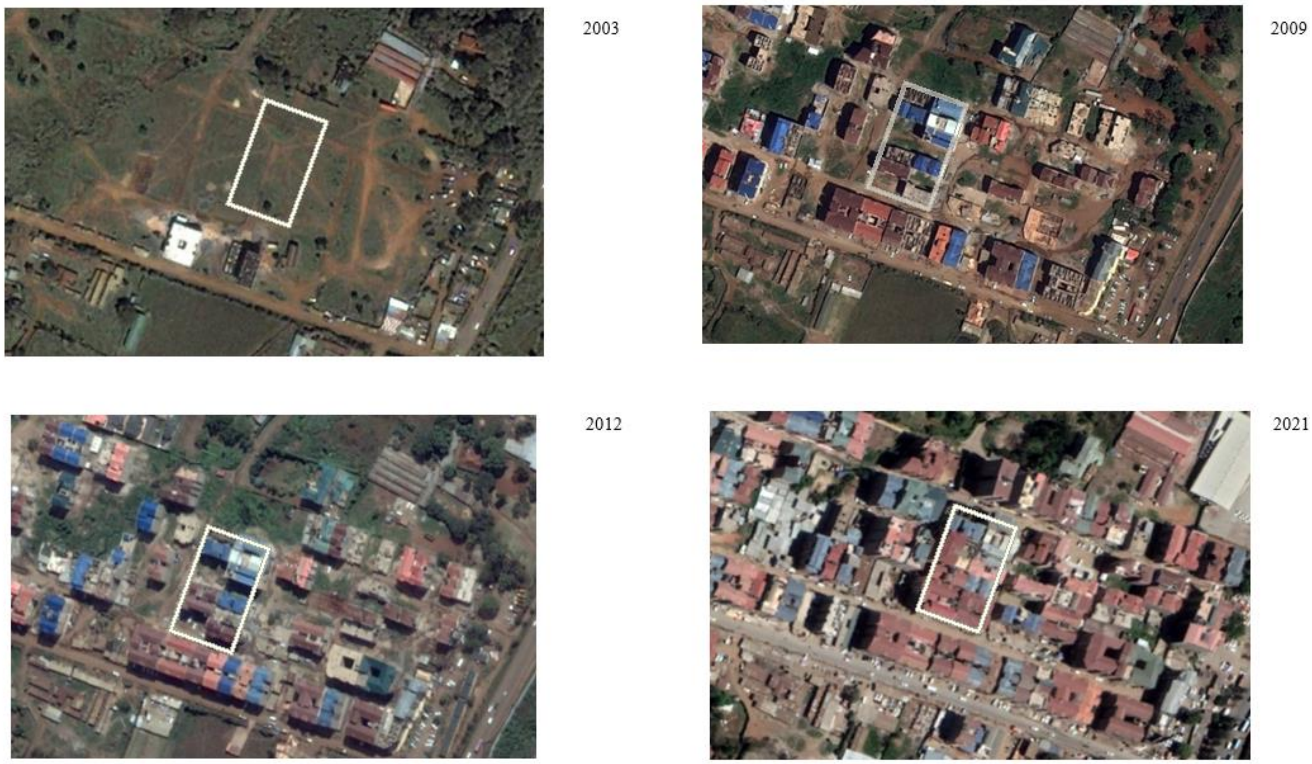


Figure 25 Chronological map view of the Roysambu block that is being studied.
Source: Author adapted from google maps, 2021.

Apartments on the eighth-acre plots are designed and built with key daylight sources from neighbouring plots. When the neighbouring plots are developed, they block the main daylight source to key spaces. The studied block represents a typical 1.6-acre urban block subdivided to ensure maximum residential units per buildings on a 1/8 acre (the minimum plot size that one can subdivide the land to), without requiring the provision of a lift. The street canyon around the block is a 6-metre-wide dual carriageway, often featuring parked cars and kiosks. The total area of the block is 6,503.2 SQM and it includes 9 plots with 3 no. ¼ acre plots 9 no. 1/8 acre plots. The block includes 12 occupied buildings and one unoccupied abandoned half- finished building.

Figure 26 Street character of Lumumba drive in Roysambu. Source; Author, 2021.

Roysambu is a social and vibrant community which is densifying at a rapid rate and considerations of daylight access have been overlooked during the densification process. The plots were subdivided in anticipation of them being inhabited by single dwelling houses but instead, due to the increasing land value of the region, developers, landowners, and institutions build high-rise apartments on the plot to maximise revenues.

Throughout the neighbourhood there is a lack of internal laundry areas within the apartment block which causes residents to opt to hang clothes outside their street-facing balconies or windows, or in the atriums which are the main sources of light into the spaces.

Figure 27 Sketch view of street in Roysambu. Source; Author, 2021

The sky view of the street canyon in the case study region is reduced by protruding balconies into the street canyon. The architectural design of the balconies also plays a key part, with the use of heavy masonry, an affordable construction material in the region, too opaque to let light in and preventing direct daylight penetration. As shown in figures 27 and 28, the urban street level in the case study region is very social with multiple street level activities such as shops, temporary stalls, people, markets, etc. This brings life, character, social capital, and neighbourhood social-economic support. However, they also block light to the ground level units, as well as impede privacy for ground-level residents, meaning most ground level units leave their curtains closed throughout the day. In dense urban neighbourhoods, the ground level is an opportunity for commercial businesses to engage directly with the street which adds vibrancy to the neighbourhood, but also removes vital residential spaces away from areas without good daylight penetration.

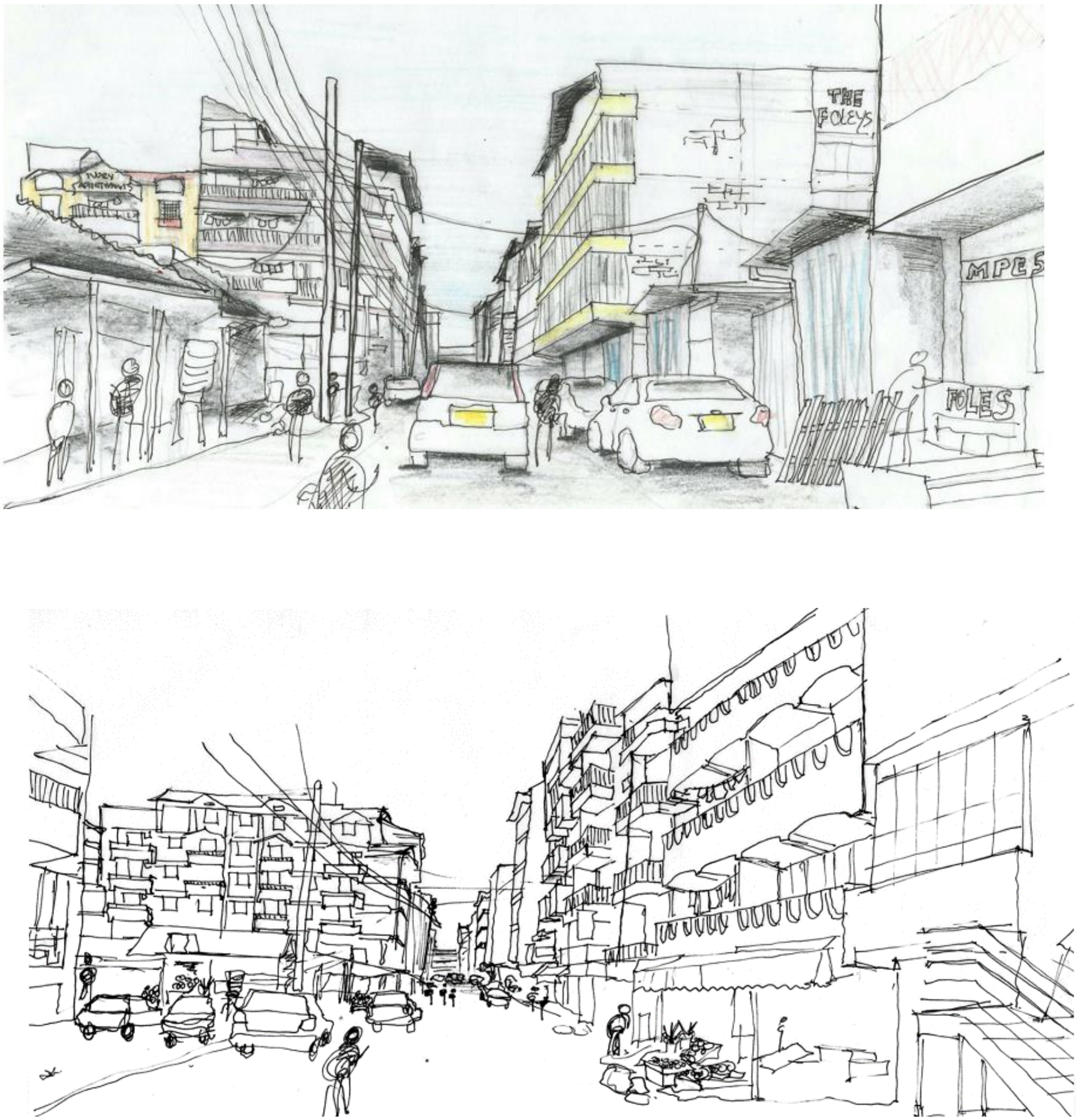


Figure 28 Two sketches showing the urban character of Roysambu. Source; Author, 2021

Buildings such as the one shown in figure 29 below are designed to allow light into the atrium from side openings into neighbouring plots, which over time will be built up and block hence vital daylight penetration and ventilation into the spaces. In many cases the neighbouring building might at first be empty, or a temporary single- or two-storey building, but eventually will become a high-rise apartment blocking light into the atrium, courtyard, or sidelight of a building.

Figure 29 Roysambu buildings are built without consideration of future upcoming developments. Source; Author 2021

In the case study region, as shown in figures 30 and 31 the blocks street orientation is a key factor, because the sun path direction was perpendicular to the long side of the buildings blocks main facades. As such the block had reduced daylight penetration to its atriums because the long aside of the atrium received the least amount of direct daylight. Urban planning of neighbourhoods should consider sun path orientations in relation to block orientation, especially in areas prone to high densification.

The case study block is oriented 18 degrees west of true north and this orientation affects the effective daylight that will penetrate the atriums because the neighbouring apartments block each other from direct sunlight. The atriums studied in the case study region behaved like wells, and as the sun moved through its daily cycle, only between 11 am to 1 pm did the overhead sun effectively penetrate to the lower levels of the atrium as shown in figures 32 and 33.

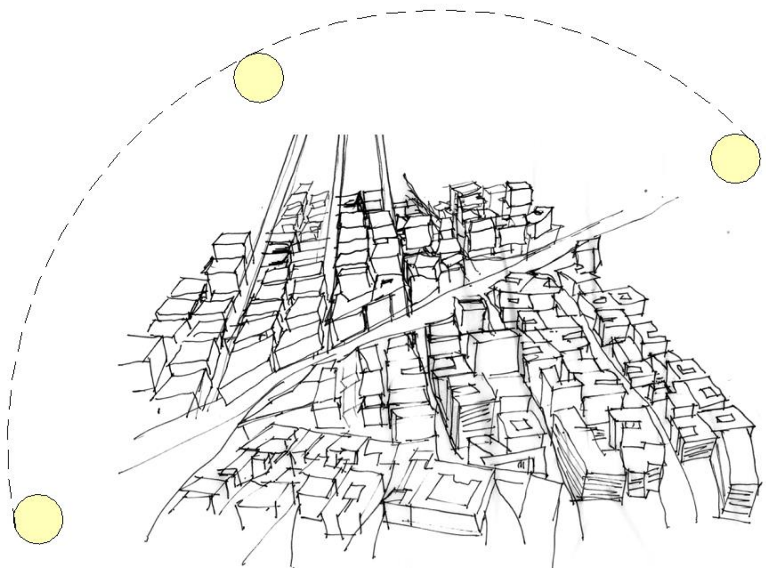


Figure 30 Steet direction vs building orientation affects daylight penetration. Source; Author 2021.

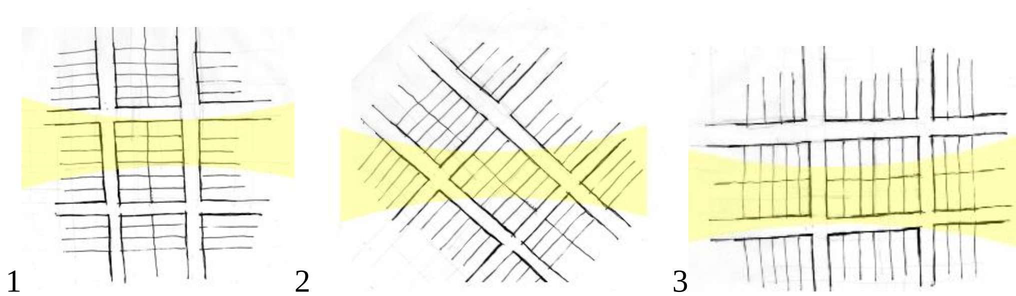


Figure 31 1) Short side of the street in line with E/W…2) Short side of the street 45 deg. to sun path. Source; …3) Short side of the street 90 deg. to sun path. Source; Author, 2021.

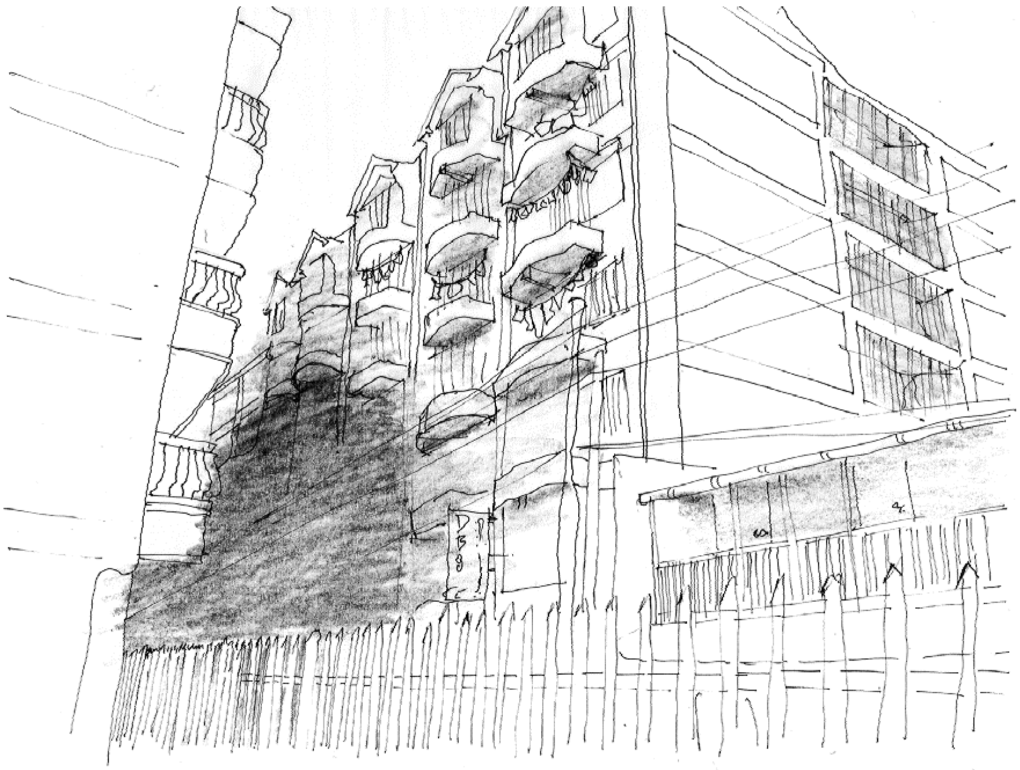


Figure 32 Building in proximity with a 6-meter street canyon block daylight from each other throughout the day. Source; Author, 2021

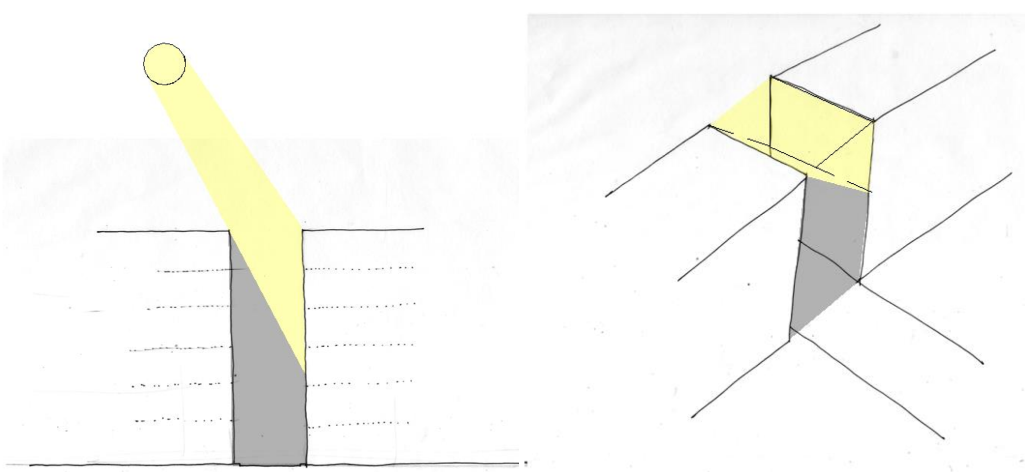


Figure 33 Shadow created by buildings blocking each other. Source; Author 2021.

