“BIM Enabled Window Optimization for Slum Rehabilitation Housing”

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Abstract:

The global challenge for developing nations is the provision of affordable housing to low-income citizens, especially in slums. More than 1 billion people currently live in slums and the number is expected to continue to surge upward due to rapid urbanization. These areas generally have very poorly developed infrastructure, with residents experiencing a wide variety of problems pertaining to thermal discomfort and infrastructure failure. Throughout the year, residents encounter considerable difficulties stemming from restricted access to energy for both heating and cooling, exacerbated by the urban heat island phenomenon. Improvement in living standards of slums is related to upgrading infrastructure, and among those, windows are crucial for indoor climate control. A well-designed window helps in reduction of heat gains, enhancement of natural ventilation, and optimization of daylight to healthier and more comfortable environments. However, windows in poor-quality housing are usually inadequately designed to take into consideration the local climatic conditions, nearby buildings, safety, and energy efficiency. Incorrect placement, size, and orientation of windows can result in indoor discomfort, health problems, and increased energy consumption. This research addresses these concerns by investigating BIM-enhanced window customization for slum housing. Building Information Modelling allows for accurate analysis and decision-making about building orientation, envelope design, and energy performance. This research will take the case study of Lallubhai Compound slum housing in Mumbai, India, and model in Autodesk Revit and Rhino a range of window designs to identify configurations that best address identified problems within SRH. The study will identify advantages and disadvantages of different typologies in improving indoor comfort and safety while minimizing energy consumption. This paper aims to improve indoor thermal environments, airflow, and natural illumination through the integration of passive design methods and advanced technologies. The proposed window configurations are designed to meet the specific needs of slum residents and to come up with energy-efficient homes that would further promote health, well-being, and overall comfort.

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1.0. Introduction

1.1. Urbanization and the Growth of Informal Settlements: Addressing Housing Challenges in Low-Income Nations

Extensive urbanization globally has directly led to a rapid growth in urban populations and increased urban density. According to The World Bank, over half of the global population lived in urban areas in 2020, and it is expected to rise to two-thirds by 2050 (The World Bank, 2020a). Most of the urban growth has occurred in developing countries, where the infrastructure of the cities is not designed to handle the large influx of migrants. According to The World Bank (2020b), in 2020, the annual growth rate in urban populations in low-income countries was 4%, whereas the growth rate was only 0.6% in high-income countries. Most of the urban centers have failed to provide adequate housing for the burgeoning population, with informal settlements, normally referred to as slums, growing very rapidly. The United Nations estimates that about 30% of the urban population around the world lived in slums and tenements in Eastern and South-Eastern Asia, Sub-Saharan Africa, and Central and Southern Asia in 2018 (United Nations, 2021a). The COVID-19 pandemic has further exposed such populations to risk and increased awareness for investment in basic infrastructure and decent living conditions (United Nations, 2020).

1.2. Challenges in Window Design in Slum Housing: Impacts on Energy Efficiency and Health

Slums are typically marked by high-density housing, low-quality material, and an absence of infrastructure, which speaks to a lesser quality of life. Some serious problems in these neighborhoods include deficiencies in appropriate daylighting, energy efficiency, and thermal comfort in residential buildings. Most slum houses are built with poor-quality material; there is hardly any insulation. Indoor temperature can, therefore, swing radically. The opening of designed windows that trap heat indoors to produce extremely high indoor temperatures, especially in warmer areas, is an issue that is worsened by poorly chosen materials. During colder seasons, on the other hand, such windows do not keep the heat indoors, and this makes

homes uncomfortably cold. Williamson and Daniel (n.d.), and Tusting et al., 2020, provide that continuous temperature extremes result in diseases such as respiratory diseases, diseases related to heat, and general high vulnerability to infectious diseases.

In slum dwellings, ill-designed windows create not only thermal but also other related problems. Most of them are sited out of poor shading, ill-placed, misaligned, and fabricated from poor material-all affecting the performance. Poor window design restricts airflow and increases indoor heat in Mumbai's hot and humid environment. Besides, various types of shading options for windows are either practically missing or highly ineffective due to which direct sunlight reaches into the building and causes an increase in indoor temperatures.

The major design defect in slum housing is inefficient shading systems. The windows are installed with minimum depth of shading or no use of shading devices such as overhangs, louvers, and external blinds at all. Where the application of shadings has been put to use, it is very common that the installation of the device is shallow or misplaced with some gaps through which direct sunlight passes. This results in too much sunlight entering the building and, therefore, increased indoor temperatures that have to be lowered by additional cooling. In those residential areas of urban poverty, where not enough resources are available, even the usage of temporary or makeshift shading materials makes things worse, with negligible to no protection against strong sunlight. Such defects further contribute to thermal discomfort and energy inefficiency in slum housing with improper placement and alignment of windows, creating a vicious circle that sustains health issues and high-energy consumption.

1.3 Focus on the Issue in India

Slums have been a problem in India since the 1950s, particularly in cities like Mumbai, due to the lack of infrastructure in terms of sanitation, water, and ventilation. As efforts have been made to upgrade slum rehabilitation housing, it still encounters major obstacles. This emphasizes that slum rehabilitation initiatives-which often take up quick housing solutions instead of long-lasting quality-urgently need key issues to be prioritized toward creating an environment that is sustainable and comfortable.

Insufficient window design directly impacts thermal comfort and energy efficiency. In the case of housing for slum rehabilitation, the windows often do not take into consideration specific climatic conditions of the area in question, such as the hot and humid environment of Mumbai. As a result, houses become too hot during the day, which causes residents to use more energy in attempts to lower the temperature. In this respect, minor changes in window shading and orientation can do a lot of good in indoor temperature regulation and energy savings, but rehabilitation projects often resort to using only low-quality materials such as plastic sheets and scraps of wood out of financial constraint, compromising windows and other architectural elements in terms of durability and performance. A study from Cambridge University shows that cutting costs often harms future sustainability and the well-being of residents, resulting in challenging living conditions that are hard to enhance in the long run (Almeroth-Williams, 2020).

1.4. The Impact of Poor Window Design

1.4.1 Water Seepage and Structural Damage in Slum Housing

Inadequately designed windows bring a set of problems in constructing houses meant for slum rehabilitation. The significant problem here is seepage of water, considering that cities such as Mumbai fall within tropical climate regions which experience heavy and continued monsoon rains. Consequently, rainwater can enter the house through poorly sealed windows. This creates dampness that may eventually cause mold growth. Over time, this can lead to structural damage to the building, weakening the walls and further adding to the overall cost of the building in terms of maintenance. Lack of proper drainage systems around the windows contributes greatly to exacerbation and permits water to penetrate into the building's interior.

1.4.2 Poor Air Flow and Indoor Air Quality

Another effect of inferior window design is insufficient ventilation. Most of the windows in low-income housing projects are installed without considering the air flow directions and hence there is inefficient natural ventilation within the houses. The residents may develop health problems as the hot and polluted air may get trapped inside when there is stagnation of air. In

regard to security, people residing in such projects prefer to fix metal grills on their windows. While these grills provide safety features, they block airflow and decrease sunlight, lowering indoor air quality and making the living space even more confined and uncomfortable to be in. (Main, n.d.).

1.4.3 Constraints of Overcrowding on Natural Light and Airflow

Other problems that occur during window design include overcrowding in slum rehabilitation colonies. Poor urban design and congestion inherent in the nature of these communities often serve as a great barrier to window placement, hence reducing efficiency in natural light and air. For instance, buildings are often constructed very close to each other; hence, windows are blocked from getting ample sunlight or air. The absence of daylight and fresh air increases the overall discomfort and unhealthy living conditions residents experience, hindering their ability to uphold a decent quality of life (Almeroth-Williams, 2020).

1.5. Research Aim

- Design energy-efficient windows for slum renewal in Mumbai and other cities with improved thermal comfort, adding to the quality of life.
- Safety concerns- striking a balance between safety and airflow with sunlight.
- Shading Windows: Use window shading to provide security, comfort in maintaining fresh air and sunlight.
- Design windows that can adapt to the climate, resist local conditions, and be durable and stable. Use high-quality, less-expensive materials that will ensure that housing is sustainable, durable, and energy-efficient.
- Design and propose safety at windows in congested urban areas that will help improve residents' quality of life and well-being.

2.0 Literature Review

2.1 Historical and Systemic Failures in Slum Housing and Infrastructure Development

Slum growth is associated with rural-urban migration in search of various economic alternatives and is unable to afford decent housing, hence, gets pushed into slums. These areas, though available at very low rates and proximity to job sites, essentially lack basic amenities such as safe water, sanitation, and electricity supply. Generally, poor connectivity intensifies access to various better opportunities for jobs, education, and health for residents of such areas, which keeps them peripheral by further aggravating the poverty spiral. Slums in Mumbai are the result of previous inefficiency and shortcomings in the housing policy of India. Chawls [1] built for mill workers were getting overcrowded and became dilapidated when the mills were closed down. Despite several Indian government efforts at addressing slum issues through policies like slum rehabilitation and redevelopment, these have often exacerbated the problem instead of providing a solution to it, as the poverty simply continues to persist. (Shree et al., 2022; Bardhan et al., 2015).

Figure 1 : Mumbai Slum Top View

Figure 2 : Slum Housing Front of Drainage

2.2 Design of the SRH Typology and the Living Unit

Slum Rehabilitation Housing can be defined as a specially designed vertical apartment complex constructed in the current slum areas of Mumbai to provide housing for the slum dwellers. The principal objective of the SRH scheme, driven by the SRA, is to replace informal settlements with legal, durable housing. These high-rise buildings can be between 5 to 30 floors in height

[1] Chawls are a type of residential building found primarily in Mumbai, India. They were originally built in the early 1900s to house migrant workers employed in the city's textile mills. These buildings are characterized by their high-density, low-cost design, often featuring long corridors with multiple small, single-room units.

and have been built next to each other in a closely knit manner in order to accommodate large populations, leaving very little open ground. The population density at SRH sites is extremely high; it averages 500,000 persons per square kilometer, while the average citywide population density in Mumbai is 25,357 persons/km². In some instances, each individual gets less than 2 square meters, which shows the congestion typical for these renewed areas. (SRA Notification, 2014)

SRH structural design is usually developed with a combination of reinforced concrete frames and brick masonry or concrete block walls. Such materials are chosen in hot, rapidly growing cities for their durability and relatively lower costs. However, they pose some challenges in terms of thermal efficiency. Concrete and brick have a very high heat capacity; in Mumbai's hot humid climate, they absorb and capture heat during the daytime, which is then reemitted at night, thereby exacerbating the urban heat island effect. This results in uncomfortable living conditions, mainly within apartments that do not offer good ventilation and are on higher floors. (Ronita Bardhan and Pan 2023)

The poor thermal regulation of these materials often leaves the occupants with no choice but to resort to mechanical cooling methods, which, in turn, increases energy consumption and costs. In the enhancement of thermal comfort, this may involve the use of new materials available with better insulation properties, such as AAC, or other techniques like passive design, involving insulation of the roof and optimization of window design for better natural ventilation. These measures can increase the habitability of SRH buildings by a great degree, thus solving the heat and energy-related problems. (Ronita Bardhan and Pan, 2023)

Figure 3 : SRH, Mumbai,India

Figure 4 : Slum, Mumbai,India

Typologies of SRH: X, I, and H Types

The SRH buildings are designed to follow certain typologies that dictate the flow of circulation, the way spaces are arranged, and the general layout of the apartments. The three major typologies for SRH designs commonly observed in Mumbai are the X Type, I Type, and H Type configurations. Each of these typologies inherently exhibits different characteristics in terms of floor plan layout, circulation patterns, and building function.

