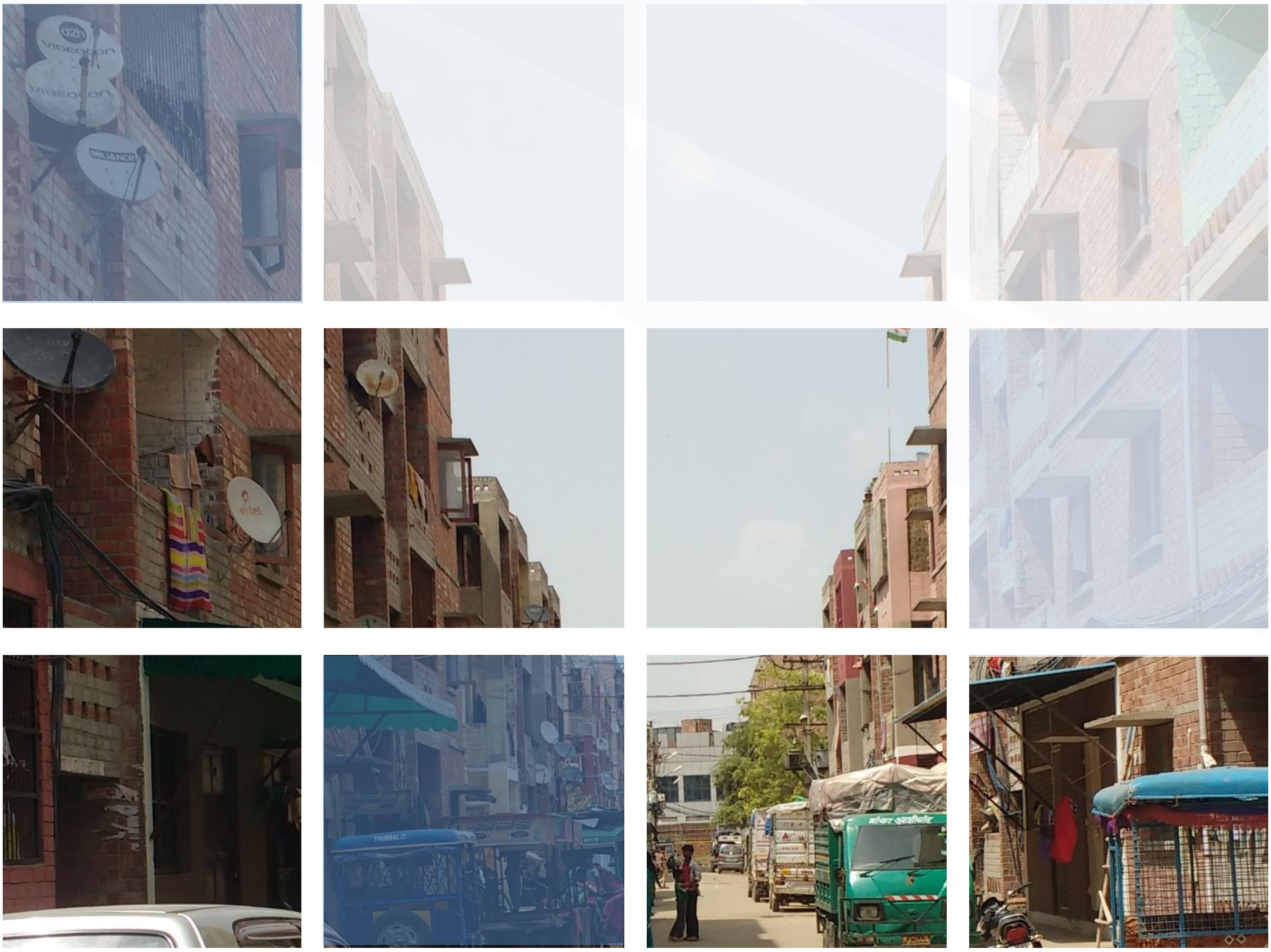
# Mainstreaming Sustainable Social Housing in India

## Findings and insights from the MaS-SHIP project



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# Acknowledgements

The MaS-SHIP team would like to thank the United Nations Environment's Sustainable Buildings and Construction Programme of the 10 Year Framework Programme (10YFP) for financially supporting this research. We would also like to acknowledge the support provided by members of the Multi-Stakeholder Advisory Committee of the SBC programme.