4.2 Overall Block Studies

The Case study block represents a typical 1.6-acre urban block subdivided to ensure maximum residential units per buildings on a 1/8 acre. The street canyon around the block is a 6-metre-wide dual carriageway, and the total area of the block is 6,503.2 SQM and it includes nine plots with three no. ¼ acre plots and nine no. 1/8 acre plots. The block includes 12 occupied buildings and 1 unoccupied abandoned half- finished building. The study will review building one to nine as shown in the figure 35 and the 3D view in figure 36 below.

Figure 34 Contextual view of case study block. Source; Author 2021.

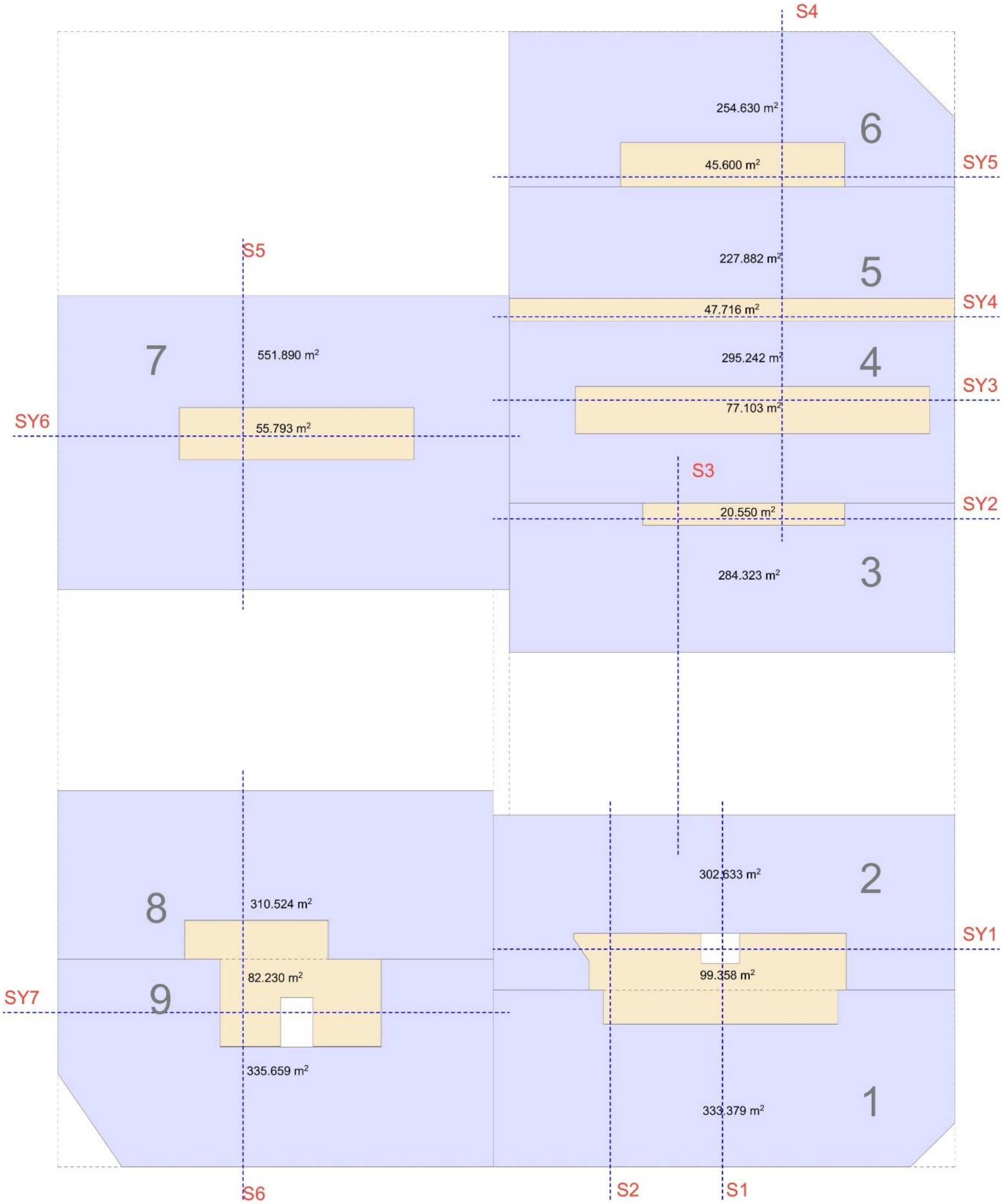


Figure 35 Simplified layout of case study block showing atrium versus built footprint and section markers for reference. Source; Author, 2021

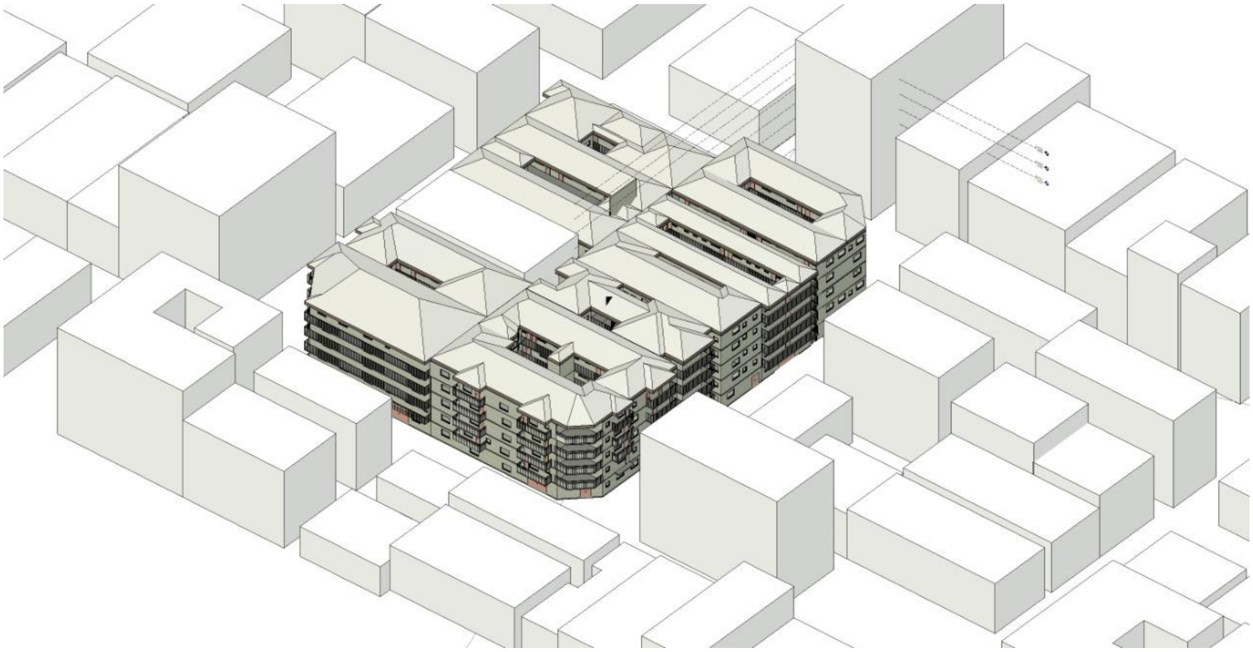


Figure 36 3D View of case study block. Source Author; 2021.

The block layout and dimensions as shown in figure 37 below shows the functional zoning in the apartments studied. Typically, the living and bedroom spaces (which people spend the most time in) along the corridor facing the atrium, with the kitchen facing externally, or into balconies. Very few apartments have the luxury of having balconies, or kitchen yard, so the atrium space is used for clothes hanging. The stair in five of the apartments are located within the atriums. This strategy aids in centralising circulation but blocks the effectiveness of daylight penetration through the atrium.

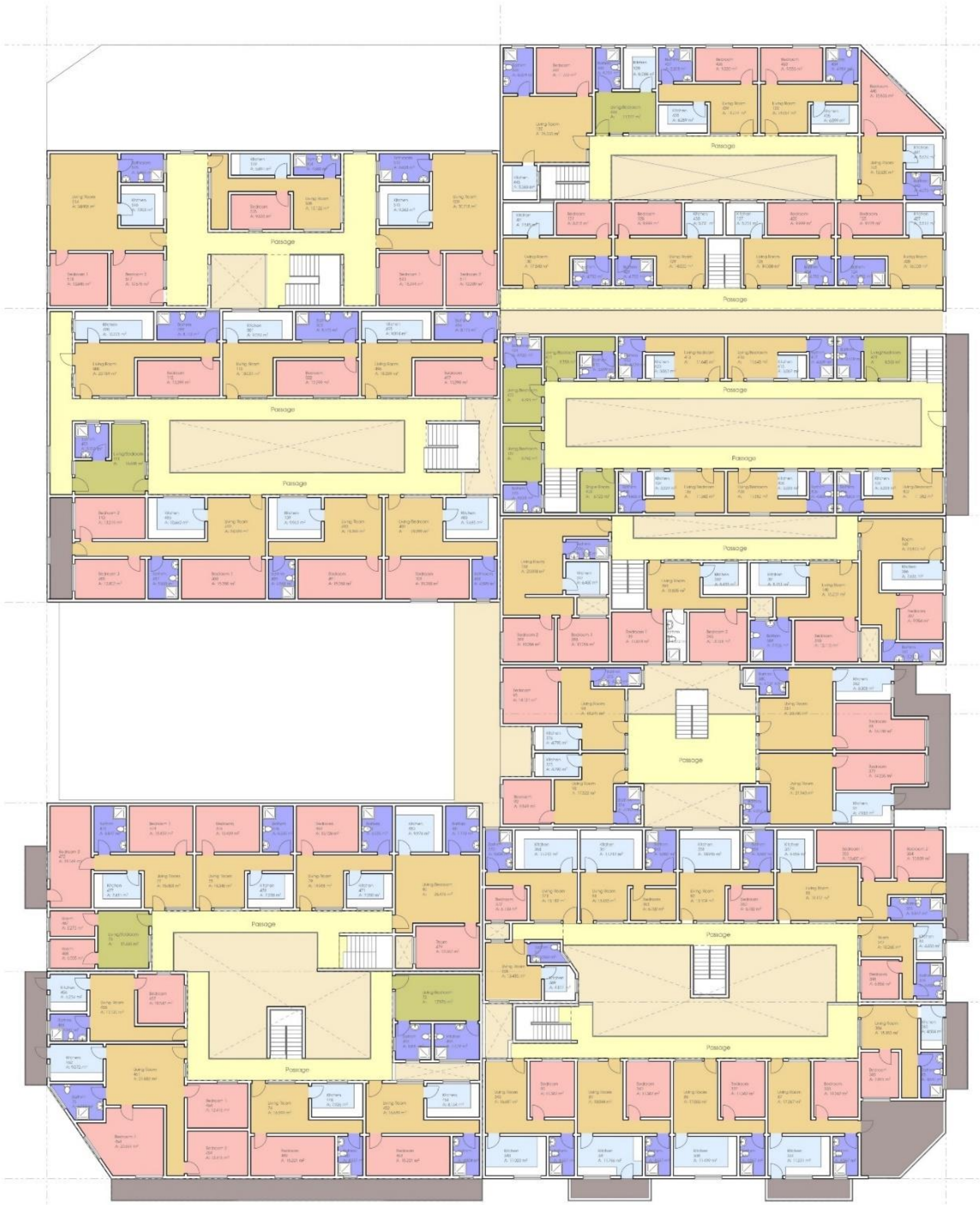


Figure 37 Functional zoning of case study block. Legend as shown in previous page. Source; Author, 2021.

4.3 Quantitative Block Calculations

Table 3 Quantitative calculations. Source; Author 2021.

Building No.	Height	Built Area	Atrium Length	Atrium Width	Atrium Area	% atrium vs built	Plan Aspect Ratio (PAR)=W /L	Section Aspect Ratio (SAR)=H/ W	Well Index (WI)= 0.5 SAR(1+PAR)	Sky View Factor(SVF)= cos(atan(H/0.5* W)
Notes							1= ideal	0=ideal	0=ideal	1=ideal
X-low yield	15	270	30	12.00	360.0	57%	0.40	1.25	0.88	0.37
x-Ideal	15	348	17	11.50	195.5	36%	0.68	1.30	1.09	0.36
1	15	333	15.9	6.10	97.0	23%	0.38	2.46	1.70	0.20
2	15	302.6	18.5	6.10	112.9	27%	0.33	2.46	1.63	0.20
3	15	284.3	13.7	1.50	20.6	7%	0.11	10.00	5.55	0.05
4	15	295.1	24.0	3.2	76.8	21%	0.13	4.69	2.66	0.11
5	15	227.9	30.0	1.6	48.0	17%	0.05	9.38	4.94	0.05
6	15	254.6	15.2	3.0	45.6	15%	0.20	5.00	2.99	0.10
7	15	551.9	15.9	3.5	55.7	9%	0.22	4.29	2.61	0.12
8	15	310.5	9.7	8.5	82.5	21%	0.88	1.76	1.66	0.27
9	15	335.7	10.9	8.5	92.7	22%	0.78	1.76	1.57	0.27

The quantitative analysis of the case study neighbourhood block revealed key correlations. The **section aspect ratio (SAR)** has a direct correlation with the atrium well index and hence the daylight factor. The higher the SAR the poorer the Well index. SAR is the relationship between the height of the atrium and the length of the atrium. If the height of the atrium is higher than its length, then the well index reduces, and the daylight performance improves. This is because atriums are meant to be effective across its entire depth, to provide daylight penetration to the lower levels of the building. For a five storey building with an average floor-to-floor height of 3.0M, then the atrium heights are typically 15M. Atrium lengths of between 15M to 30M (the typical length of a plot) are ideal for effective daylight penetration.

The **plan aspect ratio (PAR)**, that is the relationship between the width of the atrium and its length also has a direct correlation. The study found that atriums with a higher width as closer to the length provided better daylight penetration. The closer the resultant PAR was to 1, implies a squarer proportion, which in turn provided more evenly distributed spread of daylight through the atrium. **Well index** result and findings across the case study blocks correlated with the literature that the higher the well index the poorer the daylight penetration this corresponded too with sky view factor findings that the lower the **sky view factor**, the higher the well index and poorer the daylight performance as show in tables 4, 5 and 6.

Developers should carefully consider the **number of windows** with access to the atrium. This is opposite to user preferences for privacy from the public corridor. However, the higher the number of windows, the higher the area receiving daylight from the atrium provides higher daylight penetration. In most cases the residents had their curtains closed during the day, which blocks daylight penetration. Developments should consider clustering unit entrances around a shared landing space away from the atrium such that daylight from the atrium is accessed directly into the space and provides the users their **privacy**.