X Type

The name X Type comes from the shape which corridors take in its floor plan. As indicated, the corridors are in the shape of an "X" where individual apartment units access a circulation through a central corridor. Staircases and lifts are normally placed at the X intersection, allowing easy vertical movement to the residents. The layout does create wider circulation spaces around the X joints, where several pathways of circulation converge. However, the densely packed apartments around the corridors of the X would still have issues regarding natural ventilation and light because a large amount of the units are being kept further away from the exterior walls and actual airflow. (Ronita Bardhan and Pan, 2023)

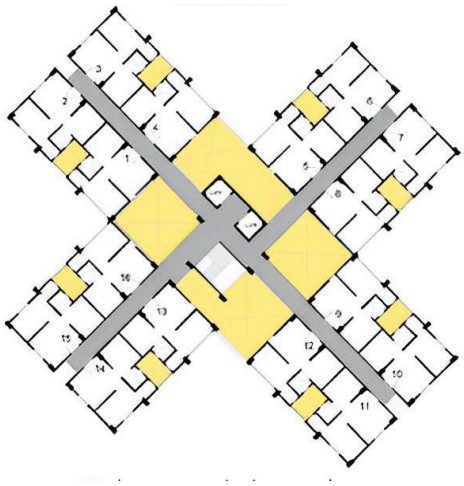


Fig 5 : PMG COLONY,MUMBAI (Pardeshi et al., 2020)

I Type

I Type-the traditional type, with double-loaded corridors, with a central corridor. This typology is very common in multi-storey residential buildings where efficiency in the use of floor area is paramount. The corridors provide the main access to all apartment units on any one floor. While the I Type layout can accommodate the maximum number of units per floor, it often falls prey to narrow corridors and passageways hindering air circulation and limiting the entry of natural sunlight in apartments distant from the exterior façade. Poor ventilation, congestion, and lack of common spaces are common complaints among residents of I Type SRH buildings whose compact design presents a recurring set of challenges. Ronita Bardhan and Pan (2023)

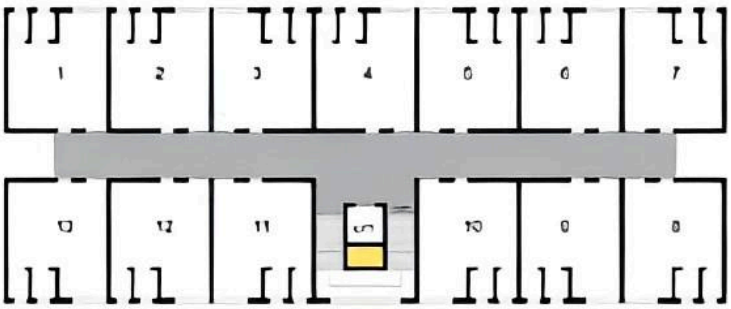


Fig 6 : Lallubhai Compound,Mumbai (Pardeshi et al., 2020)

H Type

The H Type is a layout where the access corridors are in a gallery-like arrangement around the apartment units. Access corridors quite often circumvent the central core of the building, hence affording better linkage for the residents within the complex. The H Type is designed with the purpose of improving internal circulation and fostering more interactions between residents. However, in H Type SRH buildings, the gallery corridors are often overcrowded and unhygienic due to multiple household activities being accommodated within them. This often prevents proper consideration of vital issues such as air quality, privacy, and common spaces. (Ronita Bardhan and Pan (2023))

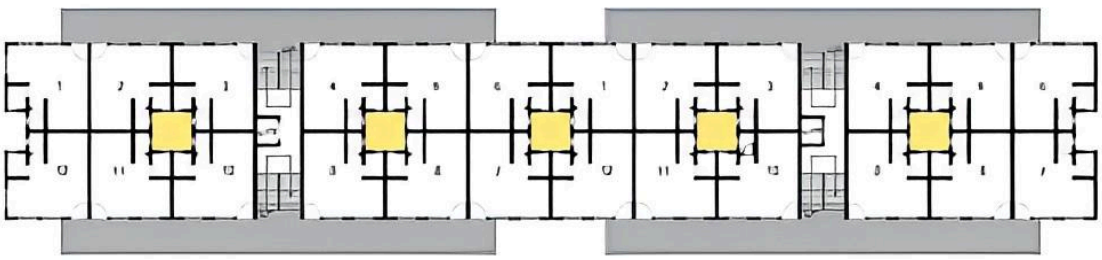


Fig 7 : Natwar Parey Compound,,Mumbai(Pardeshi et al., 2020)

Comparison of Layout:

Studied SRA Projects	Setback regulations	Distance between buildings	Window regulations	Density regulations
Natwar Parekh Compound: Insufficient Light and Ventilation Higher Incidence of TB	Building Height = G + 7, 24 m Setback Distance = 1.5 m Meets SRA Regulations	Building Height = G + 7, 24 m Distance Between = 3 m Meets SRA Regulations	16% of room area (8% after accounting for shut pane of sliding window) Barely meets general window regulations	Net Study Area = 5.05 ha Number of units built = 5568 units Study Area Density = 1103 units/ha Meets SRA Regulations
Lallu Bhai Compound: Insufficient Light and Ventilation Higher Incidence of TB	Building Height = G + 5, 18 m Setback Distance = 1.5 m Meets SRA Regulations	Building Height = G + 5, 18 m Distance Between = 3 m Meets SRA Regulations	10% of room area (5% after accounting for shut pane of sliding window) Does not meet general window regulations	Net Study Area = 5.75 ha Number of units built = 6318 units Study Area Density = 1099 units/ha Meets SRA Regulations
PMG Colony: Insufficient Light and Ventilation Comparatively lower Incidence of TB	Building Height = G + 7, 24 m Setback Distance = 8 Meets spacious general regulations	Building Height = G + 7, 24 m Distance Between = upto 16 m Meets spacious general regulations	12%–20% of room area (6% to 10% after accounting for shut pane of sliding window) Does not meet general window regulations	Net Study Area = 1.75 ha Number of units built = 1600 units Study Area Density = 914 units/ha Meets SRA Regulations

Fig 8: Comparison of layout of buildings for the three SRA colonies studied in the current article. (Pardeshi et al., 2020)

As per SRA guidelines, a typical SRH apartment consists of a living room, bedroom, kitchen, bathroom, water closet, and balcony, measuring a total of 24.9 m². Even though these units are given to slum dwellers without cost, the focus is on being compact and space-efficient rather than comfortable. Every level within a building owned by SRH is set up with living spaces positioned next to each other, linked by a hallway or common area. Sometimes, the SRH buildings are designed for combined purposes, including retail stores on the bottom level to establish a communal area. Furthermore, standard amenities like communal facilities such as toilets (either in individual units or shared on each floor), elevators, staircases, a community center, and a central green space are included. These facilities aim to provide inhabitants with a feeling of safety and property rights, ultimately enhancing their standard of living.(Ronita Bardhan and Pan, 2023)

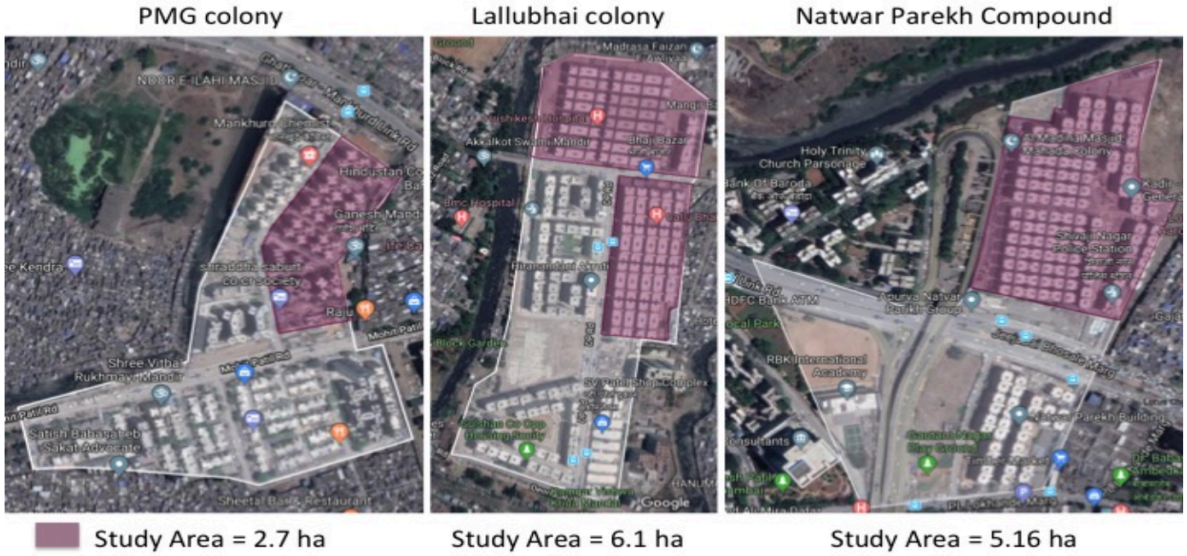


Fig: 9 Snapshots of top view of Lallubhai Compound, Natwar Parekh Compound and PMG Colony. Study area of the three resettlement colonies is highlighted.(Pardeshi et al., 2020)

2.3 Overview of Issues in Slum Rehabilitation Housing:

As residents move from slums to rehabilitation housing with free legal rights, basic services, and housing, there are still unknowns about the quality of living conditions and community dynamics, including aspects such as living space, ventilation, daylight, gender equality, and

sense of community. Often, these structures remain a threat to health because they lack sufficient sunlight and fresh air. The tall container's limited space results in the perception of 'vertical slums' (Debnath, Bardhan, and Jain, 2017a). When resettlement policies are ineffective, the lack of standard rules for design and energy factors can lead to a negative impact on social and physical liveability.