A large number of stakeholders in India have been part of the journey of developing the Decision Support Toolkit (DST) and the various tools embedded in it. Architects, habitat planners, housing developers, academics, NGOs working in social housing, students, professionals from housing finance and officers of the Government of India have actively participated in the various stakeholder workshops conducted over the past two years. Their critical assessment has helped in guiding the project to maintain its relevance in the Indian housing market.  We are grateful to all.

We are especially grateful to our project advisory group and technical reviewers - Dr Sameer Maithel and Prof Ashok Lall, who took time to critique the project, share knowledge and ensure that the clarity and quality of project outputs was maintained.

We would like to show our deep appreciation for Mr. Pramod Adhlakha (Adhlakha and Associates) and Mr. Arnab Gazi (B3B Group) for their constant support to this project. This project has been able to reach 750 householders across five cities in India to develop an empirical understanding of user perceptions of building materials and construction systems. This has been possible through the efforts of the students and academics from Vastu Kala Academy (Delhi); Jagannath University (Jaipur), Dehradun Institute of Technology (Dehradun); Vaishnavi School of Architecture (Vijaywada) and Impact School of Architecture (Bangalore), who conducted household surveys for the five housing case studies.

In a data poor environment, the support from building material manufacturers especially from Schnell Homes and Supertech Ltd. was admirable. This indicates the immense value of product disclosures to advance sustainability in the housing construction sector. We are especially thankful to Apurva Singh and Pankaj Khanna from DA for their help in gathering field data.

Finally, we would like to express our appreciation to the Building Materials and Technology Promotion Council (BMTPC) and the Ministry of Housing and Urban Affairs of the Government of India who have been following the development of this project and provided valuable guidance to the project.

# Foreword

The Sustainable Development Goals Target 11.1 seeks to “By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums”. The Housing for All by 2022 mission of the Government of India is a step towards achieving this target. The overall residential construction demand is expected to increase more than fourfold over 2005 levels as a result of meeting the urban housing shortage.

Mainstreaming Sustainable Social Housing in India project (MaS-SHIP) is a research project funded by the United Nations Environment’s 10 Year Framework Programme (10YFP), that aims to identify what the impacts and benefits of housing production at scale, such as that of the Housing for All by 2022 mission, could be – for our environment, our economy, and our communities – and to provide a method for identifying the most optimal building materials and systems.

MaS-SHIP project has been undertaken by the Low Carbon Building Research Group at Oxford Brookes University (UK), The Energy and Resources Institute (TERI), Development Alternatives and the United Nations Human Settlements Programme (UN-Habitat).

MaS-SHIP research has developed a toolkit that enables building practitioners, housing developers and policy-makers to make informed decisions for selection of sustainable building materials, systems and design strategies for social housing projects. The Decision Support Toolkit (DST) enables multi-criteria decision making to provide comparative assessment. In addition, the systematic documentation of resident experiences of living in social housing developments has helped to better understand the preferences and concerns of the residents.

This publication produced by the four consortium partners elaborates the methodology adopted for arriving at the outcomes and provides links to DST for its easy implementation. It also proposes and discusses the policy implications of mainstreaming sustainable social housing in India and the utility of the DST in supporting these endeavours.

I congratulate the consortium partners for their in-depth analysis and for providing evidence-based solutions for bridging the existing gap in an inherently data poor environment. It is clear that planning and design of social housing should require more resident participation so that design intentions are achieved in reality. I urge the building practitioner community to not only use the MaS-SHIP toolkit, but also help in augmenting its capability by further populating it with newer building systems.

Dr Shailesh Kr Agrawal
Executive Director
Building Materials Technology Promotion Council (BMTPC)

# Executive Summary

As the Government of India aims to construct 12 million social housing dwelling units through the *Housing for All* by 2022 programme, the pressure to deliver in a timely, and cost-effective way, will increase. It is vital to identify what the impacts and benefits of housing production at such a massive scale and speed could be, especially when currently sustainability is not effectively mainstreamed in social housing projects.

This report describes the wider context, objectives, methodology and findings of a two-year research project entitled MaS-SHIP. Funded by the United Nations Environment's Sustainable Buildings and Construction programme of the 10 Year Framework Programme. MaS-SHIP has produced a comprehensive data framework, tools, evidence-based knowledge, insights and policy recommendations for mainstreaming sustainable social housing in India. A socio-technical approach was adopted in the research, bringing together primary and secondary data collection with both quantitative and qualitative assessments, using literature review, stakeholder engagement, online and field surveys, statistical tests and thermal simulations. The construction and policy ecosystem were examined to identify barriers and opportunities in adopting sustainable building materials and related design and construction practices, so as to develop policy recommendations.