Market forces are the key driver for decision making, as such all developments studied had 88%-95% **ground coverage**, with the percentage of atrium to build footprints ranging from 7% in the more poorly daylit spaces to 29% in the developments with a shared atrium design with their neighbouring apartments. Developments in dense urban neighbourhood aim to maximise on profits and rental yield of their developments this is because the price of land and the long-term return on investment is a key motivation for such areas. Governments in these rapidly developing areas need to acknowledge the increasing densities and put measures to ensure compliance with health and safety. Developments studied did not meet requirements for **open space outside a windows** requirement of 2.4 meters, and those open spaces often had obstructions such as permanently placed hanging lines and parking areas (ground floor only) which blocked any daylight penetration into the spaces.

Table 4 Section Aspect Ratio (SAR) as it compares with Well Index (WI) for the studied blocks. Source; Author 2021

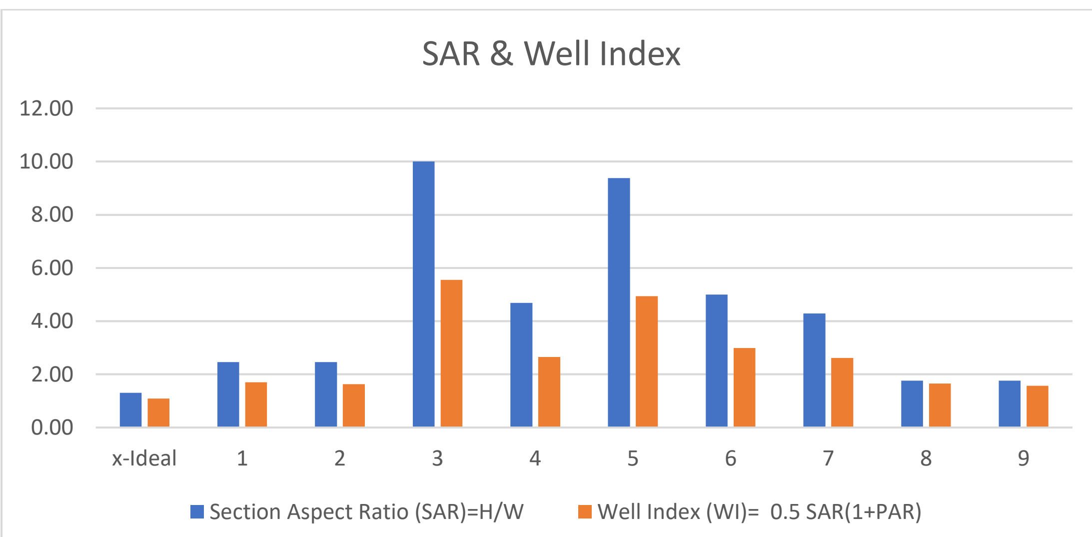


Table 5 Sky view Factor (SVF) comparison across the case study apartments. Source; Author, 2021

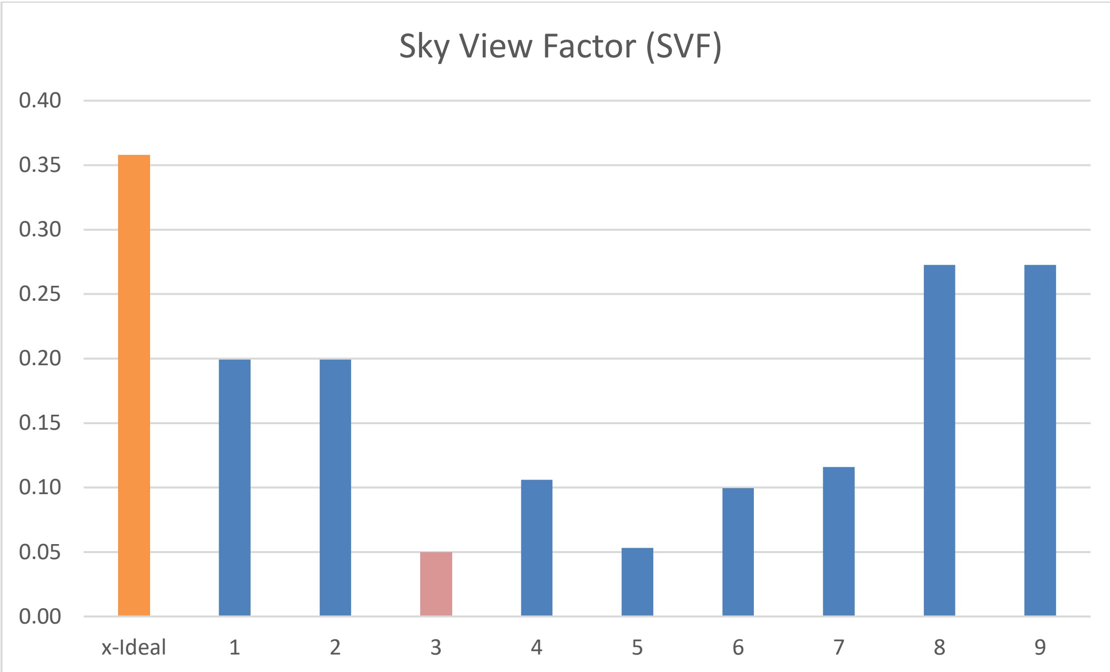
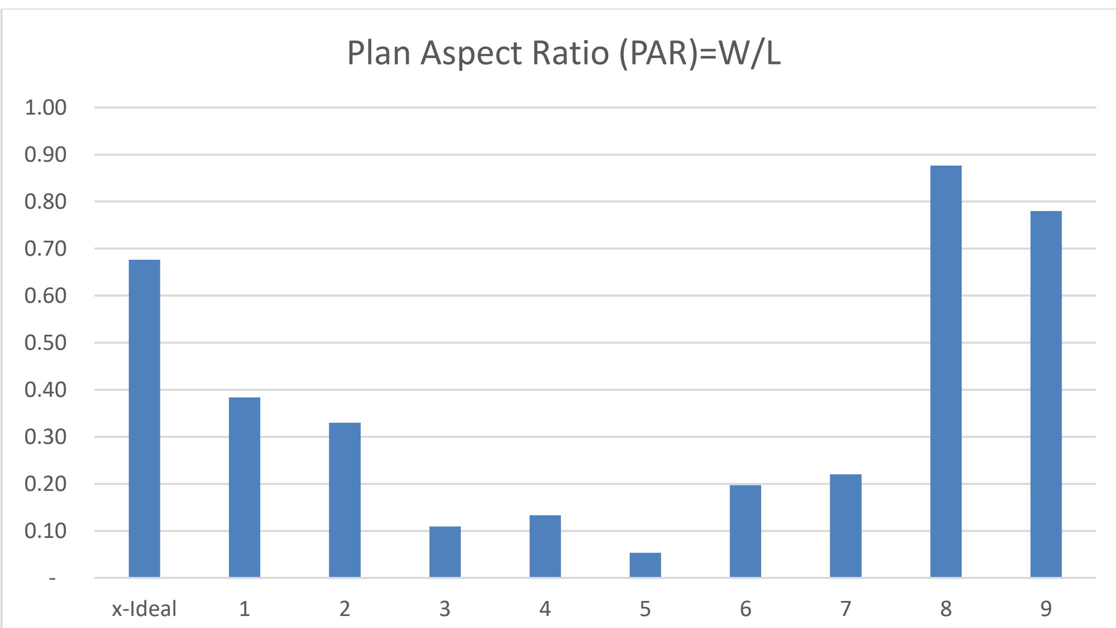


Table 6 Plan Aspect Ratio(PAR) comparison across the case study apartments. Source; Author, 2021



4.4 Daylight Factor Simulation

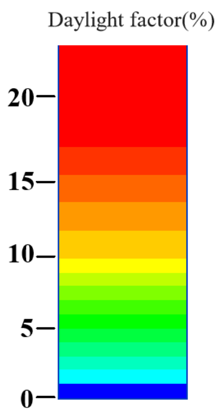
Daylight factor (DF) quantifies the amount of diffuse daylight at points within a space under an overcast-sky condition. Different spaces and their respective uses also have different lighting requirements, but most green building and global building code requirements stipulate that the minimum daylight factor is that 50% of all spaces should have minimum daylight factor of 2%, and that 3% is better.

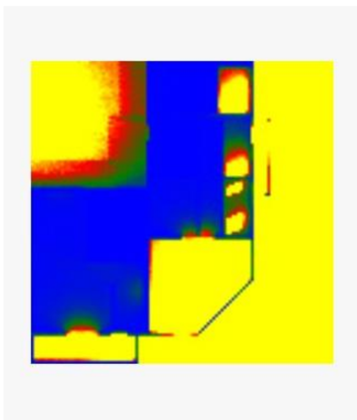
The case study block revealed poor daylight penetration across the depth of each atrium as shown in table 7, in the simulation averaged across all floors on the studied blocks. Level 4 daylight showed the atrium corridor received high levels of daylight above 15% which causes glare and high heat gain, whereas the level one daylight factor only reached less than 1% which is poor for daylight access and comes from the sky view factor which was poor due to the narrow widths of atriums in the case study block (1.3M to 43M). In addition, atriums with staircases in the centre blocked daylight access. Apartment blocks such as building 1, 2, 8, and 9, benefit from increased sky view and hence better atrium daylight penetration due to sharing the atrium space. As shown in table 8 with daylight simulation figures therein.

Table 7Annual Daylight Factor - Simulation averaged across all floors on the studied blocks. Source Author, 2021.

Annual Daylight Factor - Simulation averaged across all floors on the studied blocks				
GF	**1st F**	**2nd F**	**3rd F**	**4th F**
0.3	0.8	1.9	2.5	5.4

Table 8 Daylight simulation using REVIT Insight, for level 1 of the block being studied. Lower levels have poorest daylight access. Source; Author 2021.





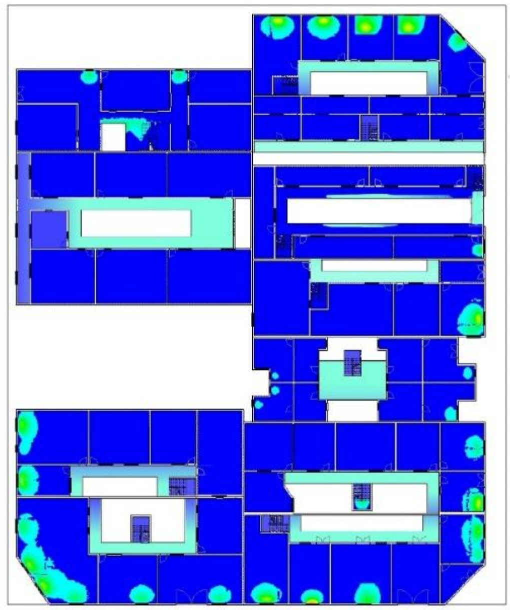


Figure 38 Review of lighting range in spaces & Figure 39 Daylight simulation legend

Figure 40 Ground floor daylight simulation. Author, 2021 & on the right

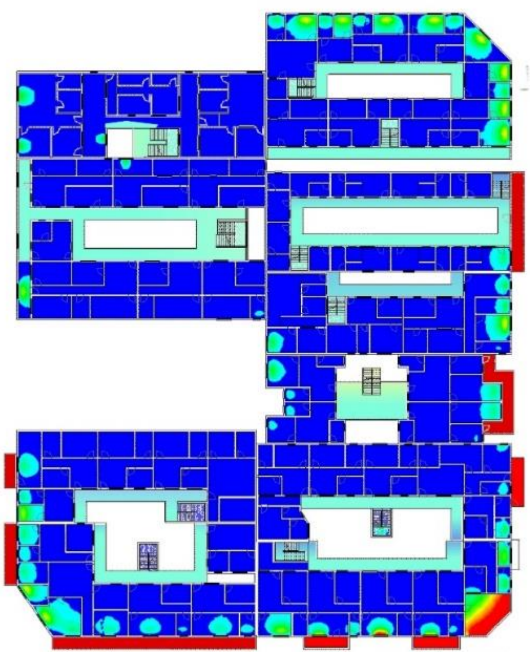
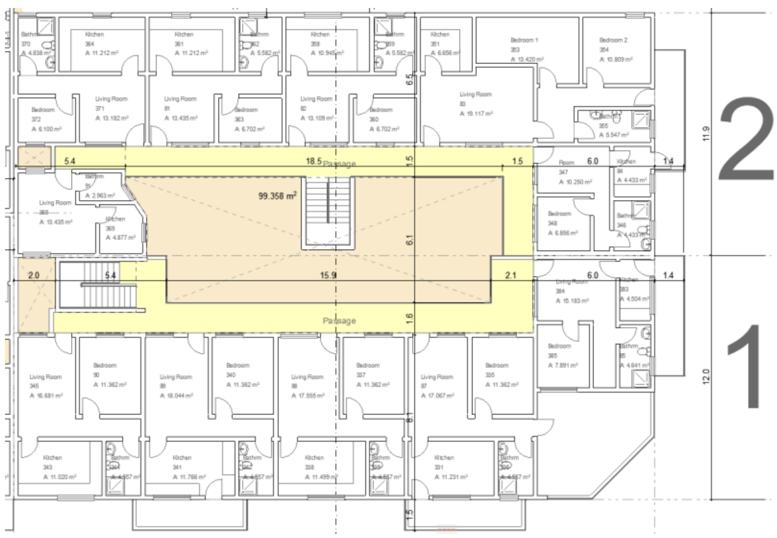
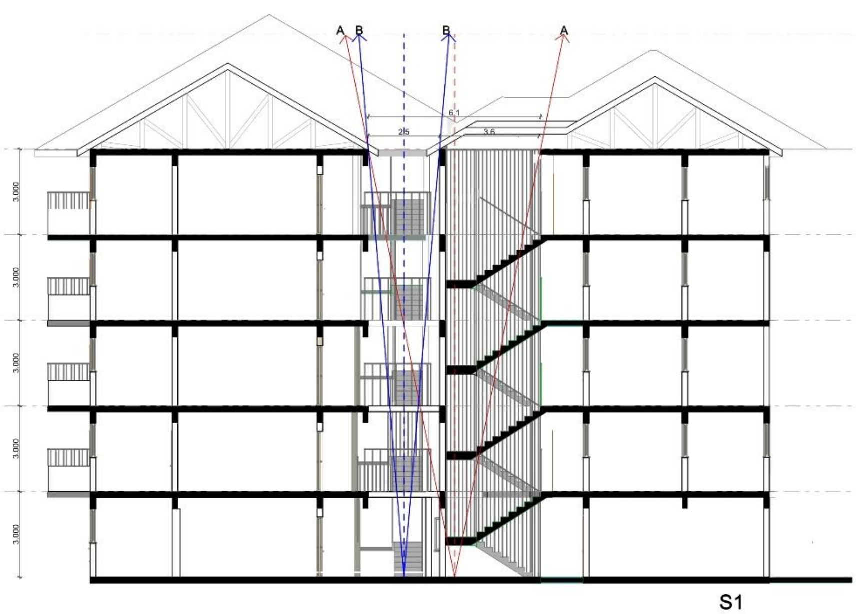


Figure 41 Level 1 daylight simulation. Author adapted for clarity, 2021. And Figure 42 Level 2 daylight simulation. Author, 2021

Figure 43 Level 3 daylight simulation. and Figure 44 Level 4 daylight simulation. Author adapted for clarity, 2021.