2.3.1 Physical Environment

2.3.1.1 Built Environment and Structural Design

The comparison of slums and rehabilitation housing (SRH) shows that there is no notable advancement in the built environment factors in rehabilitation housing (Sarkar and Bardhan, 2020b). In urban areas with poor housing, the mixture of single and double-story buildings leads to a varied cityscape that enhances ventilation and natural light. Yet, in SRH, the raised height and density of buildings, intended to house more people, lead to congested vertical constructions. The high-density setting limits communal areas and airflow because of insufficient internal spaces within buildings, resulting in a chain reaction layout. The majority of windows are located on the side sheltered from the wind, creating an unbalanced ventilation system that reflects the domino-like layout of the buildings. These high, densely populated structures disrupt air circulation, diminish sunlight contact, and obstruct views of the sky, particularly on the lower floors.

2.3.1.2 Communal and Shared Spaces

Along with inadequate airflow and lighting, these areas for rehab often lack sufficient communal spaces. The central open areas are often turned into illegal parking areas or used for activities like drug abuse, making them off-limits to residents. In contrast to the naturally developed slums with communal areas, SRH frequently does not have playgrounds, parks, or public spaces for gathering, leading to a lack of social unity and community cohesion.

2.3.1.3 Indoor Space Challenges

Issues related to space standards present major challenges in the internal areas of Slum Rehabilitation Housing (SRH). According to Sunikka-Blank, Bardhan, and Haque (2019), residents face challenges in living comfortably due to the small size of the tenement units. For instance, the typical size of a residential unit in Mumbai is around 269–300 square feet (25–28 square meters). This is much smaller in comparison to the space standards suggested by multiple international housing guidelines. As per the United Nations' guidelines for adequate housing, every person should have a minimum of 9 square meters of living area, with a family of four needing a minimum of 36 square meters. On the other hand, SRH units frequently accommodate bigger families in limited space, leading to overcrowding. According to Sarkar and Bardhan (2020b), the integration of kitchens with living spaces fails to effectively remove smoke and pollutants, leading to reduced indoor air quality and higher temperatures. Despite the increase in availability of indoor toilets, poor maintenance often leads to the presence of mold, dampness, and germs, creating health risks (Sarkar and Bardhan, 2020b).

2.3.1.4 Ventilation and Airflow Issues

The evaluation of environmental elements in SRH, like the arrangement of buildings, air circulation, comfort with temperature, quality of indoor air, and sunlight exposure, indicates notable deficiencies in comparison to slums. Slums, featuring varying building heights and open areas, promote improved ventilation and air circulation. On the other hand, SRH constructions, which have narrow streets, restricted inter-building gaps, and deep street canyons, restrict air flow, causing unease for inhabitants (Sannigrahi et al., 2020; Sarkar and Bardhan, 2019).

2.3.1.5 Thermal Comfort, Heat Stress, and Human Behavior

Heat stress is a significant concern in sustainable urban heat management, worsened by the urban heat island phenomenon and limited air circulation. Research shows that slums have better thermal performance compared to SRH due to their horizontal layouts and inter-building shadows, which provide natural ventilation and shading, thus reducing operational temperatures in SRH where these factors are lacking (Debnath, Bardhan, and Jain, 2017b). Though physical environmental factors are important, human behavior also influences how comfortable people

feel with the temperature in SRH. Inhabitants utilize different methods to deal with discomfort caused by temperature, such as opening windows and doors, using curtains to block sunlight, adding planters for shade, and changing clothing. These behavior changes have been discovered to improve thermal comfort, aiding inhabitants in coping with inadequate ventilation and heat strain (Mahatra, Bardhan, and Ramamritham, 2019).

It is interesting how adaptive comfort strategies enhance thermal comfort, but household income also plays a role in how comfortable people feel. Increased income often leads to higher expectations of comfort, which may impact residents' perceived comfort in sustainable residential habitats (SRH) even with adaptive strategies in place. This emphasizes how environmental and psychological factors are intertwined in influencing thermal comfort. In addition, residents in SRH display apathy towards aspects of the physical environment such as overcrowding, housing satisfaction, and air quality, which adds complexity to their perceptions of comfort (Jana, Sarkar, and Bardhan, 2020).

Fig 10: Photographs of the open spaces between buildings in the three colonies (Source: Doctors For You, India)

2.3.2 Energy Consequences

A modification in the constructed surroundings can influence residential electricity usage by altering household behaviors. The rise in energy usage in SRH surpasses the energy needs of slums because of increased ownership of appliances, resulting in higher electricity costs (Debnath, Bardhan, and Sunikka-Blank, 2019). According to a survey, individuals purchased energy-consuming electronic devices such as televisions, ceiling fans, and refrigerators upon relocating to new housing for rehabilitation. Buying appliances meets the residents' desire for a stable residence but also leads to a 40% rise in energy costs (Debnath, Bardhan, and Sunikka-Blank, 2019). Harsh outdoor conditions like urban heat island, pollution spread, and discomfort from heat often lead individuals to seek refuge indoors, relying on mechanical cooling systems for relief. The survey conducted by (Debnath, Bardhan and Sunikka-Blank, 2019) confirms the strong connection between indoor air quality, thermal comfort, hygiene, and appliance usage in rehabilitation housing. Ceiling fans and exhaust fans, which operate with low energy, are often utilized to boost air flow speed and reduce indoor temperatures (Malik et al., 2020).

2.3.3 Health Risks

The likelihood of contracting various illnesses in the SRH setting is substantial. The layout of the constructed surroundings has the potential to provide a good living space, diminishing health threats by ensuring easy availability of fresh air, sunlight, views of the sky, clean water, and sanitation facilities. In SRH, the occurrence of asthma, hypertension, 'sick building' syndrome, disruption of human thermoregulation, and neurodevelopmental abnormalities are accelerated by poor indoor air quality (Bardhan, Debnath, Jana, et al., 2018). The frequency of tuberculosis in rehabilitation housing sites is closely linked to the layout, windows that are closed or only partially able to open, the absence of exhaust fans, and the unfavorable outdoor surroundings of the buildings. The X type design had a lower disease incidence because of good airflow and ventilation , with 2% of households affected, while the I and H type designs had higher rates of 8–10% of households affected. Frequently, a stronger strain of the bacterium was discovered in

both of these design variations. Limited access to adequate ventilation and sunlight in the lower floors results in high rates of tuberculosis infection (Pardeshi et al., 2020). In the same vein, the higher-level units showed increased fresh air circulation and fewer instances of seeking healthcare for respiratory diseases (Bardhan, Debnath, Jana, et al., 2018).

Fig 11: Photographs of the open spaces between buildings in the three colonies (Source: Doctors For You, India)

2.4 Architectural Design Impacts on Public Health: Case of Tuberculosis Prevalence in Slum Rehabilitation Housing of Mumbai City

Several studies in Mumbai have investigated the level of determination of housing conditions in Slum Rehabilitation Housing concerning the public health outcomes-prevalence of Tuberculosis. A study involving three resettlement colonies in Mumbai sought to provide information on elements of architecture, such as natural light and ventilation, affecting health, especially in

densely populated urban areas where adverse environmental conditions worsen the spread of diseases such as TB.

Key Themes and Findings:

The research emphasizes the strong connection between higher TB rates and inadequate access to natural light and ventilation, especially on lower levels. In numerous SRH initiatives, lenient Development Control Regulations (DCR) designed to support high population densities have unintentionally impacted the quality of indoor air and access to daylight. The inappropriate situations thus created have contributed to spreading TB, a potent health concern in the dense resettlement colonies. Results of the study underlined the issues of the lower levels usually getting less sunlight and airflow in SRH facilities because of inadequate, cramped building designs with insufficient window-to-wall ratios that are important for a healthy indoor environment.

Methodology and Recommendations:

The methodology is a semi-quantitative survey of 4080 households in Mumbai with architectural factors and its impact on health. The decrease in environmental quality for lowered floor levels was further quantified with the help of analysis tools like SVF, DA, and NV simulations. The results showed that enhanced planning and architectural strategies are needed to guarantee wider spacing between buildings, detailed window layouts to ensure proper airflow, and increased sunlight entry through strategic building placement. These design variants could reduce the public health burden by decreasing the transmission of TB in SRH communities.

Literature Review Summary:

This is crucial research in highlighting the explicit linkage between design in housing and health outcomes explicitly for SRH. It points to the broader issue with urban planning policies, which prioritize density over livability, through inefficiencies in natural ventilation and access to daylight. The study further helps to develop architectural designs that address overcrowding and hence contributes to health and quality of life of the residents of SRH. The paper calls for the

inclusion of health-oriented design principles in the urban residential policies, particularly in improving natural ventilation and admission of daylight in future SRH developments.

Research Gap:

A number of research areas have been highlighted in the paper as needing more research.

Environmental Metrics: The research does not study some key environmental metrics like indoor humidity, CO2 levels, and the impact of proximity to infected individuals in regard to the transmission rate of diseases like TB.

The main limitation in this work is that of long-term data collection and health outcome analysis. The present study depends on a single survey, which might not conceptualize the far-reaching implication of the poor design of the built environment on the health of its occupants.

Architectural Solutions: While the study has given good coverage to the issues of ventilation and daylight, specific architectural design solutions to help mitigate these problems are lacking.

2.5 Optimizing Indoor Environmental Quality in Slum Rehabilitation Housing: The Role of BIM and Spatial Design Interventions

In the previous research, it has been focused on IEQ improvement in various types of residences, especially in low-income housing where the conditions mostly do not meet the minimum health requirements. One such study by Author Ahana Sarkar and Ronita Bardhan (2019), presents an analysis regarding optimal positioning of ventilators and furniture in slum rehabilitation housing in Mumbai. The improvement in IEQ would be due to the adoption of improved spatial design strategies that would have much focus on enhancing indoor airflow and providing effective temperature control in small living spaces.

In his approach, the author has adopted a structured approach comprising parametric design modeling, computational simulation, multi-objective optimization, and multi-criteria decision making. This framework thus allowed detailed examination and improvement of spatial layouts inside tenements with much accuracy. In the ODL 3 representing an optimized design layout in

this study, notable improvements comprised indoor air-velocity enhancement by 0.2 m/s and temperature reduction by 2°C. These results show that modest changes in ventilation and furniture location can improve indoor climate conditions substantially, enabling a much healthier and more comfortable place to live.

The research contributes to the broader discussion of sustainable habitat design, with a particular focus on policies related to the redevelopment of slums in India. It provides a rich set of insights on how design interventions can significantly help improve the living environment in densely populated, low-income urban areas. Consequently, their project outputs go beyond technical development, providing the basis for future policy measures that can be taken to bridge gaps in housing through design-driven interventions.

