A multi-faceted retrofit aimed at enhancing livability in Slum Rehabilitation Housing (SRH) in Mumbai, India addressing health and safety, while fostering community empowerment through affordability and sustainability.
Background

Cotton Mills pioneered the industrial landscape of Mumbai and India.

Several people lost livelihoods due to industrialization and modernization.

Lack of jobs and high living costs push several people to slums.

Slums are redeveloped into Slum Rehabilitation Housing.
Target Market

Rehabilitated Slum Dwellers in Mumbai, India

10.7 million (52.5 %)

20.5 million (total)

520,645

proposed rehabilitation houses[1]

< $7,200

annual household income [2]

74%

population falls under LIG [3]

Context

Commercially Developed Buildings

Selected Site

Slum Rehabilitation Housing (SRH)
Site Context

- G+9 Stories
- Ground floor commercial
- 10 dwellings per floor
- Total 90 households
- 4-6 residents per household
- 225 ft² habitable area
Testimonials

Small and congested apartments

“Sometimes, its more comfortable outside the house than inside”
- Altaf (Taxi Driver)

“Likes are on during daytime”
- Moolchand (Contractor)

“Kids don’t have any spaces for playing and outdoor activities”
- Mahesh (Local Community Leader)

“We women have no space for social interaction”
- Sarita (Homemaker)

Lack of community and green spaces

“Our family of six can barely move around in this dark room”
- Kamlesh (Software Engineer)

“Kids don’t have any spaces for playing and outdoor activities”
- Mahesh (Local Community Leader)

“Lights are on during daytime”
- Moolchand (Contractor)
Health & Safety Stressors

Respiratory Health
- Pollutants
- Foul Smells

Mental Health
- Open spaces
- Sky view factor

Visual Health
- Eye Strain
- Productivity
Design Goals

Improve the quality of life by supporting healthy, safe, and comfortable habitats, while promoting public spaces that empower and build resilience within all members of the community.

Health & Safety
Sustainability
Empowerment
Design Goals

Health & Safety
- Daylight Autonomy
- Air Changes per Hour
- Fire Safety

Sustainability
- Energy Efficiency
- Access to Clean Water
- Economic Resilience

Empowerment
- Feasibility & Affordability
- Inclusive Public Spaces
- Universal Accessibility
Spatial Reconfiguration

Architecture

Habitable Area per apartment

- 225 ft²
- 360 ft²

Fire Escapes

- 0
- 2

Daylight Autonomy

- 10%
- 45%
Structural Analysis

- a. UPV on slab
- b. Carbonation depth
- c. Grid for Rebound hammer
- d. Rebound hammer on column
- e. Visual inspection – Debonding of plaster

Axial Force - Earthquake Load (IS 1893-2016)

Plate Stress - Wind & Live Loads (IS 875-3:2015)
Structural Limitations

**Worst 20%**

Iterations **Removed**
Void Strategy

Structural Limitations
Worst 20% Iterations Removed

Natural Ventilation
Best 20% Iterations Selected

Daylight Performance
Top 5% Iterations Selected

Architecture | Health | Efficiency
<table>
<thead>
<tr>
<th>Void Strategy</th>
<th>Architecture</th>
<th>Health</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural Limitations</td>
<td>Natural Ventilation</td>
<td>Daylight Performance</td>
<td>Energy Demand</td>
</tr>
<tr>
<td>Worst 20% Iterations Removed</td>
<td>Best 20% Iterations Selected</td>
<td>Top 5% Iterations Selected</td>
<td>Best 3 Iterations Analyzed</td>
</tr>
</tbody>
</table>
Material Selection

R-Values

Wall
2.22
(K-m²)/W

Roof
2.5
(K-m²)/W

Window
0.38
(K-m²)/W

Foundation
4.5
(K-m²)/W
Climate Profile

**Climatic zone**
0A  
(tropical warm-humid)

**Cooling setpoint**
25°C

**Relative humidity**
50%

**Cooling degree days**
1611
**HVAC Details**

**Sensible load:** Dew membrane  
**Location:** Building level  
**Capacity:** 28.5 TR  
**Vacuum pressure:** 4.3 kPa  
**Area:** 16.64 m²

**Latent load:** Membrane dehumidifier  
**Location:** Dwelling level  
**Capacity:** 0.3 kW  
**Vacuum pressure:** 0.8 kPa  
**Area:** 0.36 m²

**Latent load:** Dew membrane  
**Location:** Floor level  
**Capacity:** 2.7 kW  
**Vacuum pressure:** 4.3 kPa  
**Area:** 0.6 m²