4.5 Individual Building Studies

	Building 1 & Building 2
Plan	 *Figure 45 Floor plan for building 1 and building 2. Source; Author, 2021.*
Section	

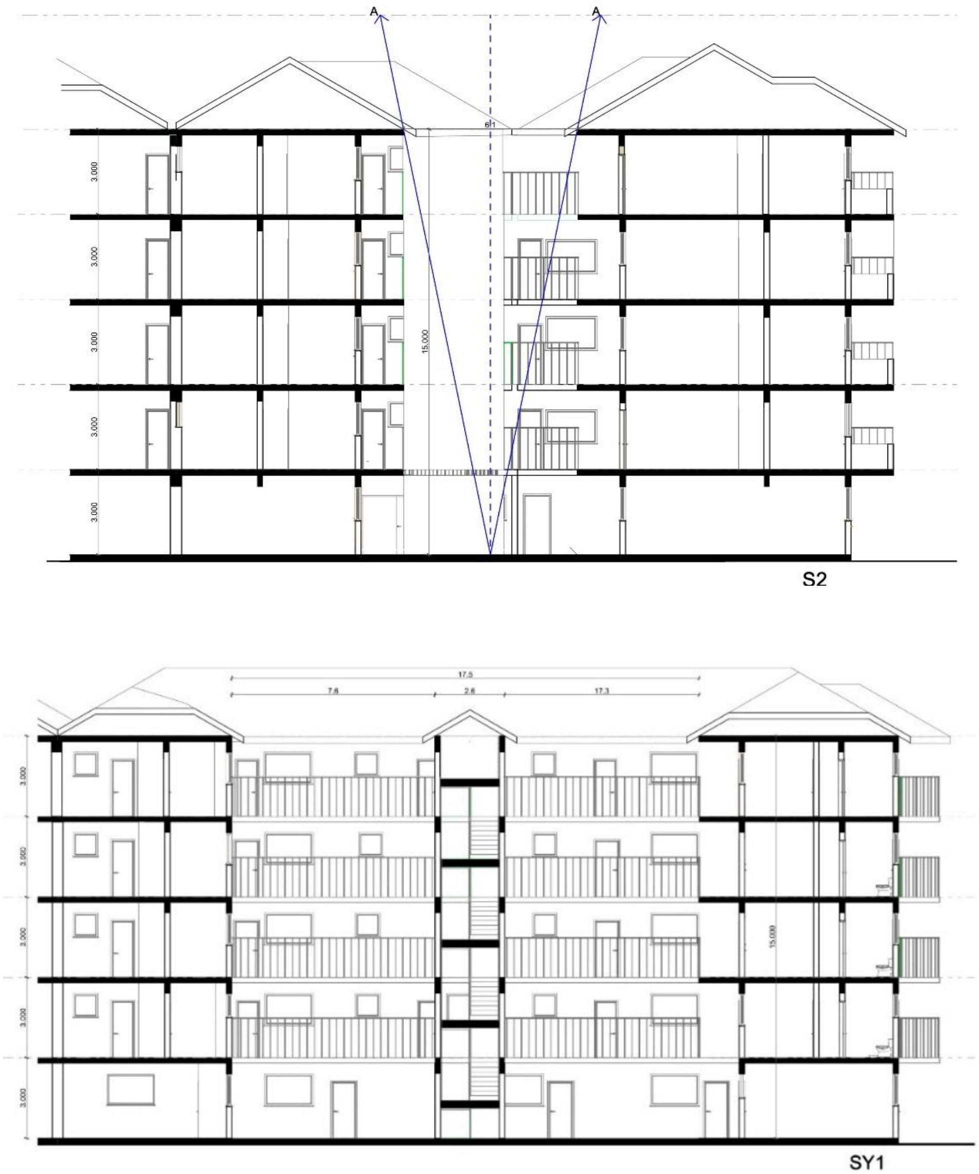
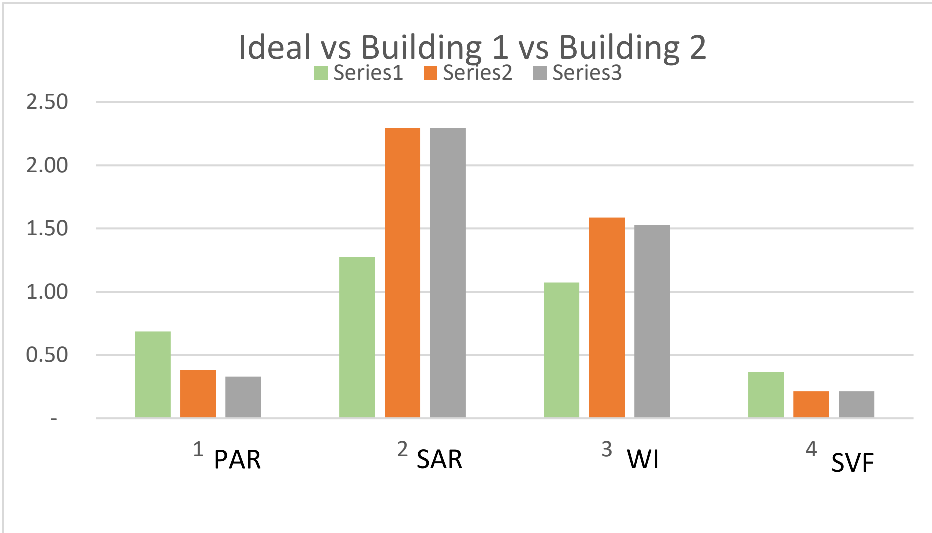


Figure 46 Sections of building 1 and 2. Source; Author, 2021.

<table>
<tr><td></td><td></td></tr>
<tr><td>Quantitative</td><td>

Table 9 Extracted charts of quantitative data. Full data set in Table 3 on page 67. Source; Author, 2021.



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<tr><td>Photos</td><td>

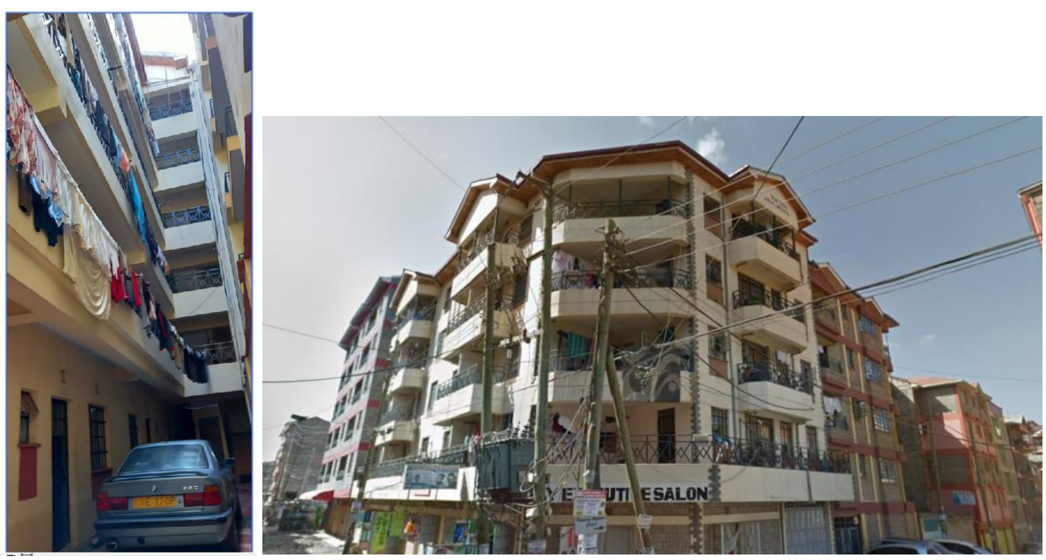

Figure 47 Building 1 front and atrium view showing the balcony type, the railing and clothes hanging. Source; Author, 2021.

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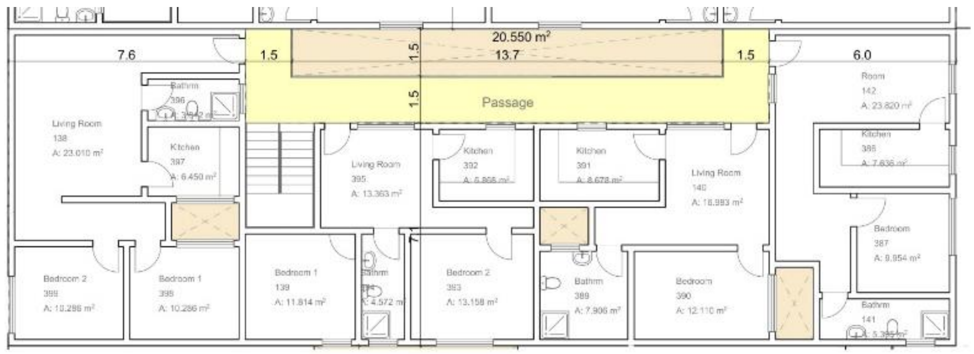
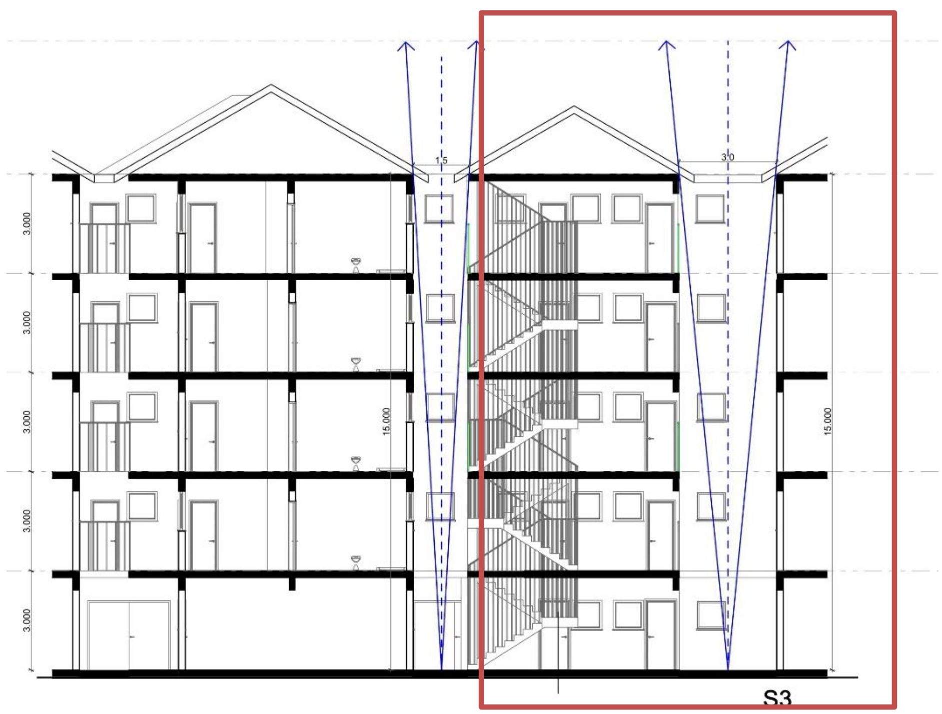
</table>

<table>
<tr><td></td><td>
Figure 48 Building 2 front and atrium view showing the balcony type, the railing. Source; Author, 2021.</td></tr>
<tr><td>Analysis</td><td>Building 1;
1. Atrium type; Individually, building 1 has a shared U-shaped atrium. It is shared with the neighbouring plot to make a shared O-shaped atrium. This atrium typology is effective in maximising daylight penetration for both buildings.
2. Well index (WI) and Daylight factor (DF- simulation); Building 1 has a well factor of which correlates to comparative medium performance for daylight factor. Building 1 has a 23% atrium are vs-built footprint due to shared atrium benefiting both plots.
3. Sky view factor (SVF); Good SVF of 0.21 as both buildings benefit from shared atriums. However, the lower levels receive poor daylight penetration from the atrium into the spaces.
4. Wall finish: Building 1 has light coloured finishes that effectively ensure maximum light reflection in the atrium. As shown in figure 45.
5. Railings: Railing type is half masonry and railing. Full railing more ideal for ensuring daylight penetration. As shown in figure 45.</td></tr>
</table>

	6. Stair: stair is recessed away from the atrium, which is ideal. 7. Other functional notes: Building 1 had the main living spaces such as the living rooms, and bedrooms facing the atrium which is not ideal for corner plots where the main living spaces should be located on the outside facade facing the street, as they are assured of direct daylight access from the street canyon. The lack of adequate laundry areas for drying clothes means the atrium is also used to dry clothes during the day, which blocks daylight. **Building 2;** 1. Atrium type; Individually, building 2 has a shared U-shaped atrium. It is shared with the neighbouring plot to make a shared O-shaped atrium. This atrium typology is effective in maximising daylight penetration for both buildings. 2. Well index (WI) and Daylight factor (DF- simulated); Building 2 has a 27% atrium are vs-built area footprint due to shared atrium benefiting both plots. With a well index of 1.02 which is moderate compared to ideal case for daylight penetration. 3. Sky view factor (SVF): Good SVF of 0.21 as both buildings benefit from shared atriums. However, the lower levels receive poor daylight penetration from atrium into the spaces as shown in the section drawing above. 4. Wall finish: Building 2 has light coloured finishes which is effective in ensuring maximum light reflection in the atrium. As shown in figure 48.

	5. Railing type; Building 2 has a higher % of railing compared to masonry which is aids in ensuring daylight penetration in the atrium. As shown n figure 48. 6. Stair- stair is located within the atrium spaces which greatly impedes day light access to all levels in the atrium. 7. Other functional notes: Functional zoning in building 2 features the living space adjacent to the corridor, which means due to privacy, the curtains are often drawn, preventing effective daylight access into the spaces. For building 2, additional light wells/ventilation channels are provided for washrooms which due to their 2m2 area does not have any daylight penetration. The lack of adequate laundry areas for drying clothes means the atrium is also used for clothes drying during the day, which block daylight. Services: such as water tanks in image figure 48 also reduce the functionality and effectiveness of the atrium.

	Building 3
Plan	 *Figure 49 Floor plan for building 3. Source; Author, 2021.*
Section	

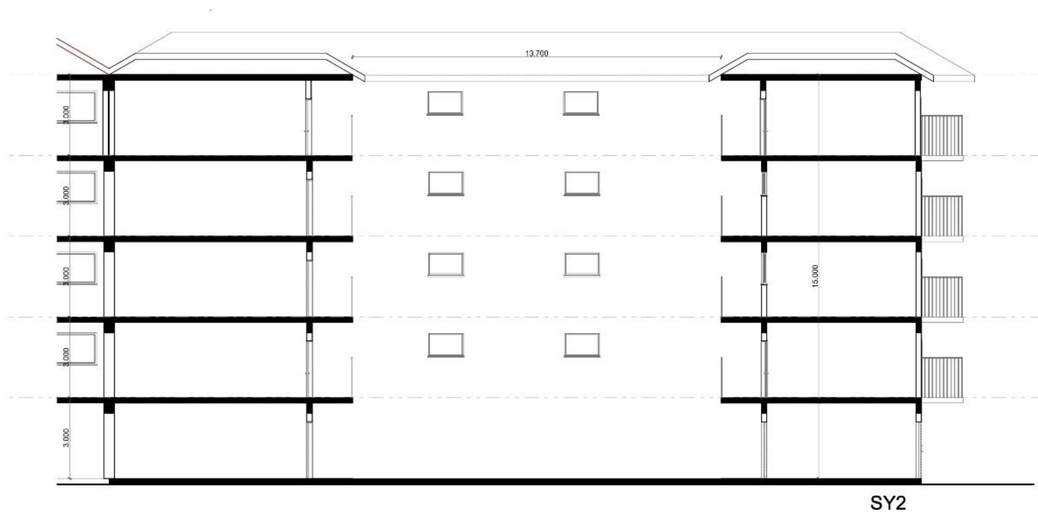
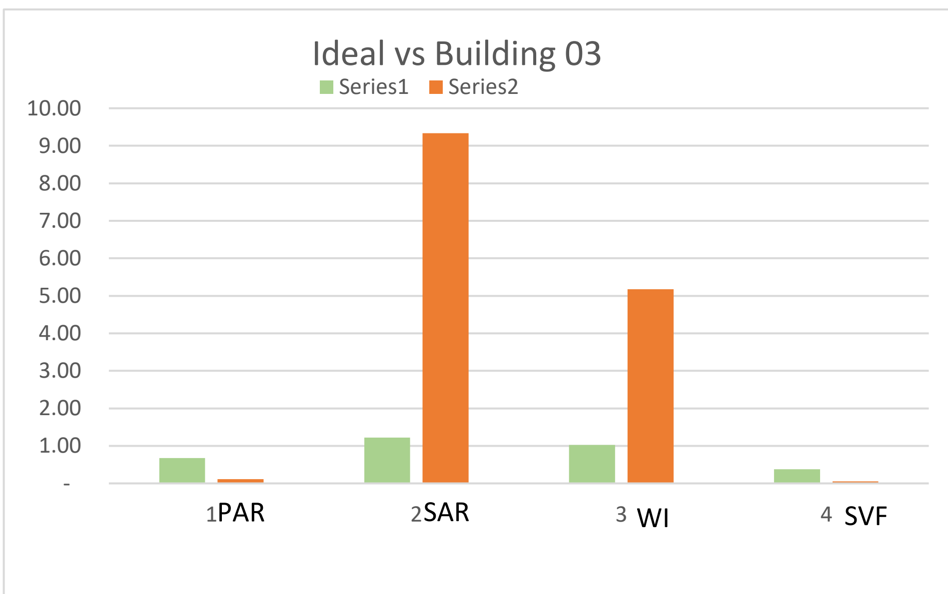


Figure 50 Sections of building 3. Source; Author, 2021.