Fig: 12 Plan and sections of the six NSGA II-derived ODLs.

2.6 The Role of BIM in Optimizing Indoor Environmental Quality in Slum Rehabilitation Housing

Building Information Modeling (BIM) is now seen as a revolutionary tool in architectural design and urban planning, especially for enhancing indoor environmental quality (IEQ) in low-income housing. Recent studies have looked into the potential of BIM in improving the placement of ventilators and furniture, with positive findings on enhancing indoor conditions, particularly in slum redevelopment housing.

Author Ahana Sarkar and Ronita Bardhan (2019) *"Improved indoor environment through optimized ventilator and furniture positioning: A case of slum rehabilitation housing, Mumbai, India"* showed how BIM can efficiently be used to create and evaluate various hypothetical interior designs, improving the positioning of ventilation systems and furniture. By optimizing these factors, the research successfully enhanced indoor air circulation, controlled temperature levels, and decreased levels of pollutants. By utilizing BIM's computational simulation features, designers could anticipate essential indoor environmental factors like air velocity, temperature, and pollutant levels, which enabled them to make educated choices when creating efficient ventilation plans.

Furthermore, BIM facilitates multiobjective optimization and multicriteria decision-making in addition to its optimization capabilities. This allows for the assessment of different design options, taking into account factors such as air quality, thermal comfort, and space utilization in order to achieve optimal indoor conditions. Moreover, BIM's ability to work together effectively allows stakeholders to participate in the design process, resulting in layouts that are technically strong and socially appropriate. This method supports sustainable habitat design by ensuring that design choices meet the practical needs and expectations of residents.

In this scenario, the importance of BIM is emphasized not just as a design tool but also as a decision-making system that considers both technology and human elements. BIM improves living conditions in low-income communities by optimizing indoor environments in slum redevelopment, supporting goals of sustainable urban development and housing equity.

3.0 Methodology:

This work proposes the BIM-based simulation method that can help in optimally designing the window in the case of the "I" typology buildings within Slum Rehabilitation Housing to enhance natural ventilation, daylight access, and thermal comfort. The selected case study is a corner housing unit on the southwest side at G+5 Lallubhai Compound in Mumbai. The unit was selected because it best represents the usual set of problems that are very common in SRH due to

corner units being highly vulnerable to several external factors, which result in very poor natural ventilation and indoor air quality.

Step 1: Data Collection, Base-Case Examination, and 3D Model Creation

The first step is to gather secondary information from already available architectural designs and environmental studies and literature related to SRH matters concerning Lallubhai Compound. This will be made use of in the development of a detailed 3D model of a corner unit that is southwest-facing on a G+5 SRH building block in Rhino. Rhino will be used because of its sophisticated capabilities in architectural modeling and its linkage to environmental analysis software, and thus it forms an appropriate basis for the simulation airflow, lighting, and thermal efficiency. This first model of the corner unit will provide a baseline against which the impact of the current window design on ventilation, daylight availability, and thermal comfort can be considered, given this unit's particular exposure to both direct sunlight and challenges with cross-ventilation.

Step 2: Scenario Development and Design Iterations

Possible design options will be created by adjusting various window design factors, such as size, location, and direction, which introduce shading systems after the initial case has been evaluated. Further consideration of design revisions will include aspects such as human actions, safety issues, Sky View Factor (SVF), airflow patterns, and integration of skylights. It will explore how various types of window configurations impact natural ventilation, daylight penetration, and indoor thermal comfort. This holistic approach is necessary in order to find the most effective design modifications for improving IEQ in SRH buildings by ensuring solutions will be effective and viable for both physical design and critical social and environmental issues of sustainable living conditions.

Step 3: Simulation and Multi-Objective Optimization

Computational modeling and simulation will be done through Climate Studio to analyze these design scenarios. Some of the key environmental factors that Climate Studio analyzes include

daylight availability, daylight autonomy, and energy use intensity. It allows for some adjustments that can be made in window specifications to better enhance indoor environmental quality. The differences in each window layout will be assessed concerning natural lighting, air circulation, and temperature conditions against that of the original model. In so doing, this step refines the window designs through simulated configurations that will result in better daylight performances with reduced dependency on artificial lighting and hence energy efficiency.

Step 4: Recommendations

These results are to be used in suggesting the best window design for improving the indoor environment of the southwest corner unit in a typical G+5 SRH block in Lallubhai Compound. The same will be helpful in improving indoor air quality, day-light availability, and comfortable indoor temperatures particularly in the corner units that give difficult orientation. The data-driven strategy solves problems in the region of poor ventilation and limited daylight within these human-inhabited compounds. This paper tends to use Rhino and Climate Studio for simulated modeling that aims to improve livelihoods in people living in urban slum rehabilitation housing. Advanced modeling ensures that the designs will be practical and meet the specificities of buildings in SRHs.

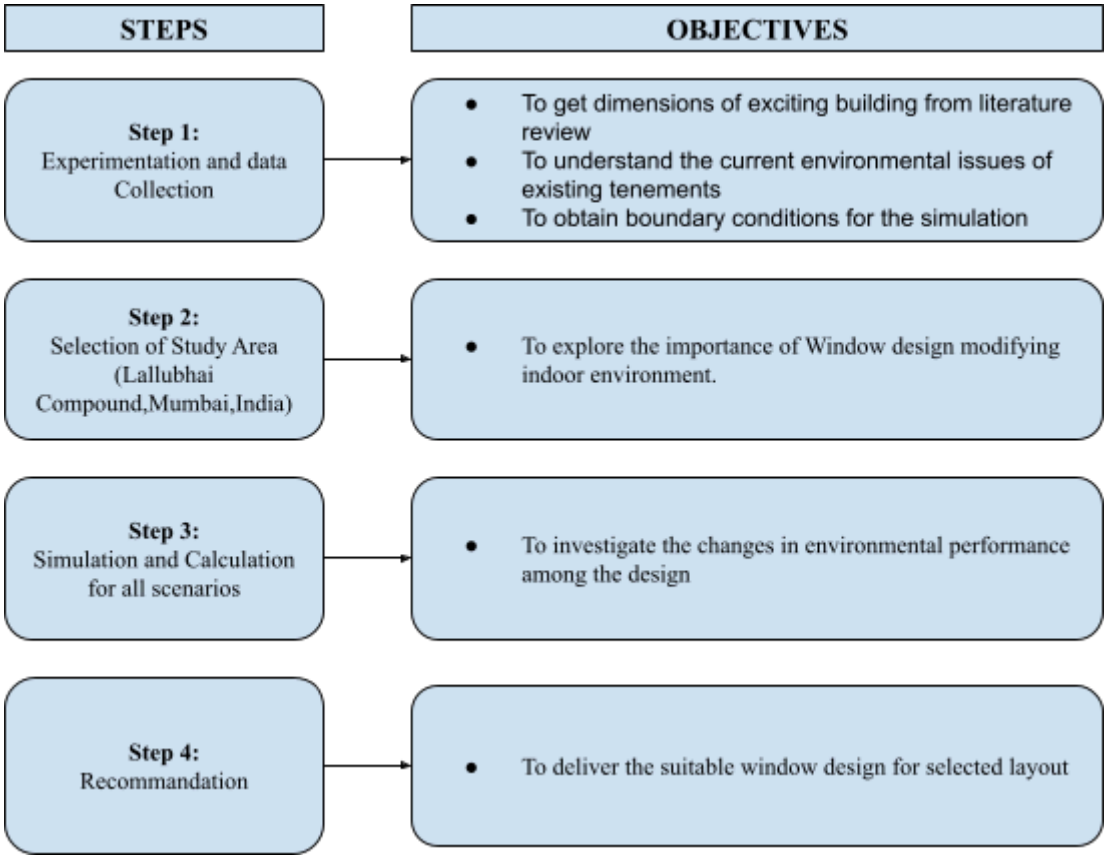


Fig 13: Methodology Chart by Author

3.1 Selected case study:

The Lallubhai rehabilitation colony in Mankhurd, Mumbai was chosen as the study area. The residential colony, which is a cluster of 65 buildings with 9300 dwellings, was constructed in 2003 under the Slum Rehabilitation Act. The tenements are one-room units with an attached bath (2.47 m2) connected to a common corridor. The interior space typically comprises two undivided zones: cooking and multipurpose living zones.

The unit contained one window (1.5 m x 1.2 m) in the multipurpose room and a door (0.9 m x 2.1 m) on the opposite wall. A furniture item (bed: 1.9 m x 1.0 m 0.635 m) was placed in the room to recognize its most favorable position for availing the maximum e-IEQ. A cook-stove (0.4 m x 0.4 m 0.4 m) placed below the window (as observed from the field survey) was considered the chief indoor source of heat and pollutants. The floor-to-ceiling height was

measured as 2.9 m. Another notable observation among the resettlement units was the hindrance of natural ventilation paths. Although privacy was the main concern behind the closing of doors for the residents of lower floors, the requirement of additional storage space forced the installment of permanent window coverings. These coverings were observed to have significant effects on the indoor natural airflow.

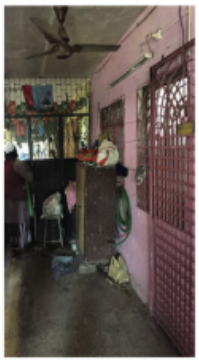


Fig 13. Permanent window obstructions observed in resettlement dwellings inhibiting ventilation paths.((Sarkar and Bardhan, 2020))

3.2 Climate Analysis:

Mumbai, a heavily populated tropical city, faces various temperature fluctuations and air quality issues that affect its urban surroundings. According to the most recent information, the typical outdoor temperature in Mumbai varies from 24°C to 31°C, with maximum temperatures hitting 35°C in the summer months (IMD, 2023). Recent measurements from 2022 show that Mumbai's air quality remains worrisome, with PM2.5 levels averaging about 65 µg/m³ and PM10 around 130 µg/m³ (CPCB, 2023). These numbers greatly surpass the World Health Organization's suggested thresholds of 10 µg/m³ for PM2.5 and 50 µg/m³ for PM10 (WHO, 2021). In light of these circumstances, the use of natural ventilation continues to be an important method for enhancing indoor air quality, especially for the less fortunate residents of Mumbai who are constrained financially and cannot afford expensive air purification options.

3.3 Creating Detailed 3D Model:

I used Rhino to model the real conditions of the building by representing the physical site features. That included declaring the characteristics of the materials for walls, windows, and shading devices. This will ensure that future thermal and daylight performance is correctly simulated. Much attention has been paid to the geometry and location of the windows, as they are highly relevant in regard to natural ventilation and sunlight penetration analysis in this corner unit. After that, a finished 3D model was taken into the Climate Studio for simulation. Save the model in a working format and import it into Climate Studio to analyze daylight availability, daylight autonomy, and energy use intensity in the building. The simulations included multi-test runs by means of different window setups and adjustments in shading, window dimensions, and positioning. These simulations, in turn, provided valuable insights with respect to varied design changes that impacted daylight distribution, ventilation, and thermal comfort.