First, MaS-SHIP created a framework of 18 attributes in collaboration with developers, practitioners and academics to measure the performance of 17 established and emerging building systems, against four criteria, including *resource efficiency, operational performance, user experience,* and *economic impact*. The findings were collated into catalogues for each material, while the methodology for calculating the mix of qualitative and quantitative attributes were developed into a new data framework.

The multiplicity of attributes required rationalized valuations relative to each other. To establish consistency, inputs of a representative sample of housing experts in India were invited to weigh each attribute. That is, a widely accepted *Analytic Hierarchy Process* (AHP) was applied to survey 200 experts including project consultants, private and public housing providers, academics, manufacturers, and building practitioners.

New information was revealed on residents' experience with building materials and systems. Large-scale surveys showed that residents also influence the demand for sustainable materials - they were found to prefer less resource and operationally inefficient materials such as English-bond brickwork because such an option affords them greater flexibility to make in house adjustments such as nailing wall-hangings. Many residents also raised grievances about factors such as discomfort because of inadequate ventilation, and their homes being located away from employment opportunities.

A key output from MaS-SHIP research has been the creation of the Decision Support Toolkit (DST), an interactive and online toolkit comprising a range of outputs, datasets, tools and insights that can help prospective users in choosing sustainable building materials and making and monitoring sustainable design interventions and construction practices in social housing projects. The DST not only addresses the absence of a comprehensive measurement framework to assess sustainable materials, but also includes design guidelines to ensure sustainability is embedded at the conception stage of a housing project. Through the development of a Sustainability Assessment Tool (SAT), it fills missing data that is needed to quantify the performance, and using Material mapping application, spatially maps the availability of sustainable building systems options. As a key component of the DST, SAT has the capability to measure the relative performance of building materials and systems for social housing projects that do not exceed four stories, using the framework of 18 attributes. Filling these knowledge gaps can assist in prioritizing sustainability considerations in housing policy and implementation.

Finally, based on the research findings, the following recommendations are made for mainstreaming sustainability into social housing projects in India:

- Develop an Overarching Sustainable Housing Policy Framework that integrates resource and energy efficiency considerations with socio-economic parameters in urban contexts.
- Develop a data collection strategy to fill missing information on factors such as job creation potential for new technologies, based on interventions such as instituting mandatory disclosure, funding primary data collection efforts, and developing a centralized, open source database for constant updating.

- Incorporate sustainability requirements in state procurement guidelines as conditions for developers to win social housing contracts.
- Provide supply side subsidies and tax breaks to incentivize private financing and construction of sustainable social housing.
- Develop awareness programs for developers with a focus on sensitizing such actors to potential convergences between cost and efficiency considerations, with environmental benefits. Identify key materials and design practices that achieve such goals and link them to its potential benefit for their prospective customers – the residents of social housing dwellings.
- Systematically develop training programs and educational materials on sustainability which should be made available to urban local bodies.
- Develop training modules for developers, masons and unskilled construction workers to adopt better construction practices with a focus on ensuring basic design factors are implemented for resident comfort.
- Engage residents in design and planning through: awareness programs to sensitize residents to the value of sustainability and influence them to demand sustainable options from housing providers.
- Study resident needs in order to apply design changes to enhance comfort, and potentially allocate additional resources to empower residents in sustainably managing their homes.

# Glossary of terms

**Affordable Housing Finance Companies (AHFC)** are alternative financial institutions that target prospective homeowners that typically have poor access to financing from formal channels. AHFCs have been able to penetrate this sector through developing innovative models to assess the creditworthiness of applicants

**Analytic Hierarchy Process (AHP)** is an effective decision-making technique involving pair wise comparisons to arrive at relative weightings or order of preference. AHP helps a decision maker to capture both subjective and objective aspects of a problem.

**Belief** of a value for an alternative (building material or system) in a particular criterion is the minimum chance of that alternative being better than the other alternative in the same criterion.

**Belief function** i.e. Theory of belief functions or Dempster – Shafer's Theory (DST) is a general framework for reasoning with uncertainty. In MCDM, it assigns probabilistic values of belief, plausibility and uncertainty to data values.

**Building systems** refers to an integrated assembly of different building materials and components which fulfils structural requirements.