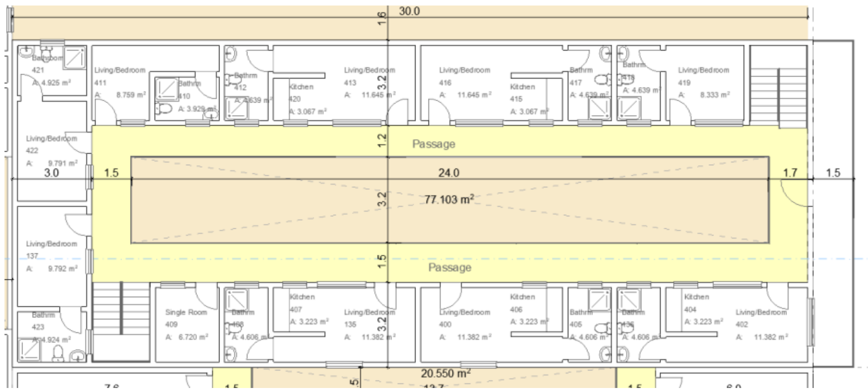
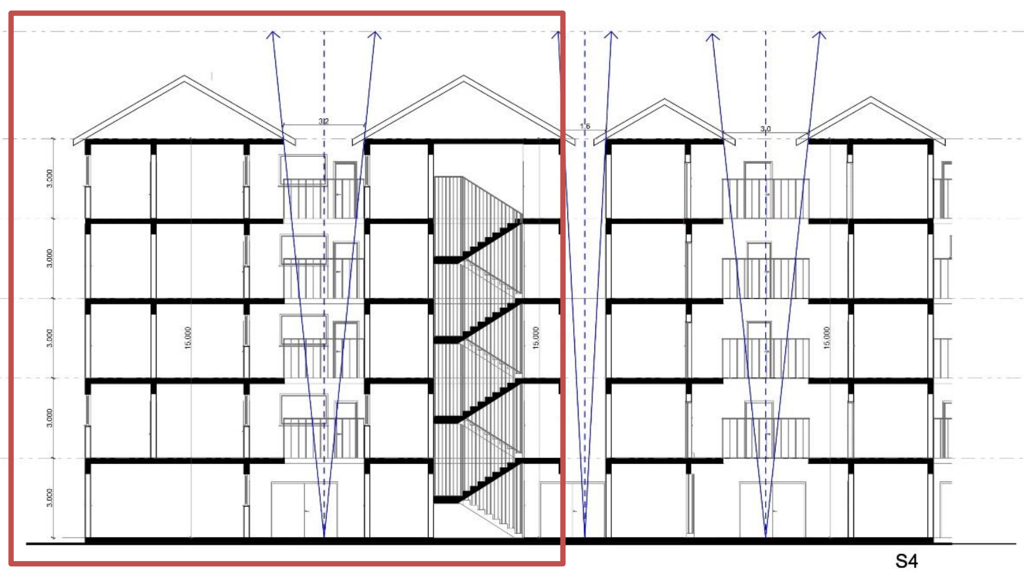
Quantitative

Table 10 Extracted chart comparing Building 3 with ideal case. Full data set in Table 3 on page 67. Source; Author, 2021



Photos	 *Figure 51 Photos of building 3 showing atrium and ground floor spaces. Source; Author 2021.*
Analysis	1. Atrium type: Building 3 has a U-shaped form with a narrow 1.5-meter atrium, creates poor daylight access. This atrium type is effective in dense urban plot, but for this case study the built area vs atrium rea of 7% was too low for the atrium to be effective. 2. Well index (WI) and Daylight factor (DF- simulated); Building 3 had a well index of 5.18 with the % of atrium vs-built footprint at 7%. The atrium percentage is very narrow as the developer wanted to optimise lettable space. However, this meant a double-banked building plan which does not allow daylight penetration into a majority of the spaces. 3. Sky view factor (SVF): Poor SVF of 0.05 means daylight penetration does not reach any of the levels effectively from the atrium. 4. Wall finish: Building 3 has pink coloured wall finish which is moderate in ensuring maximum light reflection in the atrium. As shown in figure 48.

	5. Railing type; Masonry wall railing type block daylight penetration. 6. Stair: the stair location for building 3 is recessed into the main building is ideal and better than locating it within the atrium space. 7. Other functional notes: Building 3 has large windows in the façade facing the atrium which offer better opportunities to let light into the spaces. Clothes hanging extended into the atrium area blocked daylight penetration. There are minimal units on ground floor, only used for parking and services which is appropriate given the basement-like quality of the space. However, for the minimal units that were on the ground floor, vehicular parking blocked daylight from the atrium.

	Building 04
Plan	 *Figure 52 Plan layout of building 4. Source; Author, 2021.*
Section	

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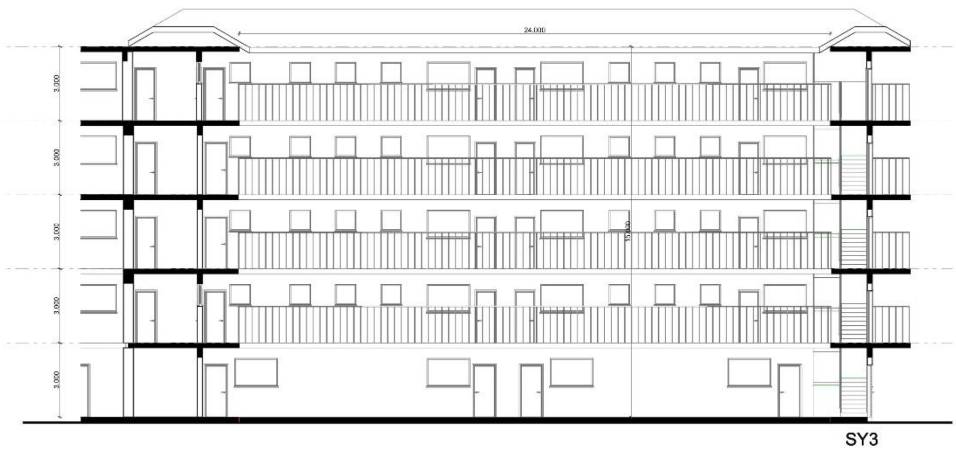

Figure 53 Sections of building 4. Source; Author, 2021.
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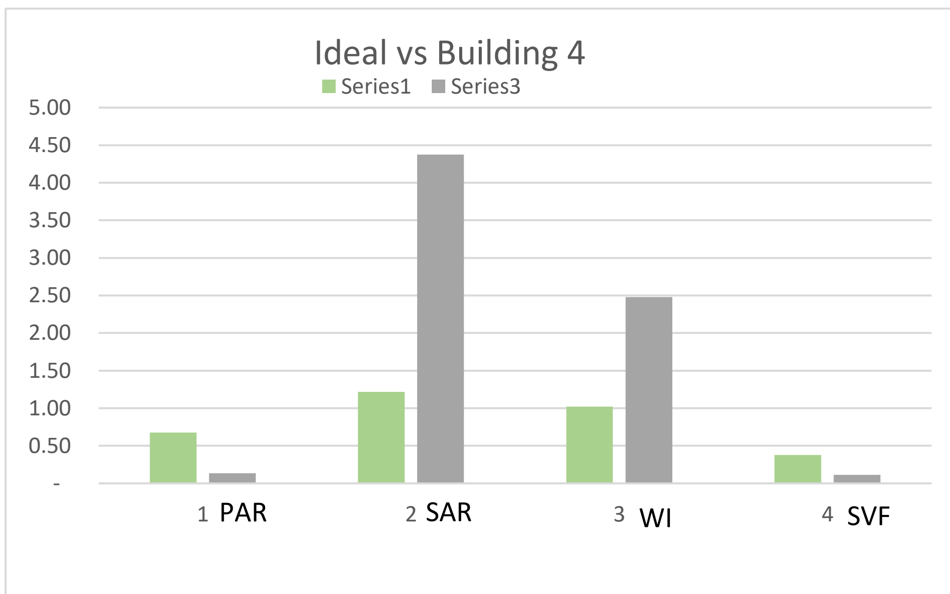
<td>
Table 11 Extracted charts of quantitative data. Full data set in Table 3 on page 67. Source; Author, 2021.



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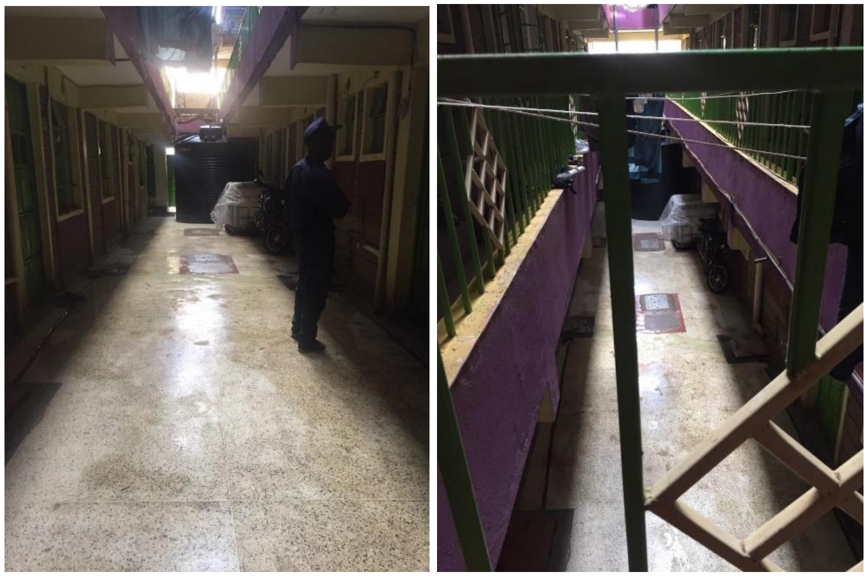
Photos	 *Figure 54 Photos of building showing atrium and ground floor spaces. Source; Author 2021.*
Analysis	1. Atrium type: This has an O- shaped atrium type which offer opportunities to maximise surface area facing the atrium. This atrium type however also increases the overall total circulation space of the development, which compromises on area left for atriums. These atrium typologies are often prone to hanging lines being placed across, which blocks daylight access. 2. Well index and Daylight factor (simulation): Building 05 has a well index of 2.54 with the % of atrium vs built footprint at 28%. These are moderate figures for effective daylight penetration. 3. Sky view factor: Poor SVF of 0.11 as the atrium takes a small percent of total built area. As such the lower levels receive no daylight penetration from atrium into the spaces. As shown in section drawing.

	4. Wall finish: the wall finishes facing the atrium are dark coloured wall finishes and reduce daylight reflection in the atrium. 5. Railing: the atrium railing is made majorly from mild steel railing which is ideal for effective daylight penetration. 6. Stair: the separation of the two stair cores, one of which is recessed into the main building space, is ideal for ensuring fire safety of the occupants, as this enables two means of escape. The first stair is recessed stairs away from the atrium space is ideal. The second staircase is located on the outer facades and benefits from a key daylight source. Stairs are service areas, which people do not spend too much time indense urban neighbourhood, daylight should be saved and optimised for the living spaces. 7. Other functional notes: The building comprises single rooms andsingle banked spaces which is ideal for such density, as the spaces do not have internal partitions to block light. The lack of adequate laundry areas for drying clothes means the atrium is also used for clothes drying during the day, which block daylight.

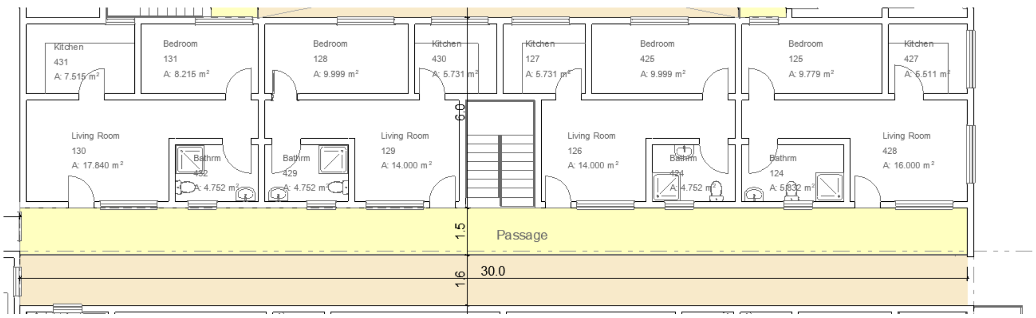
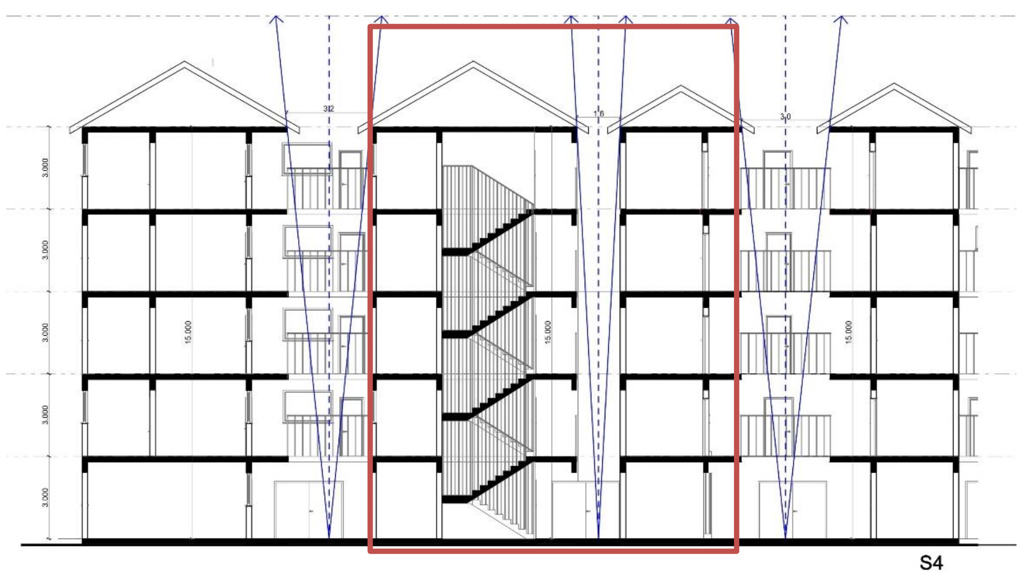
	Building 5
Plan	 *Figure 55 Plan layout of building 5. Source; Author, 2021.*
Section	

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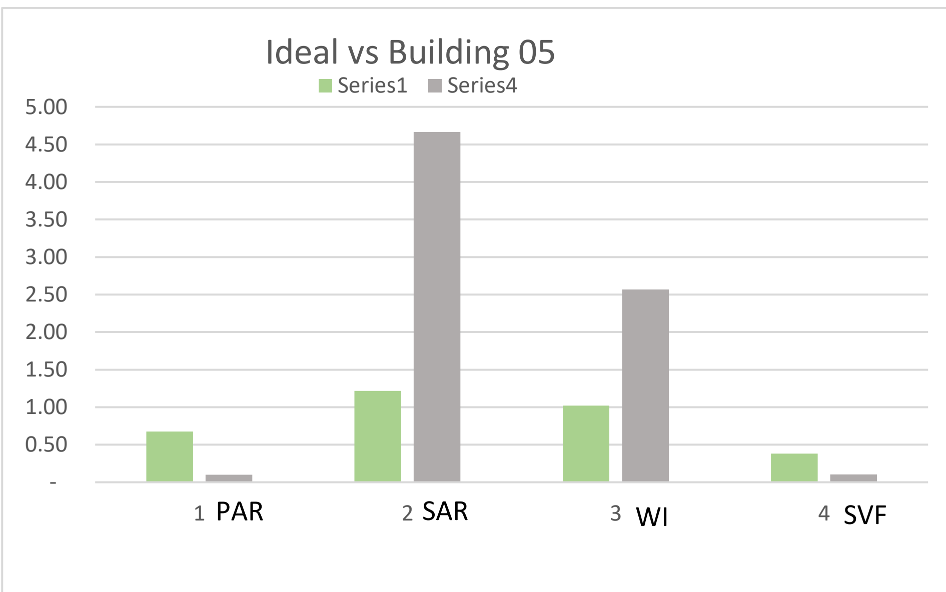
Figure 56 Sections of building 5. Source; Author, 2021.</td></tr>
<tr><td>Quantitative</td><td>Table 12 Extracted charts of quantitative data. Full data set in Table 3 on page 67. Source; Author, 2021.