Indeed, through the application of Rhino for a more detailed 3D model and Climate Studio for various environmental simulations, this workflow allows for very precise evaluation of every design option and its resultant impact on indoor environmental quality.

Fig : Detailed Plan of Lallubhai compound housing

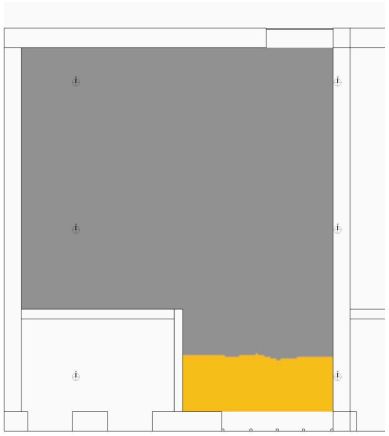
Fig: Isolated View

4. Results and discussion

Base Case: Current Condition of Slum Housing Windows

In the base case, daylight performance was analyzed for the selected southwest corner unit of a G+5 block in the Lallubhai Compound. The results were: Daylight autonomy was achieved only 13.7% of the time, falling well below the recommended benchmark. Also, 7.1% overexposure to sunlight occurred, which falls within the acceptable 10% limit. This gives an Energy Use Intensity of 47 kWh/m², quite reasonable since there were no heating and cooling systems required in this housing, since most low-cost houses do not have these systems. Even though this

unit's facade faced south, the potential for getting natural daylight was minimal, resulting in a heavy reliance on artificial lighting that reduced energy efficiency. This is why window design bears major potential for improvement with a view to fully using available natural light and ventilation.



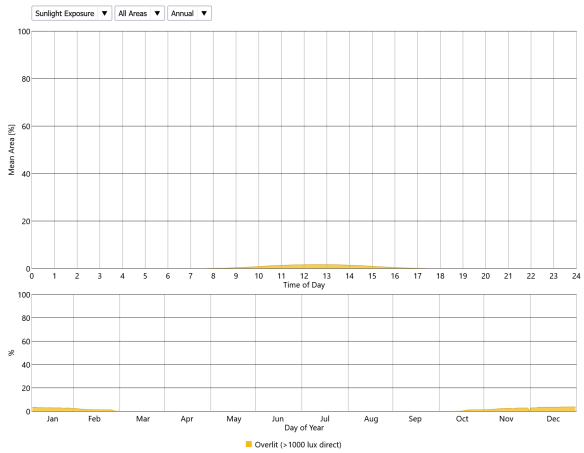
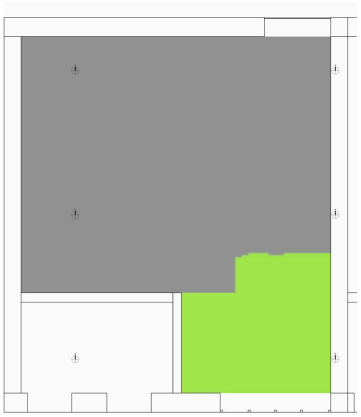


Fig : Sunlight exposure plan view

Fig : Sunlight exposure Chart



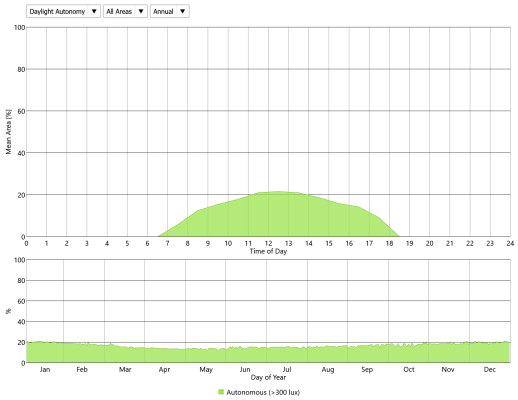
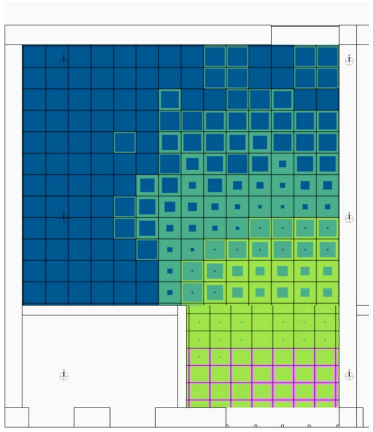


Fig : Daylight autonomous

Fig : Daylight autonomous

Fig: EUI Value



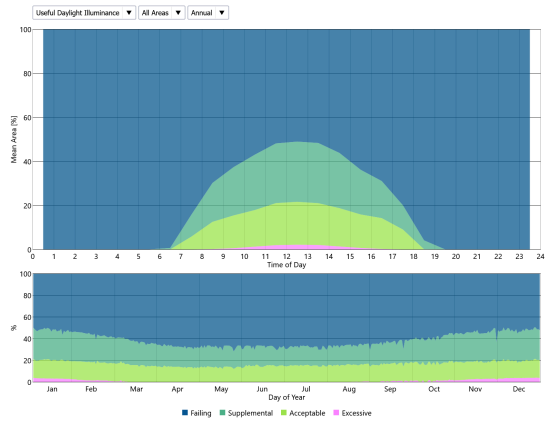
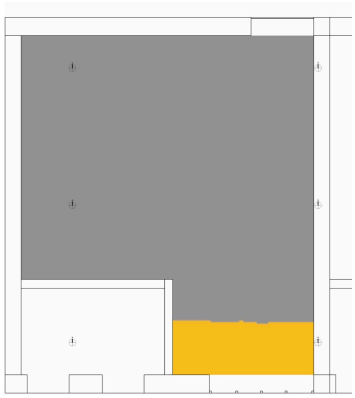


Fig : Useful daylight illuminance

Fig : Useful daylight illuminance

Scenario 1: Sliding to Openable Windows

In this model, sliding windows were replaced with openable ones with the intent of reducing obstructions for the mullions. The results of the analysis had slight improvements in that: Daylight autonomy increased to 15.7% from the base case, an improvement, though minor. Overexposure to sunlight increased slightly by 7.4%, still below the threshold of 10%. This latter case thus ensued with minor amelioration within daylight performance but did not affect the EUI seriously, and that means changing the types of windows alone without taking their size, orientation, and shading into account bears little effect on energy efficiency.



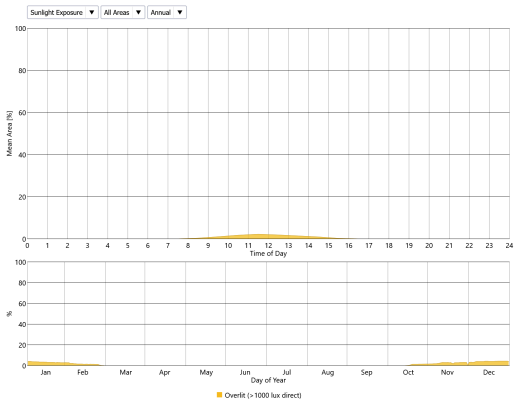
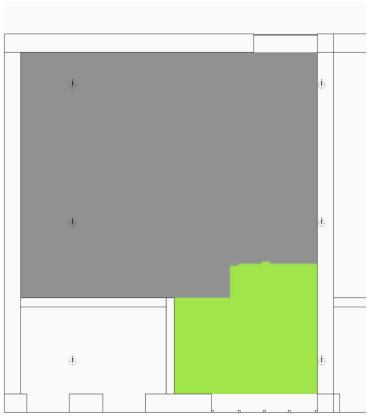


Fig : Sunlight exposure plan view

Fig : Sunlight exposure Chart



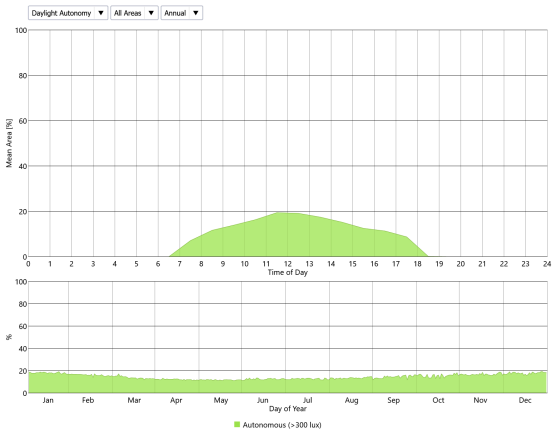
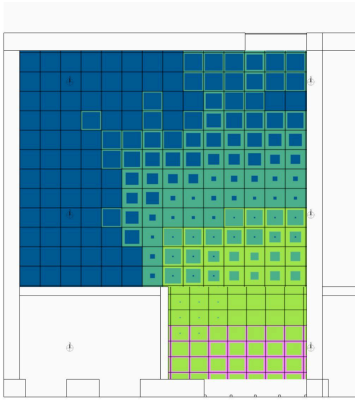


Fig : Daylight autonomous

Fig : Daylight autonomous



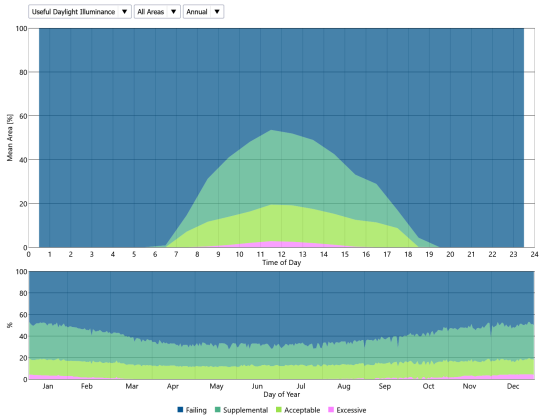
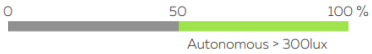
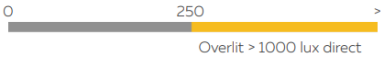


Fig : Useful daylight illuminance

Fig : Useful daylight illuminance





Scenario 2: Increased Window-to-Wall Ratio (WWR)

This was a case that increased window size to 2m x 2m with double-glazed windows to optimize daylighting and ventilation. From the results, Daylight autonomy increased to 19% of the time. In contrast, 20% of areas showed only a moderate increase in daylight autonomy. Overexposure, however, remained constant at 7.4%, similar to Scenario 1. In fact, while larger windows admit more light, the overall improvement does not come close to daylighting benchmarks; hence,

additional design interventions may well be required with a view to optimizing performance, of which shading is an important intervention.