**Membrane Dehumidification Module**

**Vacuum insulated chamber**  
**Capacity:** 26.6 TR  
**Chilled water inlet temperature:** 25 °C  
**Water outlet temperature:** 13 °C
HVAC Details

Energy Savings
7.4 > 3.8
High COP

60-85% Water vapour line
Annual Energy Savings

Environmental Impact
Water as Refrigerant
Dew-humidifier
Non-Toxic
Zero GWP & low ODP
43.5% lower operational carbon emissions

Vacuum insulated chamber
Vacuum pump
Dew-humidifier
Chilled water supply line
Chilled water return line
Daily water demand

60,000 liters per day

Grey Water (70-80%)

35,000 liters per day

Treated Water (50-60%)

15,000 liters per day

Water Efficient Fixture
UIPC 3☆ Rated

Grey Water Recycling

Rain Water Harvesting

Required Freshwater

202 ton CO$_2$e
Emissions Avoided
Energy Demand Reduction

Energy Savings (%)

- Lights: 42%
- HVAC: 50%
- Water Purifier: 30%
- Washing Machine: 36%

Annual Energy Demand (MWh)

- Base Case: 218.01 MWh
- Proposed Case: 120.87 MWh

Energy (kWh)

<table>
<thead>
<tr>
<th>Energy Demand Reduction</th>
<th>Engineering</th>
<th>Efficiency</th>
<th>11,169.00</th>
<th>1,971.00</th>
<th>95,812.50</th>
<th>27,271.75</th>
<th>8,212.50</th>
<th>1,387.00</th>
<th>47,939.04</th>
<th>15,143.51</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Washing Machine</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Purifier</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HVAC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lights</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Net Positive Energy

<table>
<thead>
<tr>
<th></th>
<th>Min</th>
<th>Average</th>
<th>Max</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Loads</strong></td>
<td>261.44</td>
<td>312.14</td>
<td>409.28</td>
<td>120,866.19</td>
</tr>
<tr>
<td><strong>Generation</strong></td>
<td>32.54</td>
<td>387.50</td>
<td>684.00</td>
<td>141,439.90</td>
</tr>
<tr>
<td><strong>Feed-in To Grid</strong></td>
<td>0</td>
<td>31.517</td>
<td>285.032</td>
<td>11503.822</td>
</tr>
<tr>
<td><strong>Consumption-From-Grid</strong></td>
<td>0</td>
<td>59.401</td>
<td>296.991</td>
<td>21681.427</td>
</tr>
</tbody>
</table>

**Energy (kWh)**

**Generation**

- Min: 261.44 kWh
- Average: 312.14 kWh
- Max: 409.28 kWh
- Total: 120,866.19 kWh

**Loads**

- Min: 261.44 kWh
- Average: 312.14 kWh
- Max: 409.28 kWh
- Total: 120,866.19 kWh

**Feed-in To Grid**

- Min: 0 kWh
- Average: 31.517 kWh
- Max: 285.032 kWh
- Total: 11503.822 kWh

**Consumption-From-Grid**

- Min: 0 kWh
- Average: 59.401 kWh
- Max: 296.991 kWh
- Total: 21681.427 kWh

**Graph**

- Y-axis: Energy (kWh)
- X-axis: Months from January to December
- Colors:
  - Generation
  - Loads
  - Feed-in To Grid
  - Consumption-From-Grid
Smart Demand Management

Data Input
- Temperature
- Humidity
- Occupancy & events
- Historical trends
- Renewable production

Processed Data
1. Linear regression
2. Feature engineering
3. Random forest
4. Light-gbm

Demand Prediction
- Market pricing

Maximize Renewable Energy Generation
- Smart meter for feedback
- Missing data imputation
- Identify trends

Minimize Grid Dependence
- Leverage Cost-Saving Strategies
- Load Shifting
Reducing Grid Dependency

Grid Interactivity

- Efficient Battery Use
  - Smart demand management system to minimize cost by effective battery use
  - Off-peak hours to charge battery for least cost

- Smart Energy Meter
  - Can be used for real-time energy pricing

- Peak Hour Power
  - Reducing dependency on the grid by leveraging PV and battery power

Demand Shifting
- Shifting the manageable loads to off-peak hours
Building Demand Response **without** Smart Energy Management System

<table>
<thead>
<tr>
<th>Time slot</th>
<th>Tariff (cents/kwh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 am to 9 am</td>
<td>nil</td>
</tr>
<tr>
<td>9 am to 12 pm</td>
<td>9.82</td>
</tr>
<tr>
<td>12 pm to 6 pm</td>
<td>nil</td>
</tr>
<tr>
<td>6 pm to 10 pm</td>
<td>19.64</td>
</tr>
<tr>
<td>10 pm to 6am</td>
<td>-14.73</td>
</tr>
</tbody>
</table>