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<td>Photos</td>
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Figure 57 Poor daylight penetration from narrow atrium of building 6. Source; Author 2021.

Figure 58 Building 5 atrium view with clothes hanging lines that block daylight penetration. Use of mild steel railing, aids in letting light in. Source, Author, 2021.
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<tr>
<td>Analysis</td>
<td>

1. Atrium type: This building has an I-Shaped atrium which is formed by a narrow straight block with an atrium along its entire length. This performed the poorest in terms of daylight penetration unless the width of the atrium is above one third the length. Once all neighbouring buildings are developed, the only unit with adequate daylight is the one facing the street, causing very poor daylight penetration. As such, this typology for dense urban blocks is highly ineffective in daylight penetration.
2. Well index and Daylight factor(simulation): Building 06 had a well index of 4.61 with the % of atrium vs built footprint at 17%. The 1.6M wide atrium with a length of 30.2M causes a low plan aspect ratio of 0.05 which is too narrow to be effective.

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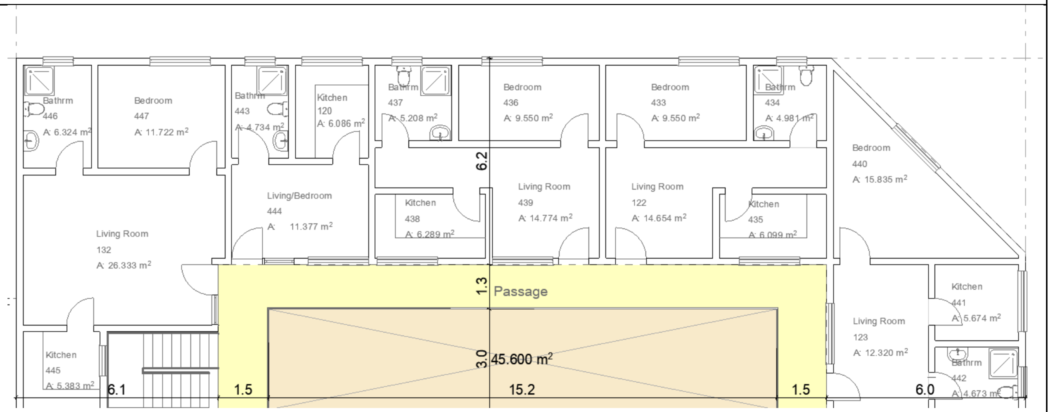
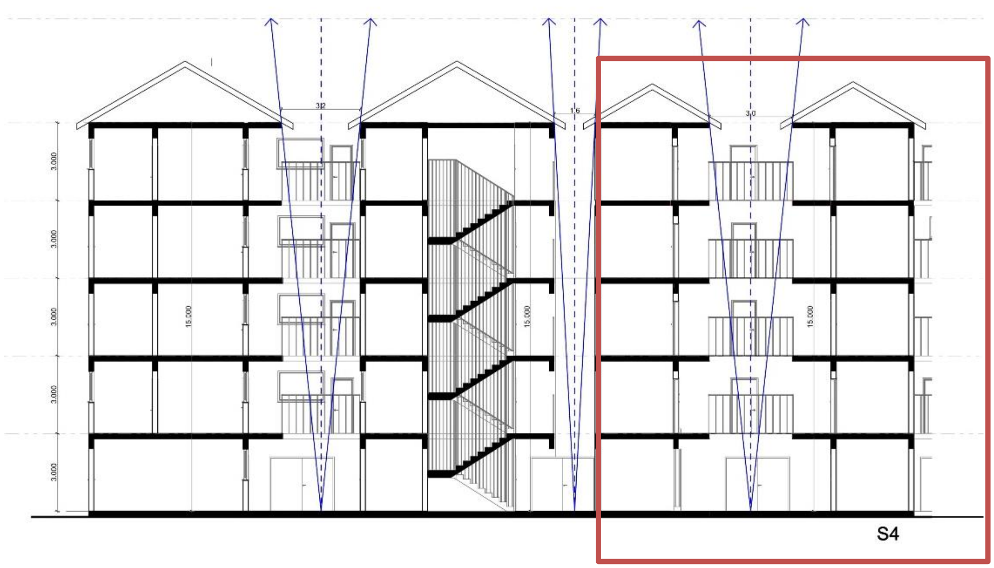
	3. Sky view factor: Poor SVF of 0.0.06 due to narrowness of atrium width. As such the most levels receive inadequate daylight penetration from atrium into the spaces. As shown in section above. 4. Wall finish: light coloured finishes which is effective in ensuring maximum light reflection in the atrium. 5. Railing: has a higher % of railing compared to masonry which is aids in ensuring daylight penetration in the atrium. 8. Stair: The stair location for building 3 is recessed into main building form is ideal and better than locating it within the atrium space. 6. Other functional notes: The atrium in this case also had clothes hanging lines which blocks almost all daylight penetration into the space. Ground floor units suffered the most as shown figure 58 In mixed urban neighbourhood opportunities to make this into a commercial rentable space would be better for well-being of users.

	Building 6
Plan	 *Figure 59 Plan layout of building 6. Source; Author, 2021.*
Section	

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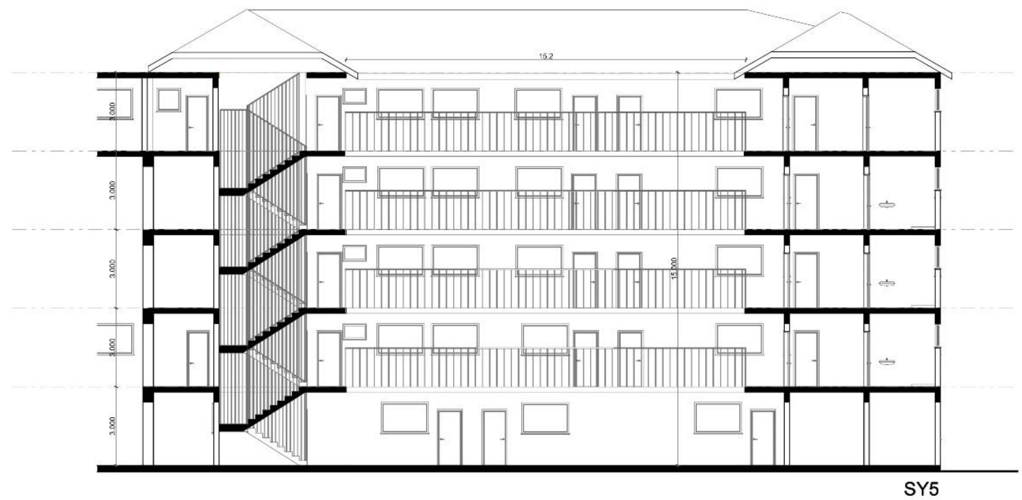

Figure 60 Section of building 6. Source; Author, 2021.
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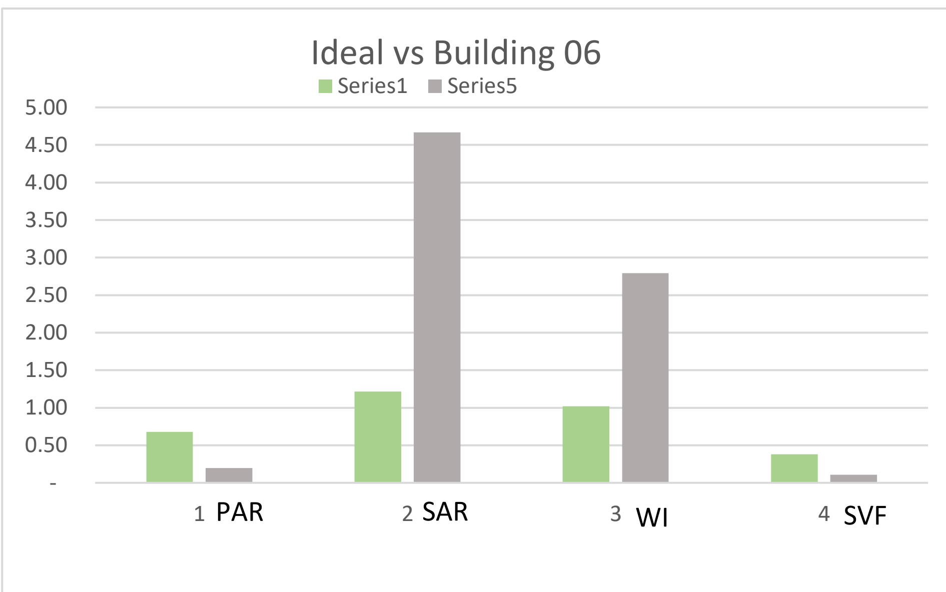
Table 13 Extracted charts of quantitative data. Full data set in Table 3 on page 67. Source; Author, 2021.



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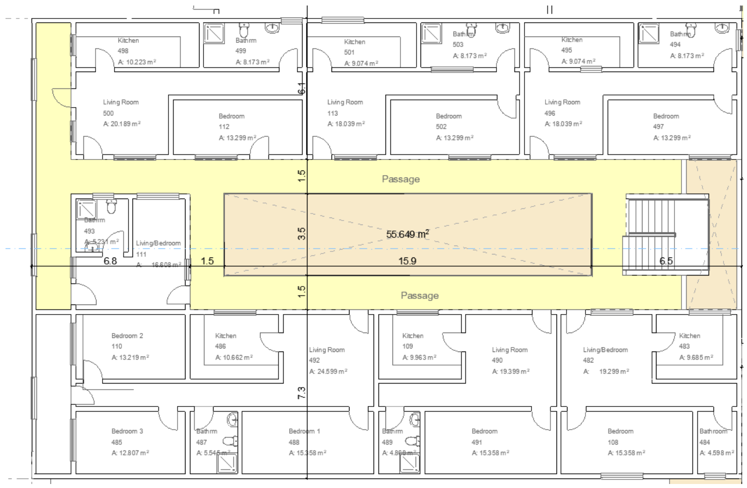
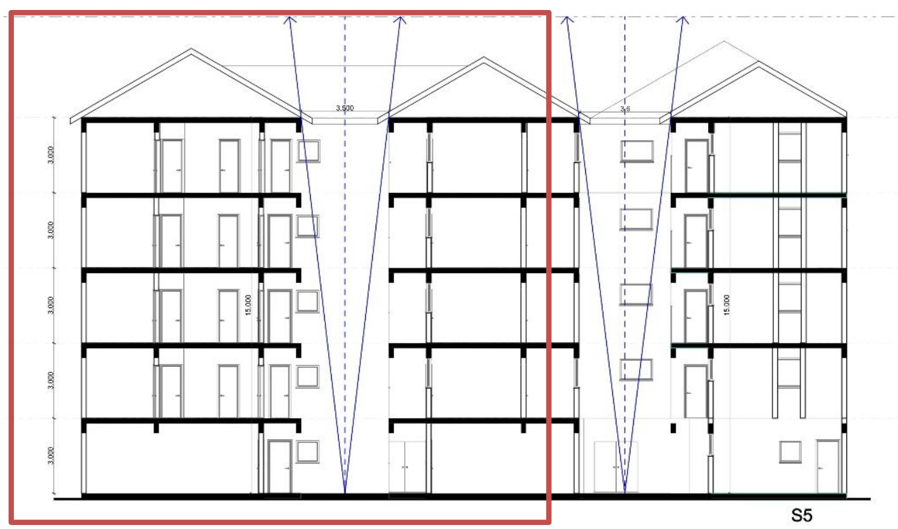
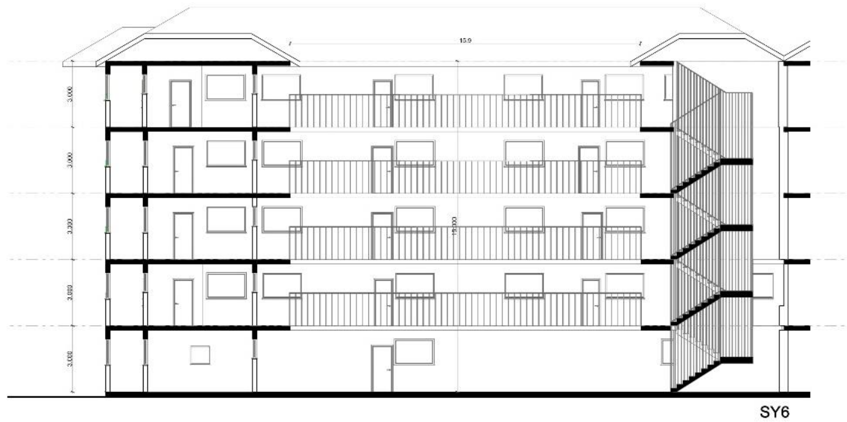
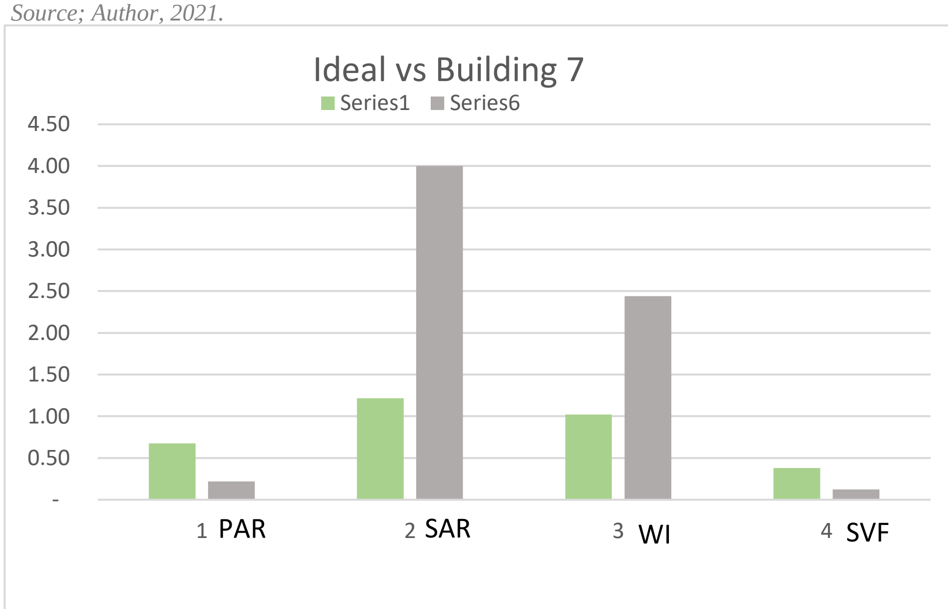
Photos	 *Figure 61 External photos of building 6. Source; Author 2021*
Analysis	1. Atrium type: This building had a U-shaped atrium but benefits from street level daylight on three sides because it is a corner plot. 2. Well index and Daylight factor(simulation): Building 7 has a well index of 0.46 with the % of atrium vs-built footprint at 18%. Which causes poor daylight penetration along its floors. 3. Sky view factor: Poor SVF of 0.11 due to narrowness of atrium width vs building depth. As such the most levels receive inadequate daylight penetration from atrium into the spaces. As shown in section above. 4. Wall finish: dark coloured wall finishes reduce light reflection in the atrium 5. Railing: masonry railing blocked daylight penetration into the spaces.