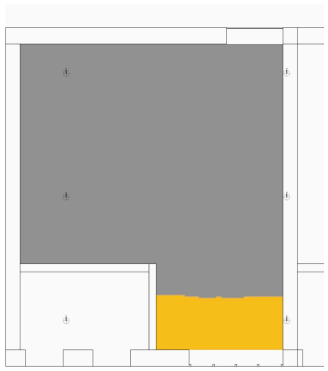


Fig : Sunlight exposure plan view

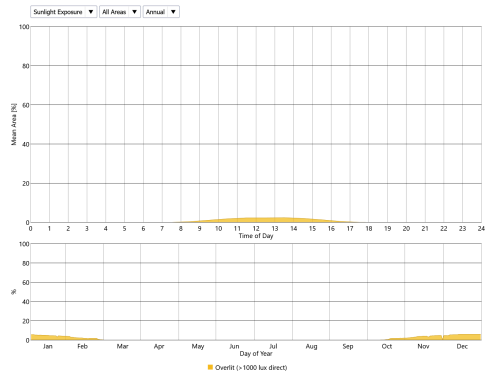


Fig : Sunlight exposure Chart

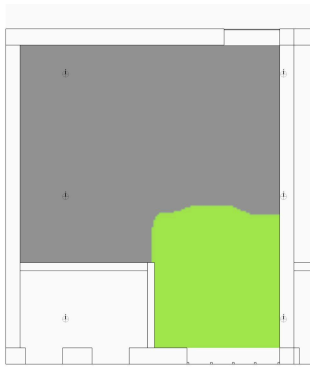


Fig : Daylight autonomous

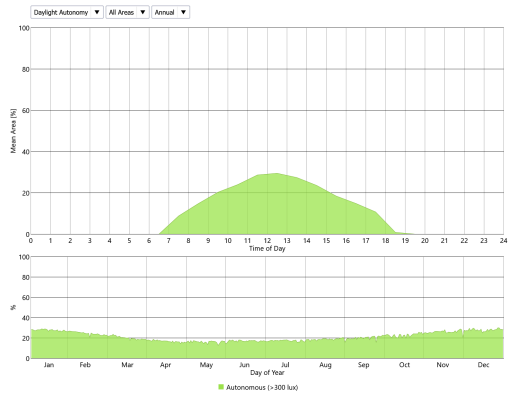


Fig : Daylight autonomous

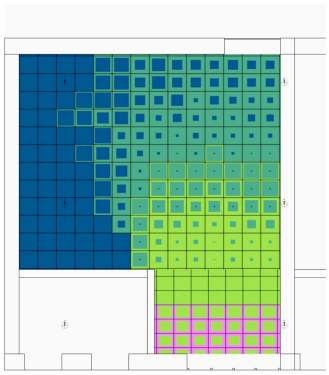


Fig : Useful daylight illuminance

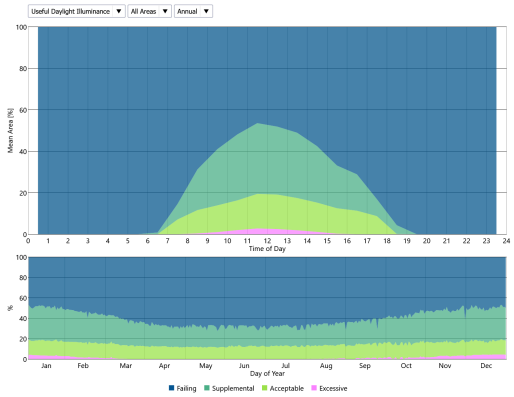
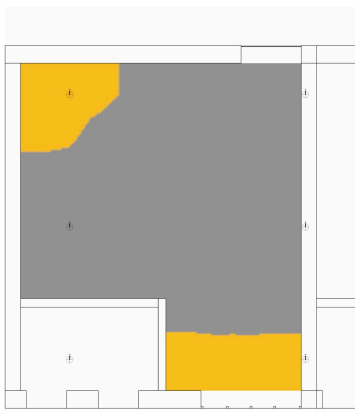


Fig : Useful daylight illuminance

Scenario 3: Increased Window size, Double Glazing, and Additional West Wall Window

In this case, window size was increased on the south façade and added on the west wall to enhance cross ventilation and diffuse daylight distribution in the space. Results are as follows, 56.4% of the time, the floor area exceeded the daylight benchmark. In the given situation, 68.1% of areas would be daylight autonomous, which is quite an improvement when considering previous scenarios. The rate of overexposure similarly increased to 14.1%, passing the recommended threshold of 10%. That could mean a fair rise in daylight autonomy, with the rise in overexposure defining a better solar control.



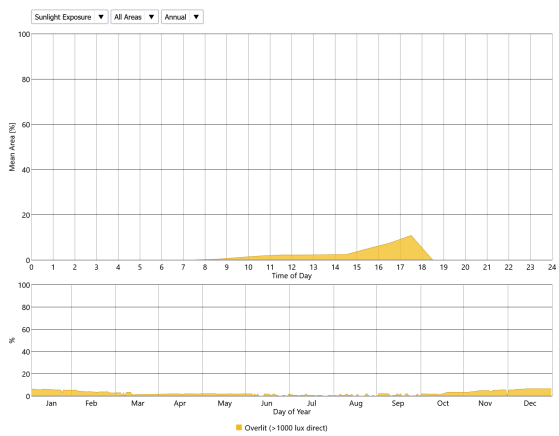


Fig : Sunlight exposure plan view

Fig : Sunlight exposure Chart

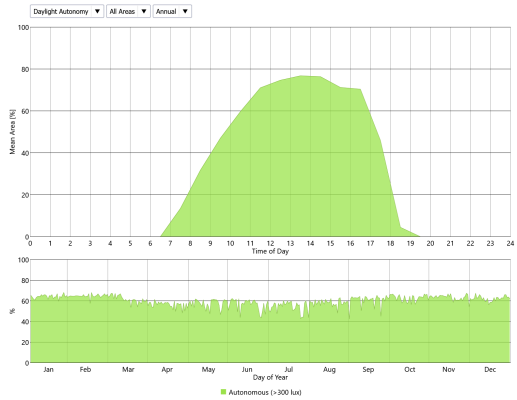


Fig : Daylight autonomous

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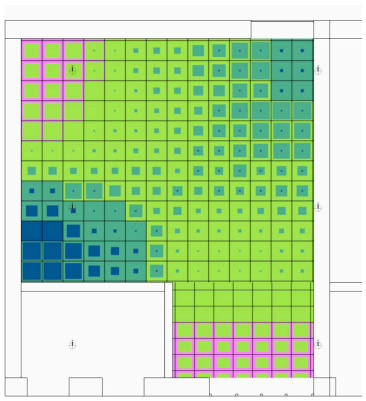


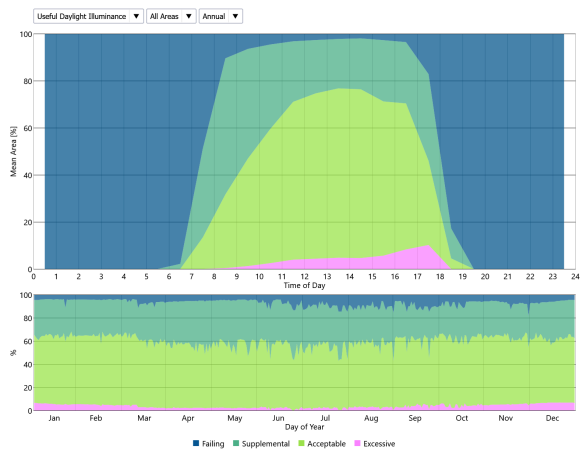
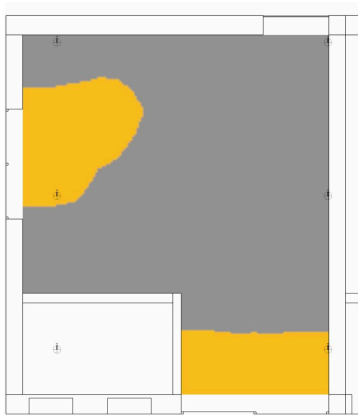


Fig : Useful daylight illuminance

Fig : Useful daylight illuminance

Scenario 4: West Wall Window Moved to Center with Louvers

In this case, the west window is situated at the middle of the wall and was provided with louvers meant for blocking sunlight. The following results were obtained: 70.1% of time floor area achieved daylight autonomy. 82.2% of them have been classified as daylight autonomous. Overexposure increased, reaching 23%, which is beyond the acceptable limits. The result was good daylight autonomy but with exceptionally high overexposure. It was thus felt that while louvers did enhance light penetration, they were incapable of regulating solar heat gain-a trade-off between shading and daylight was necessary.



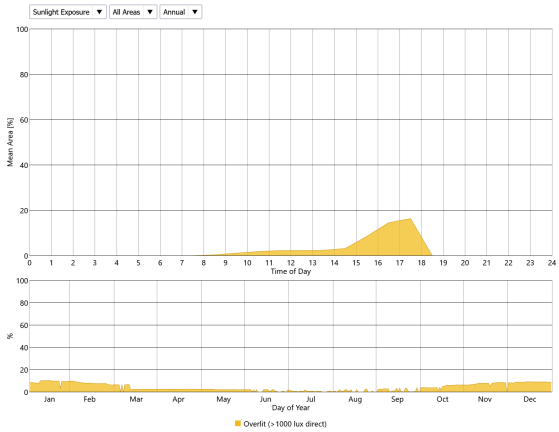
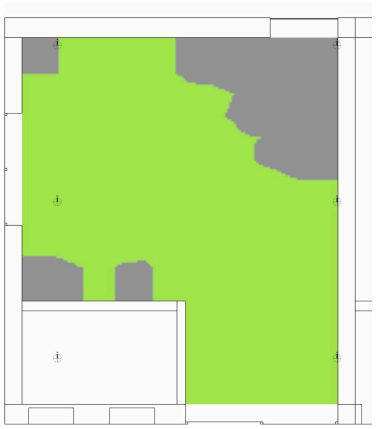