**Confidence interval** is an estimated range of values that are believed to contain the true value of population size with a specific probability.

**Confidence level** is the measure of reliability or the probability of an assumption to be true.

**Conflict of use** refers to the possibility of a finite resource being necessary for the functioning of two or more industries.

**Consistency ratio**- In AHP the judgements are checked for their consistency by calculating a ratio by dividing Consistency Index (CI) by Random Index (RI). If this ratio obtained for a judgement is greater than the prescribed value, implies that it is inconsistent and is disregarded.

**Data sampling** is a statistical analysis technique used to select a representative subset for a defined population size to identify patterns and trends in the larger data set being examined.

**Decision hierarchy** in AHP is organizing or breaking down a complex problem statement into layers to arrive at a defined goal for evaluating their relative importance.

**Decoupling** involves measures to separate the economic and social benefits that arise from activities such as industrial and housing development, from its environmentally deleterious impacts.

**Economically weaker section (EWS)** households are defined as households having an annual income of up to INR 3,00,000 (Rupees Three Lakhs/ Three Hundred Thousand). States and Union Territories have the flexibility to redefine the annual income criteria as per local conditions in consultation with the Central Government.

**Floor area ratio (FAR)** is the relationship between the total amount of usable floor area that a building has, or has been permitted for the building, and the total area of the lot on which the building stands. This ratio is determined by dividing the total, or gross, floor area of the building by the gross area of the lot. A higher ratio is more likely to indicate a dense or urban construction. Local governments use FAR for zoning codes.

**Housing shortage** is defined as the number of households in need of shelter/ a house and the households who need a liveable house. Housing shortage includes households living in obsolescent houses, non-serviceable katcha houses, congested houses needing new houses and households that are in homeless conditions.

**Lower income group (LIG)** households are defined as households having an annual income between INR 3,00,001 (Rupees Three Lakhs and one/ Three Hundred Thousand and One) up to INR 6,00,000 (Rupees Six Lakhs/Six Hundred Thousand). States and Union Territories have the flexibility to redefine the annual income criteria as per local conditions in consultation with the Central Government.

**Multi-Criteria Decision Making (MCDM)** is a process that evaluates differing criteria for an informed decision making. Amongst the various MCDM methods available, the ones used in MaS-SHIP are AHP and belief function based TOPSIS.

**Nominal ratio scale** is defined as the simplest scale used for the purpose of classification. The variables associated with the numbers are only for categorization with no quantitative connotation.

**Plausibility** of a value for an alternative (building material or system) in a particular criterion is the maximum chance of that alternative being better than the other alternative in the same criterion.

**Population size** is the appropriate statistical sample set extracted from the available set.

**Pradhan Mantri Awaas Yojana (PMAY)** was launched in June 2015 as a social welfare flagship program with an aim to provide affordable housing to urban poor. PMAY proposed to build 20 million (2 crore) houses for EWS & LIG in urban areas by the year 2022 through a financial assistance of ₹2 trillion (US$30 billion) from the central government.

**TOPSIS** stands for Technique for Order of Preference by Similarity to Ideal Solution. It is a MCDM method that enables selection of an alternative based on its geometric distance from the positive and negative ideal solution.

**Uncertainty** is the difference between plausibility and belief values i.e. the certainty regarding probability of a value of an alternative (building material or system) being better than the other in the same criterion.

**Weighting** is the measure of relative importance of an attribute with respect to the others.

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# Chapter 1

## Introduction to MaS-SHIP

## 1.1. Background and context

India is urbanising at a rapid pace and is projected to add 416 million new urban dwellers by 2050 (UN DESA, 2018). The majority of this is attributed to the growing rate of rural to urban migration, which in turn has rendered stress on the existing basic amenities and infrastructure. According to a recent estimate by the Ministry of Housing and Urban Affairs (MoHUA), the total urban housing shortage at the end of 2017 was about 10 million, with majority of this pertaining to the houses for the Economically Weaker Sections (EWS) and Low-Income Groups (LIG) (PIB Gov.of India MoHUA, 2017). Through its "Housing for All by 2022" mission, the Government of India intends to close this gap by aiming to construct 12 million housing units over the programme duration (2015-2022) through a combination of slum upgradation projects in partnership with the private sector, direct government-led housing delivery, a credit-linked subsidy scheme as well as support to beneficiary-led construction (MoHUA, Govt. of India, 2017). However, such a focus has multiple implications.