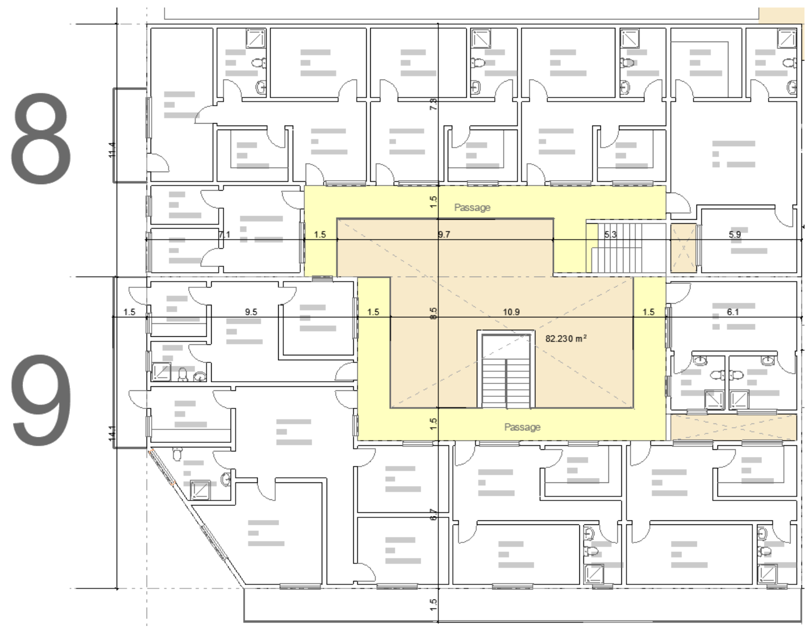
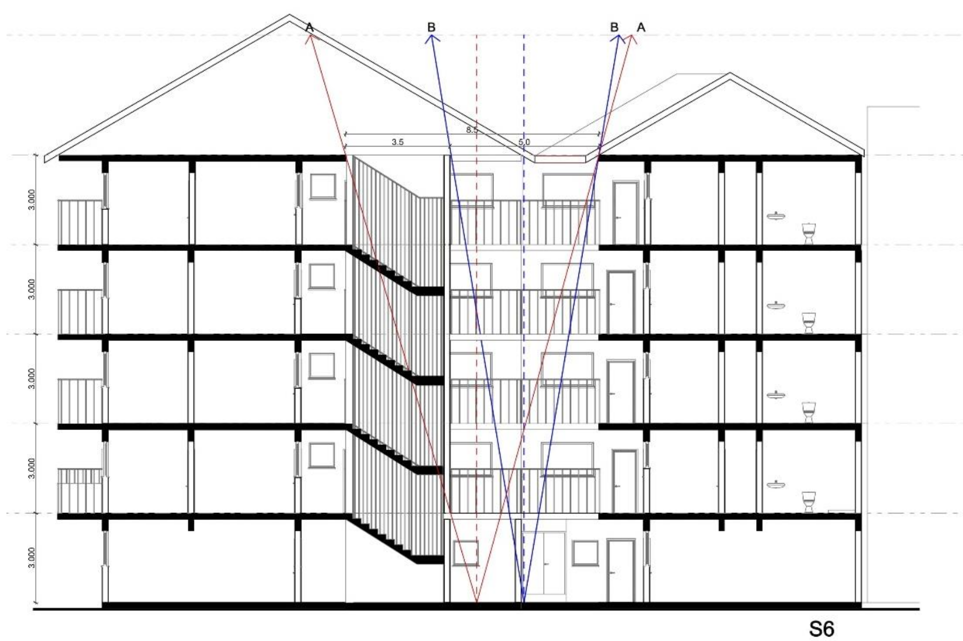
	6. Stair: the stair is located recessed into main building form which is ideal and is better than locating it in the atrium space. 7. Other functional notes: unit arrangement featured living spaces along the outer façade which is ideal as they benefit directly from light sources from the street. This building had dedicated laundry areas on the outside facing the street which enabled the atrium to remain laundry free, but impeded daylight into some of the street side spaces.

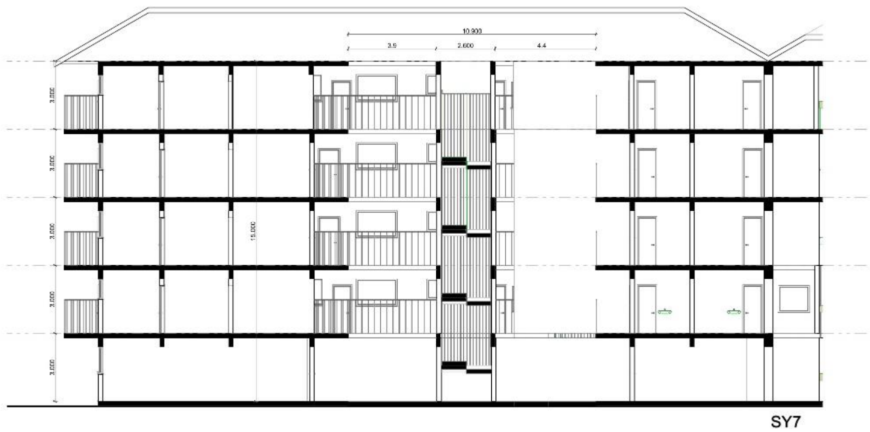
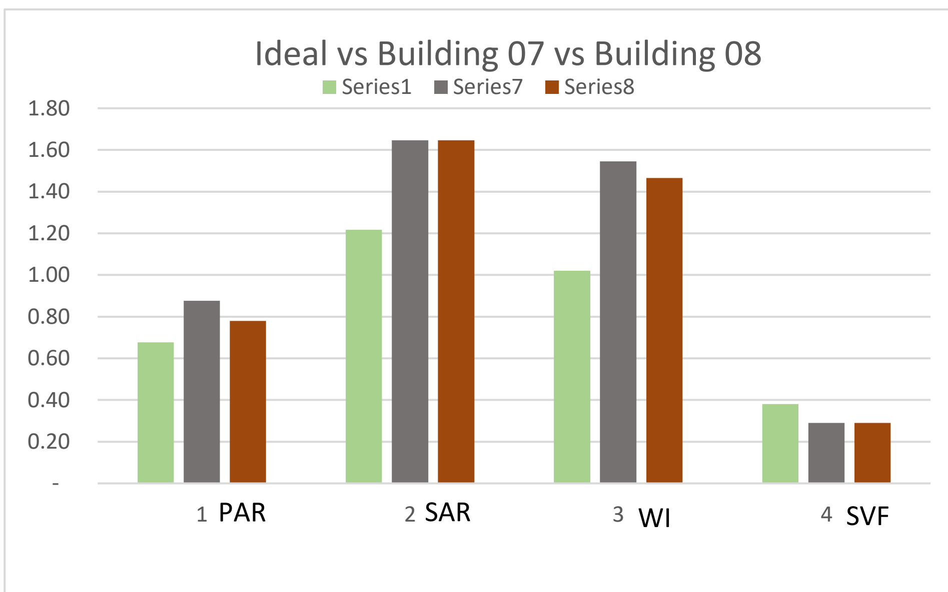
	Building 7
Plan	 *Figure 62 Plan layout of building 7. Source; Author, 2021.*
Section	

	 *Figure 63 Sections of building 7. Source; Author, 2021.*
Quantitative	*Table 14 Extracted charts of quantitative data. Full data set in Table 3 on page 67.* *Source; Author, 2021.* 

Photos	 *Figure 64 Photos of building showing atrium and external view. Source; Author 2021.*
Analysis	1. Atrium type: This building has an O-shaped block with central atrium, and the circulation around its perimeter. Central atrium with corridor on either side maximizes the surface area of units facing the atrium, they however also increase the overall total circulation space infringing into the atrium space. 2. Well index and Daylight factor (simulation): Building 7 has a well index of 2.44 with the % of atrium vs built footprint at 9%. Which causes poor daylight penetration along its floors. 7. Sky view factor: Poor SVF of 0.12 due to narrowness of atrium width vs building depth. As such the most levels receive inadequate daylight penetration from atrium into the spaces. As shown in section above. 3. Wall finish: the building features dark coloured wall and atrium finishes which impedes daylight reflection.

	4. Railing: railing design for building 7 features a low wall and a large portion mild steel railing, which enables better daylight access through the atrium. 5. Stair: stair is located within the atrium spaces which greatly impedes day light to all levels in the atrium. 6. Other functional notes: The atrium is not adequately sized to account for corridor widths, stairs and hanging lines to be effective for daylight provision. In building 7 the building units are much deeper, which reduces daylight penetration into the spaces. This triple loaded building mass prevents any daylight getting to deeper spaces. Clothes hanging lines designed to extend beyond the railing blocks daylight to the spaces from the atrium.

	Building 8 and 9
Plan	 *Figure 65 Plan layout of building 8 and 9. Source; Author, 2021.*
Section	

	 *Figure 66 Sections of building 8 and 9. Source; Author, 2021.*
Quantitative	*Table 15 Extracted charts of quantitative data. Full data set in Table 3 on page 67 Source; Author, 2021* 

<table>
<tr><td>Photos</td><td>
Figure 67 Photos of building showing atrium, ground floor spaces and external view. Source; Author, 2021</td></tr>
<tr><td>Analysis</td><td>Building 8
1. Atrium type: Individually, building 8 has a shared U-shaped atrium. It is shared with the neighbouring plot to make a shared O-shaped atrium. This atrium typology is effective in maximising daylight penetration for both buildings.
2. Well index and Daylight factor(simulation): Building 8 has a moderate well index of 1.55 with the % of atrium vs-built footprint at 21%. This is moderate against the ideal case as daylight penetration benefits from shared atrium.
3. Sky view factor: Good SVF of 0.29 as both buildings benefit from shared atriums. However, the lower levels receive no daylight penetration from the atrium into the spaces. As shown in section above.</td></tr>
</table>

	4. Wall finish: has light coloured finishes which is effective in ensuring maximum light reflection in the atrium. 5. Railing: railing type is half masonry and railing. Full railing more ideal for ensuring daylight penetration. 6. Stair: The stair location at the centre of the atrium also contribute to daylight blocking into the spaces. 7. Other functional notes: The unit arrangement featured living spaces along the corridor, which benefit from the atrium daylight. In addition, clothes hanging lines have been designed to extend beyond the railing blocks daylight to the spaces from the atrium. Atrium space should be left clear of key services such as stairs, water tanks and parking, to aid it their effectiveness in daylight penetration. Clothes hanging spaces and services on the roof or internally (if space allows) should be allocated for each apartment. **Building 9** 1. Atrium type: Individually, building 9 has a shared U-shaped atrium. It is shared with the neighbouring plot to make a shared O-shaped atrium. This atrium typology is effective in maximising daylight penetration for both buildings. 2. Well index and Daylight factor (simulation): Building 12 has a well index of 1.47 with the % of atrium vs-built footprint at 22%. Shared atrium optimizes

	daylight between two developments and ids ideal for dense urban developments. 3. Sky view factor: Good SVF of 0.29 as both buildings benefit from shared atriums. However, the lower levels receive no daylight penetration from atrium into the spaces. As shown in section above. 4. Wall finish: has light coloured finishes which is effective in ensuring maximum light reflection in the atrium. 5. Railing: railing design for building 7 features a low wall and a large portion mild steel railing, which enables better daylight access through the atrium. 6. Stair: The stair location at the centre of the atrium also contribute to daylight blocking into the spaces. 7. Other functional notes: In addition, clothes hanging lines have been designed to extend beyond the railing blocks daylight to the spaces from the atrium. Atrium space should be left clear of key services such as stairs, water tanks and parking, to aid it their effectiveness in daylight penetration. Clothes hanging spaces and services on the roof or internally (if space allows) should be allocated for each apartment. The buildings unit arrangement featured living spaces along the outer façade which is ideal as they benefit directly from light sources from the street canyons. For corner plots, to improve daylight penetration in the main living spaces (i.e., living rooms and bedrooms), should be ideally located on the outside facade facing the street, as they assured of direct daylight access from the street canyon.

4.6 Summary of Findings

The Roysambu case study block provided useful insights on the various type, sizes of atriums as well as their functional design that hinder or aid in daylight penetration. Key assumptions are that the typical plot size would remain consistent was found to be untrue in the field as different owners customised their beacons over time. Parameters established in the literature review were found to correlate to the findings in the field as analysed. The data and findings are summarised in table 16 below.

	Close to ideal	50% close to ideal	>80% away from ideal
Legend	Good	Medium	Poor

Table 16 Roysambu case study summaries. Source; Author, 2021.

Building No.	**Built area**	Well Index	Sky view factor	Wall finishes	Railing	Stair
Notes		0=ideal	1=ideal			
X-low yield* See design guideline in chapter 5	270.00	0.82	0.39	Light coloured	See through	Recessed/ not in atrium
X- Realistic compromise* See design guideline in chapter 5	348.0	1.02	0.38	Light coloured	See through	Recessed/ not in atrium
1	333.4	1.59	0.21			
2	302.6	1.53	0.21			
3	284.3	5.18	0.05			
4	295.1	2.48	0.11			
5	227.9	2.57	0.11			
6	254.6	2.79	0.11			
7	551.9	2.44	0.12			
8	310.5	1.55	0.29			
9	335.7	1.47	0.29			

5 CONCLUSIONS

The objectives of this research were to study existing literature on atrium design for daylight penetration in dense apartment blocks and establish the key parameters. Thereafter using qualitative and quantitative research methods using Roysambu neighbourhood as a case study neighbourhood to study the effect of daylight penetration of atriums in dense apartments blocks. Then from the findings and analysis, make recommendations on how atriums can be more effective in daylight penetration in dense apartment blocks, such as Roysambu. As such, the research questions are listed below.

1. What is the existing knowledge on atrium design for daylight penetration in apartment blocks?
2. What is the status of daylight penetration of atriums in apartment blocks in Roysambu-Nairobi?
3. How should atrium design for dense apartment blocks such a Roysambu be effective for daylight penetration?

5.1 Question 1; What is the existing knowledge on atrium design for daylight penetration in apartment blocks?

Variable	**Code**	**Sub variable**
Daylight penetration	D	Daylight Factor (DF)-quantity of light
	DV2	Distribution of light

Context	IV1	IV1.1- Block design IV1.2- Sky view factor IV1.3- Relation to neighbouring buildings IV1.4- Relation to road
The Apartment	IV2- General	*IV2.1- Plot size* *IV2.2- Ground coverage (GC)* *IV2.3- Plot ratio (PR)* *IV2.4- Number of floors*
	IV3- Materials	IV3.1- Wall material IV3.2- Wall finish IV3.3- Colour
	IV4- Openings	*IV4.1- Size* IV4.2- Position IV4.3- % of window to floor area IV4.4- Distance outside open window IV4.5- Window blocks (i.e curtains)
	IV5- Layout	IV5.1- Analysis of internal spatial configuration and impact on functional uses of the atrium
Atrium	IV6- Roof	IV6.1- Roof type; open to sky or covered IV6.2- Roof material if covered
	IV7- Geometry	IV7.1- PAR= Width / Length (Closer to 1 the better) IV7.2- SAR= Height/Width (Lower the SAR the better) IV7.3- Well Index (WI)=0.5SAR/(1+PAR)- The higher the WI the higher the Daylight Factor (DF)

5.2 Question 2; What is the status of daylight penetration of atriums in apartment blocks in Roysambu - Nairobi?

Contextual parameters

Throughout the neighbourhood there is a lack of internal laundry areas within the apartment block which causes residents to hang clothes outside windows and outside their street-facing balconies or windows, which are the main sources of light into the spaces. Adequate laundry areas should be allocated within each apartment block or on the roof space. The sky view from the street canyon is reduced by protruding balconies into the street levels. Considering the permissible extension of balconies onto the street is key to improving daylight quality at street level. The construction materials of balconies to be lightweight and transparent such as mild steel railing allows better daylight penetration than opaque materials such as masonry but keeping privacy and safety in mind. In dense urban neighbourhoods, the ground level is an opportunity for commercial businesses to engage directly with the street. It adds vibrancy to the neighbourhood, but also removes vital residential spaces away from areas without good daylight penetration.