Fig : Sunlight exposure plan view

Fig : Sunlight exposure Chart



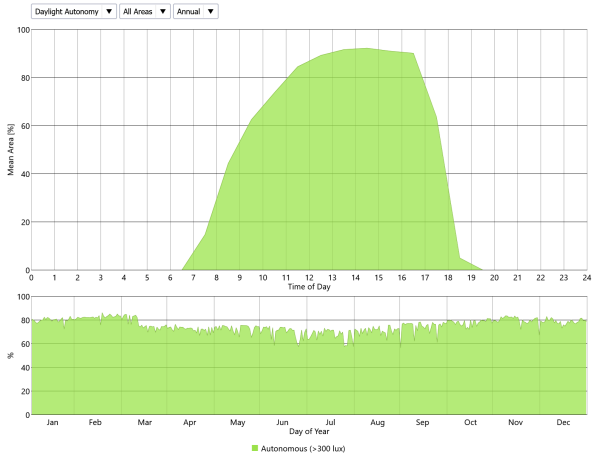
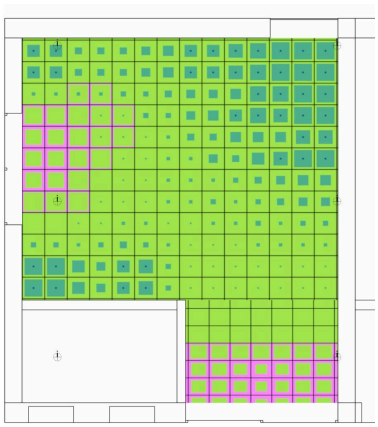


Fig : Daylight autonomous

Fig : Daylight autonomous



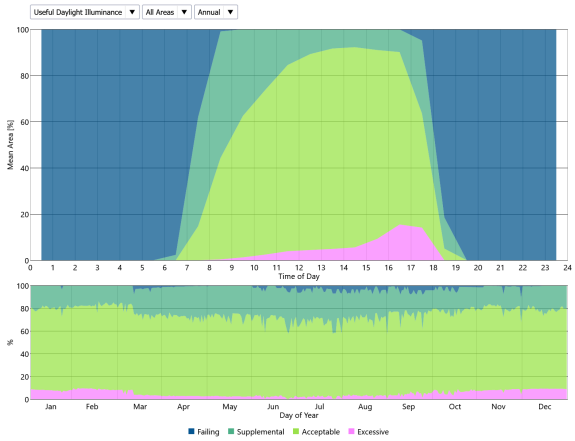


Fig : Useful daylight illuminance

Fig : Useful daylight illuminance

Scenario 5: Windows with Louvers and Shading Devices

In the above case, installation of louvers and shading devices on the bigger window improved the sunlight control as illustrated below:

50.7% of the time, the floor area met the daylight benchmark. 57% of the areas were defined as daylight autonomous. Overexposure was controlled at 10.6%, which is slightly over the recommended 10%. Although daylight autonomy was reduced from the previous scenario, this configuration was able to minimize overexposure to a threshold value. Further, the demand for artificial lighting reduces, improving 2 kWh/m² on EUI. Including shading devices can achieve an effective balance between daylight and energy efficiency in this scenario.

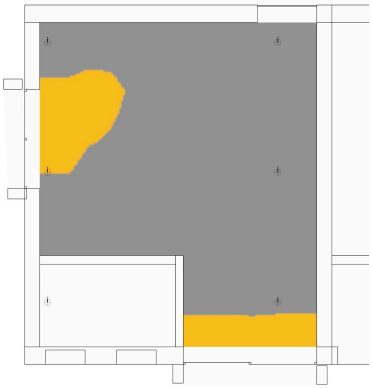


Fig : Sunlight exposure plan view

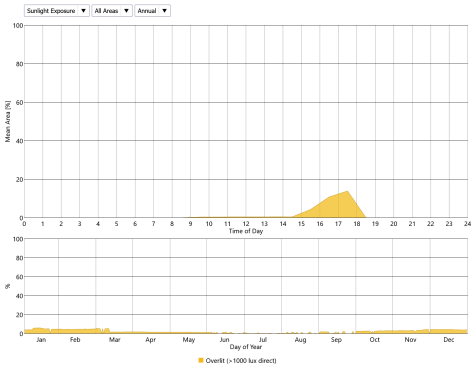
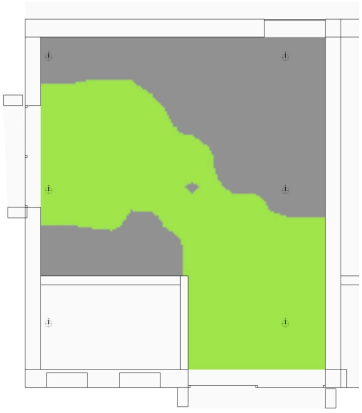


Fig : Sunlight exposure Chart



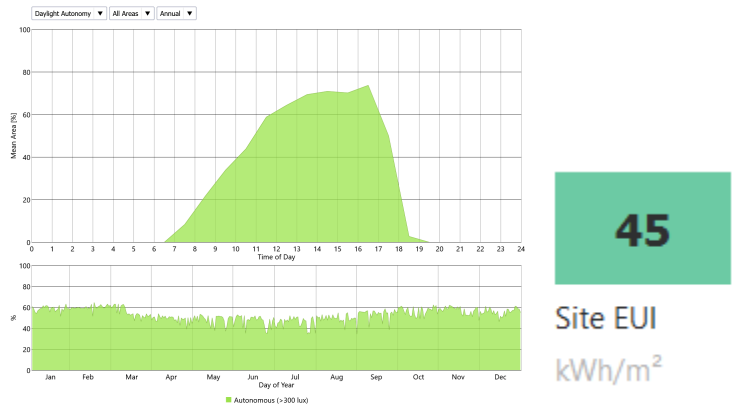
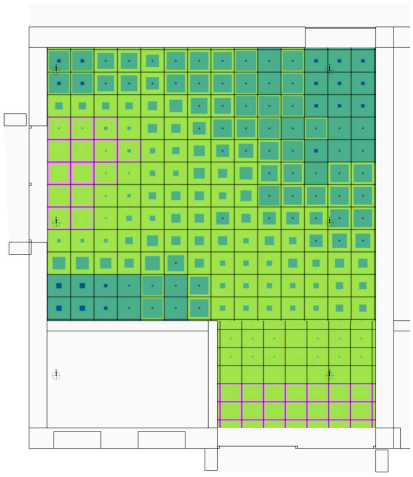


Fig : Daylight autonomous

Fig : Daylight autonomous



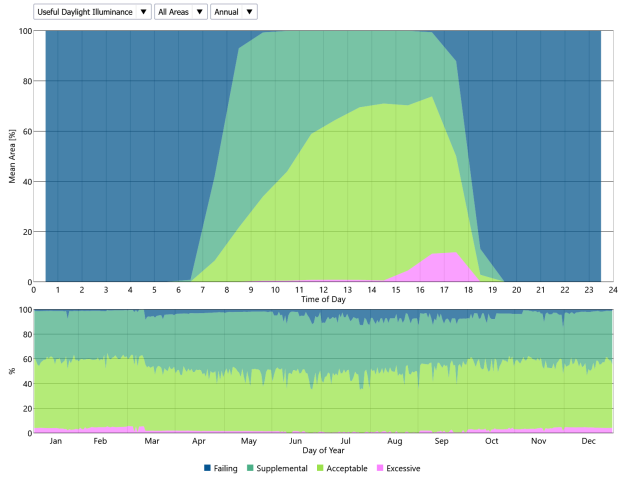


Fig : Useful daylight illuminance

Fig : Useful daylight illuminance

Use of Sustainable and Durable Window Materials

- Along with these design modifications, the replacement of low-quality materials with some affordable, durable substitutes like recycled aluminum and treated bamboo was considered. These considered daylight effects include:
- Daylight impact: There is not much variation in daylight performance; however, these materials provided better insulation.

- Thermal impact: New materials provided improved thermal insulation by reducing heat transfer through window frames.
- Energy impact: Higher insulation - thus even lower cooling energy consumption.
- Long-term value comprises the incorporation of durable materials that reduce the need for future repairs, ensuring cost and environmental sustainability for the house over time.

5. Conclusions

This research developed optimized window designs for slum rehabilitation housing in Mumbai, with prime consideration to daylight autonomy, natural ventilation, and thermal comfort. This is achieved through the integration of BIM with simulation tools like Rhino and Climate Studio by testing several design scenarios considering their capacity to enhance indoor environmental quality.

Increasing the WWR, combined with double-glazing and the use of shading devices, resulted in high daylight access with reduced energy consumption. Daylight autonomy reached 56.4% in the best case, which decreased the EUI by up to 2 kWh/m² in units oriented toward the southwest. While several cases showed overexposure from sunlight exceeded recommended limits, the inclusion of louvers and shading became effective in reducing such situations and improving thermal comfort.

The research proved that good window design can actually help in solving the problems of overcrowding, inadequate air circulation, and excessive heat gain in the low-income houses, as in the case of Mumbai. This further ratifies the finding that BIM-based decision-making has the potential to engender sustainable, cost-effective changes in slum rehabilitation projects, thereby upgrading not just energy efficiency but overall quality of life for residents.

In this respect, the present study demonstrates that by thoroughly optimizing window location, size, and shading, important amelioration of indoor environmental conditions could be achieved in slum housing. These integrated strategies, using durable and sustainable materials, may provide a promising way toward improvement in living conditions in the low-income urban area, managing affordability with environmental responsibility.

6. Limitation

Despite such promising results, there are a few limitations that have to be recognized: The present research is based on a small-scale building where the energy savings potential could not be significant due to the intrinsically low energy demand of such building categories. This methodology might be greater in buildings of a larger scale. Geographical locations investigated were limited to the hot and humid climate of Mumbai. It limits the general applicability of the results to regions that have other climatic conditions. Moreover, in the study, visual comfort and lighting loads were not considered, which is an important issue in real applications. Finally, due to typical financial constraints of slum housing, only certain materials and design options were explored in optimizations and may have constrained the full potential of the optimization.

Future Research

Future research should investigate how the optimization of windows can be integrated into a more comprehensive planning of slum sites and urban layouts. More specifically, the focus should be on placing buildings ideally and shaping blocks strategically to optimize sunlight and airflow. The block distance and building orientation greatly affect window performance and indoor comfort. These designs need to be tested to assess their ability to adjust to various climates and larger scale development initiatives. Future research should consider visual comfort modeling and investigate how passive design strategies, such as roof insulation or strategic landscaping, can improve window design optimizations. In summary, thorough planning of slum revitalization needs to take into account elements like location and urban density in order to guarantee that the actions can be expanded and maintained efficiently.