First, housing construction must factor in the environmental risks embedded in its processes. For example, increase in building construction is associated with a rise in energy consumption at an annual rate of 9% compared to the increase in overall national energy consumption of 4.3% (UN-Habitat, 2015a). Residential construction consists of the largest portion of this growth (AEEE, 2015). Continued energy consumption in an inefficient manner runs the risk of increased greenhouse gas emissions. Furthermore, the demand for raw materials, such as sand and soil, are expected to grow as construction rises. This can increase the risk of land and riparian degradation. Given the criticality of such resources in sustaining other sectors such as agriculture, increased competition can cause social conflict (Caleb et al. 2017).

Second, the speed at which housing is to be delivered must not only prioritise the provision of shelter at affordable rates, but also incorporate the adequacy of a home as well as the international Human Right to Adequate Housing, and include its seven criteria: tenure security, affordability, habitability, availability of services, accessibility, location, and cultural adequacy. This means housing policies and construction practices should account for multiple factors, including, inter alia, and access to basic facilities, infrastructure, and employment opportunities (UN-Habitat, 2017). Poor access to adequate housing is associated with several measures of well-being such as health and chronic poverty (UN-Habitat, 2015b).

Third, housing construction should harness the job creation potential of the construction sector. In 2013-2014, the real estate sector contributed to 6.3% of GDP and employed approximately 7.6 million people (Gopalan & Venkataraman, 2015). The sector's output value is expected to grow at a compound annual growth rate (CAGR) of 4.16% for the 2017-2021 period compared to 3.95% between 2012 and 2016 (Global Data, 2017). These projections are promising. However, rapid housing delivery may also involve utilization of less labour intensive, and more mechanized, and efficient building systems for construction. Neglecting the sector's potential could deepen the country's ongoing challenges with meeting the employment needs of the country's burgeoning youth population.

Furthermore, there is India's commitment at the global level regarding mitigating climate change and resource efficiency in particular. Also, under the 2030 Agenda for Sustainable Development that proposed 17 Sustainable Development Goals*, Goal 11: Make cities and human settlements inclusive*, *safe, resilient and sustainable* and *Goal 12: Ensure sustainable consumption and production patterns* - particularly focus on the impacts of the rapid pace of urbanisation and growth in the construction sector. While the Government of India has allocated tremendous resources to 'ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums, by 2030' (Goal 11-target 11.1), the delivery of less sustainable housing still represents a challenge to other sustainability dimensions. Although there is increasing knowledge about sustainable development in India, sustainability is yet to become mainstream in housing construction, evident by the limited uptake of alternative construction materials that are environment friendly and cost effective.

Given this context, the "Mainstreaming Sustainable Social Housing in India project (MaS-SHIP)" was designed to build upon work previously undertaken in the field of sustainable social housing globally and India in particular, while recognizing the priorities set by the Government of India, as well as their inherent constraints. In India, social housing is a rarely used term (Herda et al., 2017). Instead, government and the private sector typically use affordable housing to frame housing policy and practice. However, this term can be applied to any income group whereas social housing applies to a country's most economically vulnerable.

MaS-SHIP framed its studies within the parameters of social housing because it focused on India's