Building Demand Response **with** Smart Energy Management System

**Demand Shift & Response**

**Grid Interactivity**
Resilience Strategies

Grid Disruption

3 Day Backup for Dwellings
- 92.88 kWh/day

7 Day Backup for Building critical loads
- 16.372 kWh/day

Essential Loads:
- Lights
- Fans
- Power Sockets

Critical Loads:
- Elevator
- Pump
- Corridor Lights

Grid Interactivity

PV Failure
- Failure Rate of 0.05% per year

Battery Failure
- Lead acid can be easily replenished

Battery charge at beginning: 725 kWh
Battery charge (total) = 92,872 kWh
Source EUI Reduction with Design Decisions

- Base case: 76.81 kBtu/ft²/yr
- Void strategy: 20.76 kBtu/ft²/yr
- Envelope optimization: -3.92 kBtu/ft²/yr
- Window & Shading: -3.92 kBtu/ft²/yr
- Appliances & Lighting: -3.92 kBtu/ft²/yr
- HVAC: 4% reduction
- Smart automation system: 15% reduction
- Solar cooking: 38% reduction
Cradle-to-Grave Emissions

Cumulative Annual Emissions

Total Carbon Emissions Avoided

6,819 ton CO₂e
Post-retrofit Life Cycle Emissions (40 years)

102 ton CO$_2$e

Sequestrated by Retrofit
Circularity

Renewable Sources

Agrocrete Blocks
AgriBioPanel
Cork Insulation

Rainwater Harvesting

Samsara

Services

uPVC Double-glazed Window

Structural Steel

Reuse
Recycle

Grey Water

Demolition Waste

Manufacturing

Raw Materials

Finite Sources

Life Cycle

33
Payback Period

Total Investment in Retrofit Process: $0.44 million

Lifetime Savings in Net Present Value (8% Interest): $0.44 million

Investment cannot be recovered only from savings within realistic time.

Proposed Rent: $35 - $40

Payback Period: 10 years
### Payback Period

<table>
<thead>
<tr>
<th>Market</th>
<th>Life Cycle</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Construction cost of retrofit</strong> $17.6/ft$^2</td>
<td><strong>Total Investment in Solar Cooking</strong> $9,980</td>
<td><strong>Communal Kitchen Payback</strong> 3 Years</td>
</tr>
<tr>
<td><strong>Total investment for retrofitting</strong> $438,206</td>
<td><strong>Investment in HVAC Systems</strong> $35,273</td>
<td><strong>Central HVAC Payback</strong> 9 Years</td>
</tr>
<tr>
<td><strong>Complete payback of retrofitting considering revenues</strong> 10 Years</td>
<td><strong>Investment in PV Systems</strong> $91,880</td>
<td><strong>On-site Energy Payback</strong> 13 Years</td>
</tr>
<tr>
<td><strong>Demolition and Waste Processing</strong> End of Life 40 Years</td>
<td><strong>1,539 ton CO$_2$e avoided by Solar Cooking</strong></td>
<td><strong>1,281 ton CO$_2$e avoided by HVAC Retrofit</strong></td>
</tr>
<tr>
<td><strong>6,147 ton CO$_2$e avoided by On-site Generation</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Retrofit vs New Construction

Life Cycle Carbon Emissions (Cradle-to-Grave)

- **Existing Case (30 years)**
  - Embodied Carbon: 2927.2 ton CO₂e
  - Operational Carbon: 105.7
  - Total: 3033.9

- **Retrofit (40 years)**
  - Embodied Carbon: -356.0
  - Operational Carbon: 3199.4
  - Total: 3543.4

- **New Construction (50 years)**
  - Embodied Carbon: -445.0
  - Operational Carbon: 2584.8
  - Total: 2139.8

Core and Shell Construction Cost

- **Retrofit**
  - HVAC System: $8854.9
  - Core Cutting: $105.7
  - Demolition: $216.6

- **New Construction**
  - HVAC System: $438,206
  - Core Cutting: $1,272,496

- 8% less CO₂ emissions
- 67% more expensive

$438,206

$1,272,496
Design Impact

Community | Health | Efficiency

<table>
<thead>
<tr>
<th>Cooking Fuel</th>
<th>Lighting</th>
<th>Open Spaces</th>
<th>Thermal Comfort</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRHns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slums</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Cost of utilities:
- SRHns: $240/yr
- Slums: $540/yr