Acknowledgement:

List of Figures:

Reference list

1. Abed, F.M., Omer Khalil Ahmed and Ahmed Ashour Ahmed (2018). Effect of climate and design parameters on the temperature distribution of a room. *Journal of building engineering*, 17, pp.115–124. doi:https://doi.org/10.1016/j.jobe.2018.02.007.
2. ADEQUATE HOUSING AND SLUM UPGRADING. (n.d.). Available at: https://unhabitat.org/sites/default/files/2020/06/indicator_11.1.1_training_module_adequate_housing_and_slum_upgrading.pdf.
3. Aklin, M., Bayer, P., Harish, S.P. and Urpelainen, J. (2015). Quantifying slum electrification in India and explaining local variation. *Energy*, 80, pp.203–212. doi:https://doi.org/10.1016/j.energy.2014.11.063.
4. Almeroth-Williams, T. (2020). *Fixing India's slum rehabilitation housing*. [online] University of Cambridge. Available at: https://www.cam.ac.uk/stories/indias-slum-rehabilitation-housing.
5. Bardhan, R. and Debnath, R. (2016). Towards daylight inclusive bye-law: Daylight as an energy saving route for affordable housing in India. *Energy for Sustainable Development*, 34, pp.1–9. doi:https://doi.org/10.1016/j.esd.2016.06.005.
6. Bardhan, R., Debnath, R., Jana, A. and Norford, L.K. (2018a). Investigating the association of healthcare-seeking behavior with the freshness of indoor spaces in low-income tenement housing in Mumbai. *Habitat International*, [online] 71, pp.156–168. doi:https://doi.org/10.1016/j.habitatint.2017.12.007.

7. Bardhan, R., Debnath, R., Malik, J. and Sarkar, A. (2018b). Low-income housing layouts under socio-architectural complexities: A parametric study for sustainable slum rehabilitation. *Sustainable Cities and Society*, 41, pp.126–138. doi:https://doi.org/10.1016/j.scs.2018.04.038.
8. Brager, G. and Baker, L. (2009). Occupant satisfaction in mixed-mode buildings. *Building Research & Information*, 37(4), pp.369–380. doi:https://doi.org/10.1080/09613210902899785.
9. Chi, F., Xu, Y. and Pan, J. (2022). Impact of shading systems with various type-number configuration combinations on energy consumption in traditional dwelling (China). *Energy*, 255, p.124520. doi:https://doi.org/10.1016/j.energy.2022.124520.
10. Cox, H., Escombe, R., McDermid, C., Mtshemla, Y., Spelman, T., Virginia De Azevedo and London, L. (2012). Wind-Driven Roof Turbines: A Novel Way to Improve Ventilation for TB Infection Control in Health Facilities. *PLOS ONE*, 7(1), pp.e29589–e29589. doi:https://doi.org/10.1371/journal.pone.0029589.
11. Field, M.J. and Institute Of Medicine (U.S.). Committee On Regulating Occupational Exposure To Tuberculosis (2001). *Tuberculosis in the workplace*. Washington, D.C.: National Academy Press.
12. GavaliHindavi R and RalegaonkarRahul (2019). Application of information modelling for sustainable urban-poor housing in India. 172(2), pp.68–75. doi:https://doi.org/10.1680/jensu.18.00015.
13. George, C.E., Norman, G., Wadugodapitya, A., Rao, S.V., Nalige, S., Radhakrishnan, V., Behar, S. and de Witte, L. (2019). Health issues in a Bangalore slum: findings from a household survey using a mobile screening toolkit in Devarajeevanahalli. *BMC Public Health*, 19(1). doi:https://doi.org/10.1186/s12889-019-6756-7.
14. Hisao Ishibuchi, Noritaka Tsukamoto and Yusuke Nojima (2008). Evolutionary many-objective optimization: A short review. *2008 IEEE Congress on Evolutionary Computation (IEEE World Congress on Computational Intelligence)*. doi:https://doi.org/10.1109/cec.2008.4631121.
15. Killemsetty, N., Johnson, M. and Patel, A. (2021). Understanding housing preferences of slum dwellers in India: A community-based operations research approach. *European Journal of Operational Research*. doi:https://doi.org/10.1016/j.ejor.2021.06.055.
16. Kim, S., Zadeh, P.A., Staub-French, S., Froese, T. and Cavka, B.T. (2016). Assessment of the Impact of Window Size, Position and Orientation on Building Energy Load Using BIM. *Procedia Engineering*, [online] 145, pp.1424–1431. doi:https://doi.org/10.1016/j.proeng.2016.04.179.
17. Kshetrimayum, B., Bardhan, R. and Kubota, T. (2020). Factors Affecting Residential Satisfaction in Slum Rehabilitation Housing in Mumbai. *Sustainability*, 12(6), p.2344. doi:https://doi.org/10.3390/su12062344.
18. Lai, P.-C., Low, C.-T., Tse, W.-S.C., Tsui, C.-K., Lee, H. and Hui, P.-K. (2013). Risk of tuberculosis in high-rise and high density dwellings: an exploratory spatial analysis. *Environmental Pollution (Barking, Essex: 1987)*, [online] 183, pp.40–45. doi:https://doi.org/10.1016/j.envpol.2012.11.025.

19. Lim, Y.-W., Seghier, T.E., Harun, M.F., Ahmad, M.H., Samah, A.A. and Majid, H.A. (2019). Computational BIM for Building Envelope Sustainability Optimization. *MATEC Web of Conferences*, 278, p.04001. doi:https://doi.org/10.1051/matecconf/201927804001.
20. Main. (n.d.). *MIT architects tackle India's slum problem*. [online] Available at: https://energy.mit.edu/news/mit-architects-tackle-indias-slum-problem/.
21. Marzouk, M., Mahmoud Bahi and El-Anwar, O. (2023). Optimizing Sanitation Network Upgrading Projects in Slum Areas. *Journal of Urban Health*, 100(4), pp.811–833. doi:https://doi.org/10.1007/s11524-023-00751-w.
22. Olumuyiwa Bayode Adegun (2023). Strategies for addressing exposure to extreme heat in a slum community. *Proceedings of the Institution of Civil Engineers. Municipal engineer/Proceedings of ICE. Municipal engineer*, pp.1–22. doi:https://doi.org/10.1680/jmuen.23.00022.
23. Pardeshi, P., Jadhav, B., Singh, R., Kapoor, N., Bardhan, R., Jana, A., David, S. and Roy, N. (2020). Association between architectural parameters and burden of tuberculosis in three resettlement colonies of M-East Ward, Mumbai, India. *Cities & Health*, 4(3), pp.303–320. doi:https://doi.org/10.1080/23748834.2020.1731919.
24. Prajakta Jangam and Vishakha Sakhare (2023). A way to sustainable development of a slum rehabilitation residential project through building information model. *IOP conference series. Earth and environmental science*, 1280(1), pp.012015–012015. doi:https://doi.org/10.1088/1755-1315/1280/1/012015.
25. Prasad Khanolkar (2022). *Passages of Play in Urban India*. Taylor & Francis.
26. Pučko, Z., Maučec, D. and Šuman, N. (2020). Energy and Cost Analysis of Building Envelope Components Using BIM: A Systematic Approach. *Energies*, 13(10), p.2643. doi:https://doi.org/10.3390/en13102643.
27. Pushpendra Kumar Chaturvedi, Kumar, N. and Lamba, R. (2024). Multi-objective optimization for visual, thermal, and cooling energy performance of building envelope design in the composite climate of Jaipur (India). *Energy & Environment*. doi:https://doi.org/10.1177/0958305x241228513.
28. Ronita Bardhan and Pan, J.-Y. (2023). The Why? How? What? and What-ifs of Mass Slum Rehabilitation Housing in India. *Routledge eBooks*, pp.254–275. doi:https://doi.org/10.4324/9781003191407-18.
29. Salgude, R.R., Shubham Dilip Sawant and Vishakha Sakhare (2024). Achieving low energy and low CO2 emission through effective application of window to wall ratio and window glass considering orientation. *Journal of Building Pathology and Rehabilitation*, 9(1). doi:https://doi.org/10.1007/s41024-024-00391-w.
30. Sarkar, A. and Bardhan, R. (2019). Optimal interior design for naturally ventilated low-income housing: a design-route for environmental quality and cooling energy saving. *Advances in Building Energy Research*, 14(4), pp.494–526. doi:https://doi.org/10.1080/17512549.2019.1626764.
31. Sarkar, A. and Bardhan, R. (2020a). Improved indoor environment through optimised ventilator and furniture positioning: A case of slum rehabilitation housing, Mumbai, India. *Frontiers of Architectural Research*, 9(2), pp.350–369. doi:https://doi.org/10.1016/j.foar.2019.12.001.

32. Sarkar, A. and Bardhan, R. (2020b). Socio-physical liveability through socio-spatiality in low-income resettlement archetypes - A case of slum rehabilitation housing in Mumbai, India. *Cities*, 105, p.102840. doi:https://doi.org/10.1016/j.cities.2020.102840.
33. Singh, S. and Venkatasailanathan Ramadesigan (2020). *Advances in Energy Research, Vol. 1*. Springer Nature.
34. TOWARDS ECO-NIWAS SAMHITA IMPLEMENTATION IN GUJARAT: BUILDING ENVELOPE SOLUTION SETS. (n.d.). Available at: https://www.beepindia.org/wp-content/uploads/2022/09/Building-Envelope-Solution-Sets-Implementation-Gujrat_web.pdf [Accessed 20 Sep. 2024].
35. Truong, N.-S., Duc Long Luong, Ngo, N.-T. and Quang Trung Nguyen (2023). Optimizing Envelope Design and Window Performance for Energy-Efficient Buildings Through Integration of Building Information and Energy Modeling (BIM-BEM). *Lecture notes in civil engineering*, pp.584–595. doi:https://doi.org/10.1007/978-981-99-7434-4_60.
36. Waziri, A. (n.d.). TOWARDS FIRE SAFETY AND SECURITY IN GRILLS HOUSING: A REVIEW OF APPROOACH. *www.academia.edu*. [online] Available at: https://www.academia.edu/2581005/TOWARDS_FIRE_SAFETY_AND_SECURITY_IN_GRILLS_HOUSING_A_REVIEW_OF_APPROOACH.
37. WHO consolidated guidelines on tuberculosis. Module 4. (2022). World Health Organization.
38. Wood, R., Morrow, C., Ginsberg, S., Piccoli, E., Kalil, D., Sassi, A., Walensky, R.P. and Andrews, J.R. (2014). Quantification of Shared Air: A Social and Environmental Determinant of Airborne Disease Transmission. *PLoS ONE*, 9(9), p.e106622. doi:https://doi.org/10.1371/journal.pone.0106622.
39. World Health Organization (2019). *Global Tuberculosis Report 2019*. S.L.: World Health Organization.
40. World Health Organization (2023). *Global tuberculosis report 2023*. World Health Organization.
41. World Health Organization (2024). *The top 10 causes of death*. [online] World Health Organization. Available at: https://www.who.int/news-room/fact-sheets/detail/the-top-10-causes-of-death.
42. www.sra.org.uk. (2019). *Reporting and Notification Obligations - Guidance*. [online] Available at: https://www.sra.org.uk/solicitors/guidance/reporting-notification-obligations/.