Buildings were observed to have been designed to allow light into the atrium from side openings into neighbouring plots, which over time will be built up and block vital daylight penetration and ventilation into the spaces. It is key for developers to design with the view that neighbouring plot will be built and not consider, neighbouring plots as their primary source of daylight and for the government to monitor this. Street orientation also affects how light hits the faces of each block, as the city densifies urban planning should consider optimised street orientation for effective daylight penetration to the buildings and the street and sun path. Developing nations with rapidly urbanising neighbourhoods should consider minimum 9-meter widths (as opposed to the current 6 meters), or give height restrictions, or consider placing requirements for buildings to have setbacks. This will enable proper daylighting at street level and in apartments spaces, especially on the lower levels.

The quantitative analysis of the case study neighbourhood block revealed key correlations. The **section aspect ratio (SAR)** has a direct correlation with the atrium well index and hence the daylight factor. The higher the SAR the poorer the Well index. SAR is the relationship between the height of the atrium and the length of the atrium. If the height of the atrium is higher than its length, then the well index reduces, and the daylight performance improves. This is because atriums are meant to be effective across their entire depth, to provide daylight penetration to the lower levels of the building. For a five-storey building with an average floor-to-floor height of 3.0M, then the atrium heights are typically 15M. Atrium lengths of between 15M to 30M (the typical length of a plot) are ideal for effective daylight penetration.

Building and atrium design parameters

For corner plots, to improve daylight penetration in the main living spaces (i.e., living rooms and bedrooms), they should ideally be located on the outside facade facing the street, as they are assured of direct daylight access from the street canyon. For centre plots, to improve daylight penetration in the main living spaces (i.e., living, bedrooms) should be located closer to the atrium to benefit from direct daylight penetration, unless they are the street-facing units. Single banked, single space units (such as studios) with minimal internal partitions aid in ensuring effective atrium daylight penetration of the building. Or partitions to be fitted with windows to enable daylight penetration deeper into the space.

Staircases are service areas and not used for extended periods of time, so location that is recessed away from the atrium is ideal for urban dense apartments. Light coloured wall finishes aid in reflecting daylight and improving the effectiveness of the atrium in dense urban apartments. Atrium space should be left clear of key services such as stairs, water tanks and parking, to aid it their effectiveness in daylight penetration. Clothes hanging spaces and services on the roof or internally (if space allows) should be allocated for each apartment. The entire blocks can consider a shared underground parking, which overall is less costly for the individual developer.

Transparent / see through railing in atriums such as mild steel, aluminium, or timber, offer better daylight penetration than opaque options such as masonry or concrete. This is because it aids in letting light through rather than block or reflecting it away from the corridor or internal spaces. Residential units on ground floor in dense urban neighbourhoods suffer from insecurity, lack of privacy, and have the lowest daylight penetration. They are ideal for commercial use due to the street frontage. Dense urban neighbourhoods should adopt the mixed urban development typology with commercial units on ground floor. Closed atrium roofing should not feature in dense urban development as they are the main source for daylight, and ventilation. Large windows offer better opportunities to let light into the spaces. Urban blocks subdivided into eighths, or sixteenth-sized parcels should be designed to have 3-6-metre-wide central service lane to aid in daylight and ventilation of the spaces. Atria in dense apartments should not be split to optimize the depth of daylight penetration.

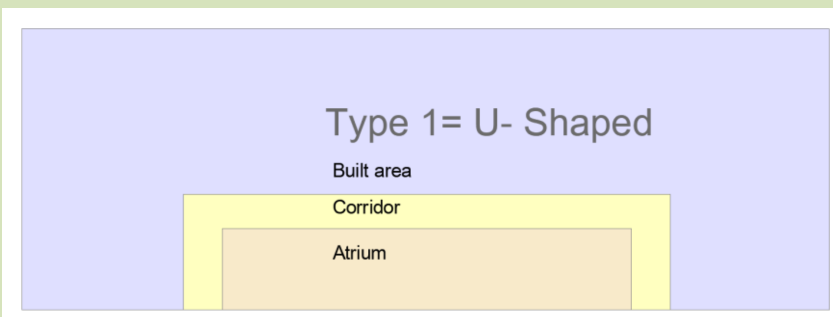
The county government should enforce the building regulation of minimum 2.4 M allowable open space outside windows for the health and safety of residents, as well as to ensure effective daylight penetration and as such triple banked spaces should not be permitted. Corridor dimensions should be considered as not part of the effective open space in the building, as they end up protruding into the atrium and reduces the effectiveness of the atrium in daylight provision. Ratios of less than 20% of built footprint being the atrium causes poor daylight penetration. Many of the observed findings and recommendations already feature as key rules and guidelines in the building code. As such policy paper recommendation include consideration on enforcement of already existing laws in rapidly urban developments. This includes the regulation and monitoring of building professionals working in this context to ensure the rules are being followed and if not, punishments are in order.

Atrium typologies and block design considerations

The study identified three atrium typologies. The study identified five different atrium types in the case study neighbourhood namely the narrow block, the O-shaped blocks, and the U-shaped plot (at the corner or the centre of the block) which all had distinctive characteristics, advantages, and disadvantages.

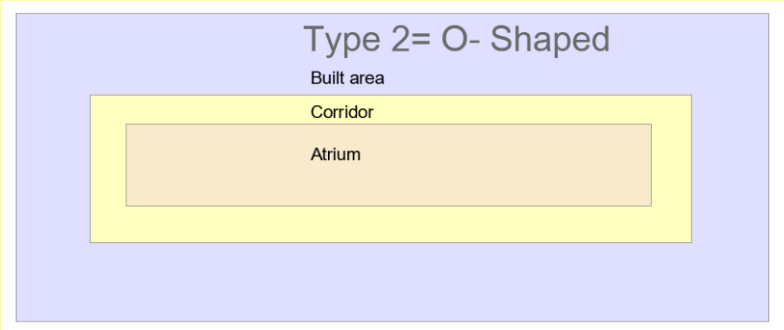
	Close to ideal	50% close to ideal	>80% away from ideal
Legend- Ranking	Good	Medium	Poor

Atrium type- U-Shaped



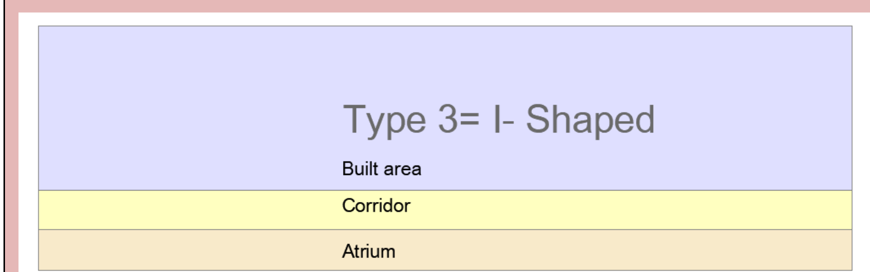
The U-shaped atria type was the most popular atria type observed due to its ability to reduce circulation / corridor, maintain access to each unit and maximise lettable space. This typology was used for both central plot within the neighbourhood block, as well as the corner plots. In the corner plots this was observed to be effective as corner plots have the benefits of lighting from two streets. In the case study neighbourhood block, the corner plots for building 1 and 2 as well as 8 and 9 had a shared atrium which both developments benefited from higher daylight penetration. The U-shaped atrium typology is the most effective in daylight penetration, especially is neighbouring developments face each other to maximise the open space.

Atrium type- O-Shaped



The O-Shaped central atrium in the case study region has been adopted for both large plot and small plots and tried to maximize rental space whist ensuring corridor access to each unit. In this case the corridors around the atria impede effective daylight access to the spaces, especially if used also for clothes hanging. For this typology, the atria were not adequately sized to account for corridor widths, stairs and hanging lines to be effective for daylight provision. Minimum corridor widths around atria must be specified in the building code as a percentage of total atria space to avoid poor daylight in centralised atria.

Atrium type- I-Shaped



The narrow straight block is a thin atrium running alongside one of the building long edges. Once all neighbouring building are developed, the only unit with adequate daylight is the one facing the street, causing poor daylight penetration. In addition, the thin atrium typically had clothes hanging lines blocks any daylight that did get into the spaces. Unless accompanied by an inefficiently sized atrium (see Ch 5.3), this typology for dense urban blocks is highly ineffective in daylight penetration.

5.3 Question 3; How should atrium design for dense apartment blocks such a Roysambu be effective for daylight penetration?

Recommendations

The study identified the **ideal scenario** for the 50 x 100 ft plot atrium to be the shared U-shaped atrium typology. This is because it provides the typical market rental yield, but with neighbouring properties should maximize daylight access through shared atriums.

The **low yield scenario** below is based on reducing the building footprint below the average typical for this region. The case study region averages a built footprint of 321 SQM per plot, as such the ideal low yield scenario is not realistic and applicable to current market forces. Realistic compromise is a scenario based on U- Shaped courtyard, which maintains a market rental yield average but with optimised dimensions for an effective atrium on a 50 X 100 ft plot. The atrium as illustrated in figure 67 is square in nature bringing the plot ratio (PR) as close to 1 as possible, to ensure effective daylight penetration. In addition, it is recommended to step back floor plates on higher floors to maximise sky view access to lower floors.

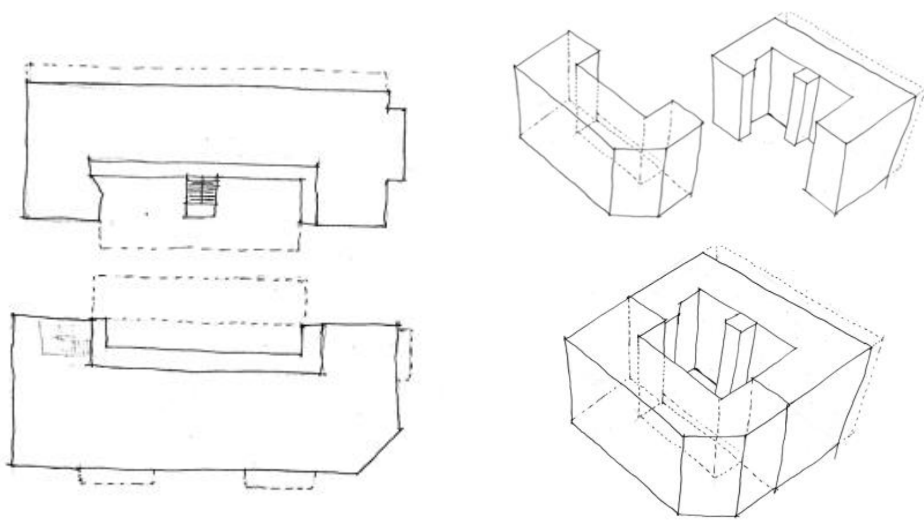


Figure 68 Shared atriums benefit from higher daylight penetration. Source; Author 2021.

Building No.	Height	Built Area	Atrium Length	Atrium Width	Atrium Area	% Atrium vs built	Plan Aspect Ratio (PAR)=W/L	Section Aspect Ratio (SAR)=H/W	Well Index (WI)= 0.5 SAR(1+PAR)	Sky View Factor (SVF)= cos (atan(H/0.5*W)
Notes							1= ideal	0=ideal	0=ideal	1=ideal
X-low yield	15	270	30	12.00	360.0	57%	0.40	1.25	0.88	0.37
x-Ideal	15	348	17	11.50	195.5	36%	0.68	1.30	1.09	0.36

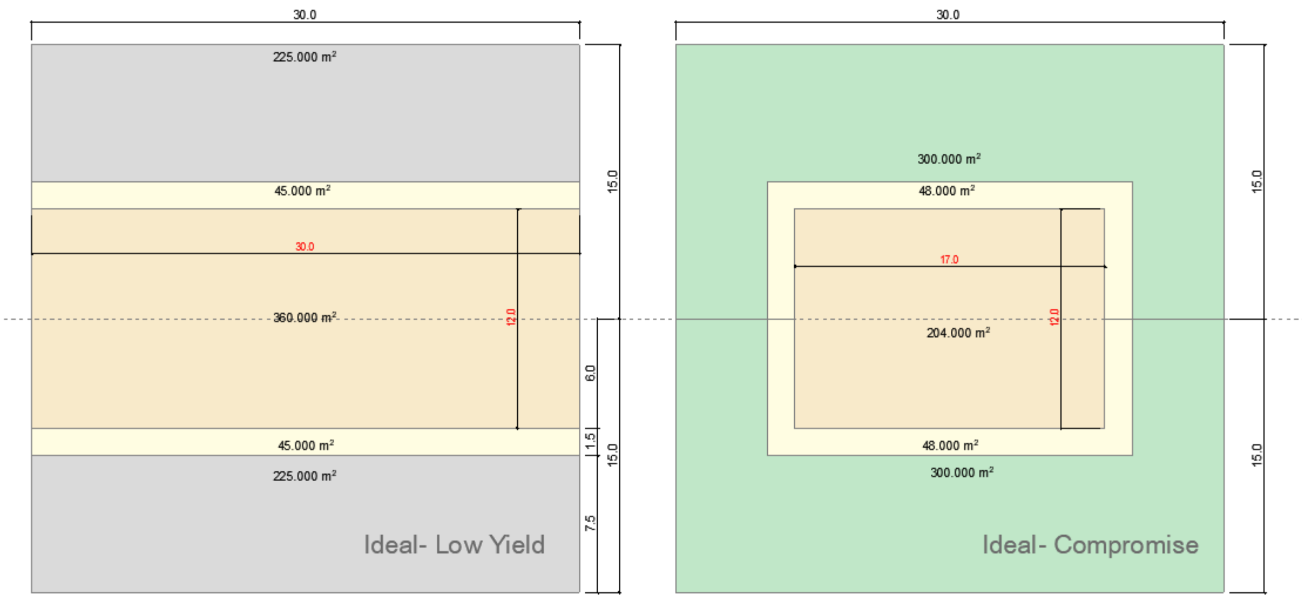


Figure 69 Ideal and low yield scenarios. Source; Author, 2021.

Design guidelines for atriums in dense urban neighbourhoods

- The U-shaped centralised shared atrium is an ideal typology, as illustrated in figure 68 above. This is because it maximises lettable space, minimises corridor space and developments benefit from shared daylight access.
- Staircases as service areas should be recessed in the main built footprint and not permitted in the atrium to prioritise daylight to living spaces.
- Atrium should be painted with light-coloured wall finishes to aid in reflecting daylight along the atrium.

- Clothes hanging spaces should be prohibited in atriums and instead, be allocated space on the roof or within the apartment.
- Railings in atriums should be made from transparent materials such as mild steel, aluminium, or timber. This is because they offer better daylight penetration than opaque options such as masonry or concrete.
- Dense urban neighbourhoods should adopt the mixed urban development typology with commercial units on ground floor because residential units on ground floor suffer from insecurity, lack of privacy, and have the lowest daylight penetration.
- Atrium should never be closed overhead with a roof covering.
- Windows facing the atrium should be above 50% of wall surface to maximise daylight penetration into the spaces.
- The county government should enforce building regulations on minimum allowable open space outside windows for the health and safety of residents, as well as to ensure effective daylight penetration.
- Triple banked spaces should not be permitted in dense urban neighbourhoods.
- In dense urban neighbourhoods in Nairobi the apartment blocks are typically 5 storeys, to avoid the expensive additional cost of having an elevator above 6 stories according to building regulation. They have an average floor-to-floor height of 3.0M, then the atrium heights are typically 15.0M. Atrium lengths of between 15M to 30M (the typical length of a plot) are ideal for effective daylight penetration.

5.4 Further Research

Daylighting in dense urban neighbourhoods with taller structures which feature lifts is key. These can be seen in Kileleshwa and Kilimani neighbourhoods in Kenya. Considerations of effective daylighting for seven to thirty stories will be important as that is how many neighbourhoods in Nairobi are heading. Effectiveness of Atrium design as it relates to ventilation in similar neighbourhoods is also important. As atrium also serve the functions of being the main source of fresh air into spaces. The shortcoming of the study is in relation to understanding the developer and user more intricately. User behaviour in low-income neighbourhoods is key to how these neighbourhoods work should be studied.

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