Quality of life:
- SRHns: Poor
- Slums: Worse
**Summary**

### Passive Performance
- **Ventilation**: 1 to 4 ACH
- **Daylight Autonomy**: 10 to 45% Hours
- **Envelope**: 28% less load

### Energy Performance
- **Generation**: 143 MWh
- **Consumption**: 120 MWh
- **Net +ve Energy Building**

### Net Carbon Offset
- **79.5%**: On-site PV Generation
- **19.9%**: Solar-powered Cooking
- **Net +ve Carbon Retrofit**

### Water Savings
- **80%**: IGBC Net-Zero Water Building

### Construction Timeline
- **3 months**: Structural Additions & Repairs
- **6 months**: Constructing New Dwelling Units
- **1 months**: Shifting Tenants within the Building
- **2 months**: Demolition of Poor-performing Units
- **2 months**: Creating Community Spaces

### Affordability
- **Monthly Income to Mortgage Ratio**: 10% to 55%

### Project Summary
- **Location**: Mumbai, India
- **Location**: Mumbai, India
- **Climate Zone**: 0A (Coastal Warm-Humid)
- **Lot Size**: 5,509 ft² (512 m²)
- **Dwelling Size**: 360 ft² (33.5 m²)
- **Building Size**: 66,700 ft² (15 stories)
- **Occupancy**: 450 people (148 ft²/person)

### Source EUI (kBtu/ft²/yr)
- **Without Renewables**: 20.76
- **With Renewables**: -3.92

### HVAC Systems
- **Membrane based Heat Pump System**: 28.5 TR
- **Membrane Dehumidifier**: 1.5 TR
- **Refrigerant**: Chilled Water
Thank you!

Questions?
Circulation space = 26.6%
## Free Plan Concept

### Architecture

<table>
<thead>
<tr>
<th>Description (for a given floor)</th>
<th>Before retrofit</th>
<th>After retrofit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doors</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Windows</td>
<td>20</td>
<td>32</td>
</tr>
<tr>
<td>External walls</td>
<td>124 m</td>
<td>96 m</td>
</tr>
<tr>
<td>Internal walls</td>
<td>148 m</td>
<td>162 m</td>
</tr>
</tbody>
</table>
Sections

Architecture

Key plan

Section 1

Section 2
Envelope Details

Existing Assembly

Retrofit Assembly

Retrofit Assembly - External wall

Retrofit Assembly - Roof slab
Climatic Conditions

Appendix A

Urban CFD Analysis

Sunlight Hours

1 JAN 1:00 - 31 DEC 24:00
Hourly Data: Wind Speed (m/s)
Calm for 19.58% of the time = 1715 hours.
Each closed circle is equal to 0.9% = 75 hours.
Building Code Considerations

Min Water Demand
Water Supply System Sizing
Wastewater & Sewage
- CPEEHO, UPCI, Mumbai DCR

Fire Escapes
System Specifications
Water Tanks & Sprinklers
- NBC, Mumbai DCR

Spatial Dimensions
Min Habitable Area
Structural Specifications
- NBC, IS 456, 10262

Min Lighting Requirements
Min Appliance Ratings
- ECBC, BEE

Air Changes per Hour (ACH)
Recommended Air Flow Rate
Min Window Areas
- NBC, CSIR, ECBC

Wall-Window Ratio
Infiltration Rate
U-values & SHGC
- LEED, ECBC, ENS
Floor Plan Iterations

Appendix C

- Base Case = 60% area of all DUs are underlit (<300 lux)
- Iterations reduce underlit areas to only 28%
- Final Proposal:
  - 10 DUs per floor
  - Avg underlit area < 20%
  - 60% walls retained
Our focus is primarily on:

- Second-life Materials
- Circularity
- Social Life Cycle Assessment

**System Boundary**

<table>
<thead>
<tr>
<th>Technical</th>
<th>Geographical</th>
<th>Temporal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cradle-to-Grave</td>
<td>Material procurement: Local Sources</td>
<td>GWP over a Lifespan of 40 years</td>
</tr>
</tbody>
</table>

**Limitations of Study**

- **Impact Coverage**
  - Life Cycle Carbon 40 Years of GWP

- **Methodological**
  - Data Sensitivity Unavailability of Data

- **Assumption**
  - Labor Intensive Construction (7% of materials phase)
Market Potential

Appendix E

**Replicability**
- Light house projects
- Consuming local resources

**Scalability**
- Affordable housing schemes
- Modular construction

**Limitations**
- Skilled labor
- Space constrained