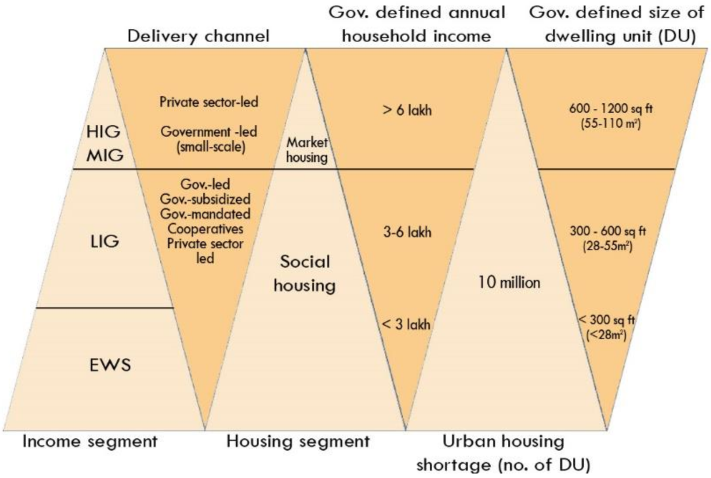

***Figure 1:*** *Social housing definitions as implied by the project*

poorest segments – the Economically Weaker Segments (EWSs) and Low Income Groups (LIGs) (Figure 1) – because the majority of the country's housing shortage, estimated to be between 10 million (MoHUA, 2017) to 12 million units (FSG, 2018) , is concentrated amongst such segments. It must also be noted that India's approach to providing social housing is different from typical strategies that involve one of, or some combination of, demand or supply side public subsidies for low income groups. Instead, Indian interventions consist of public sector, fiscal incentives along with policy frameworks and regulatory incentives, exemptions and relaxations to induce greater private sector supply. For example, the central government's PMAY initiative (MoHUA, 2017) consists of, inter alia, discounted loans to support prospective homeowners. In addition, many state governments have often relaxed land and building regulations to incentivize private developers to construct housing for low income groups (Herda et al., 2017).

The MaS-SHIP project has been funded by the Sustainable Building and Construction (SBC) Trust Fund which is one of the means of implementation of the Ten-Year Framework of Programmes on Sustainable Consumption and Production (SCP) Patterns (10YFP) managed by United Nations Environment (UNE). The goal of the SBC programme is to promote resource efficiency, mitigation and adaptation efforts, and the shift to SCP patterns in the buildings and construction sector of developing countries and countries with economies in transition.

The purpose of this report is to describe the aims, methods, findings and policy implications of the MaS-SHIP project.

## 1.2. MaS-SHIP aims and objectives

The MaS-SHIP project was designed to integrate sustainability in social housing projects in India through the adoption of sustainable building materials and systems, as well as design and management practices. To achieve this aim, the following objectives were set out to:

- Critically review housing, urban development and climate change related policies and programmes to define the drivers, barriers and opportunities for integrating sustainability in social housing in India
- Identify and select a set of 'attributes' to define the sustainability performance of 'established' and 'emerging' building materials and systems for social housing projects, in consensus with experts.
- Gather data from desk research and field surveys (with manufactures and practitioners) to assess the sustainability performance of selected building materials and systems against the 'attributes'.
- Conduct a nationwide (online) survey of leading experts from housing, sustainability and construction sectors to gather their opinions about relative weightings (importance) for the selected attributes.
- Undertake surveys with residents regarding their experience with building systems and perception of living in case study social housing developments, located in five cities across India covering different climatic zones.
- Develop and test interactive tools to enable developers, practitioners and policy-makers make informed decisions about integrating

sustainability in the design and specification of building systems in social housing projects.

- Produce policy implications and insights for mainstreaming sustainable social housing in India.

## 1.3. Methodological approach

The project adopted a socio-technical approach bringing together lessons from previous research, stakeholder engagement methods, with field surveys, statistical analysis and thermal simulation. A review of literature helped to define the extent and scale of challenges and opportunities for mainstreaming sustainability in social housing in India. It also helped to identify a list of established and emerging building materials and systems appropriate for the social housing sector, as well as attributes to assess their sustainability performance in terms of environment, resource efficiency, user experience and economic impact. The methodological approach is shown in Figure 2.

### • Literature review

An extensive review of relevant literature (policy documents, journal articles, reports) was conducted to analyse the problem of (social) housing shortage and provision in India, along with the Government's response at the national and state level. National and international case studies of social housing projects were used to derive learning that could positively influence the Government of India's prerogative to provide housing for all. The literature review helped to gather background evidence about policy drivers (and barriers) for integrating sustainability into low-income housing and the development of tools to help in making such decisions. It also informed the selection of attributes to evaluate sustainability performance of selected building materials and systems.

### • Stakeholder workshops

Stakeholder engagement through workshops formed a key research tool to gather collective opinions from experts during the course of the project. These events allowed an interactive exchange between the MaS-SHIP team, and various experts associated with the housing and sustainability sector. A total of eight stakeholder engagement workshops were held in three different cities in India at various stages of the project that led to engagement with 112 organizations that included policy-makers, academics, housing developers (public and private), building material manufacturers, architects, building consultants and the voluntary sector.

The stakeholder events attracted participants from various organizations working in the field of housing development in India. Some of the key participating organizations were:

- **Policy makers:** BMTPC, Bureau of Energy Efficiency (BEE), Housing and Urban Development Corporation (HUDCO), iCED, (An institute of CAG of India), National Buildings Construction Corporation (NBCC), MoHUA
- **Academia:** Indian Institute of Technology (IIT), Delhi, Jamia Millia Islamia Central University, Tata Institute of Social Sciences (TISS)

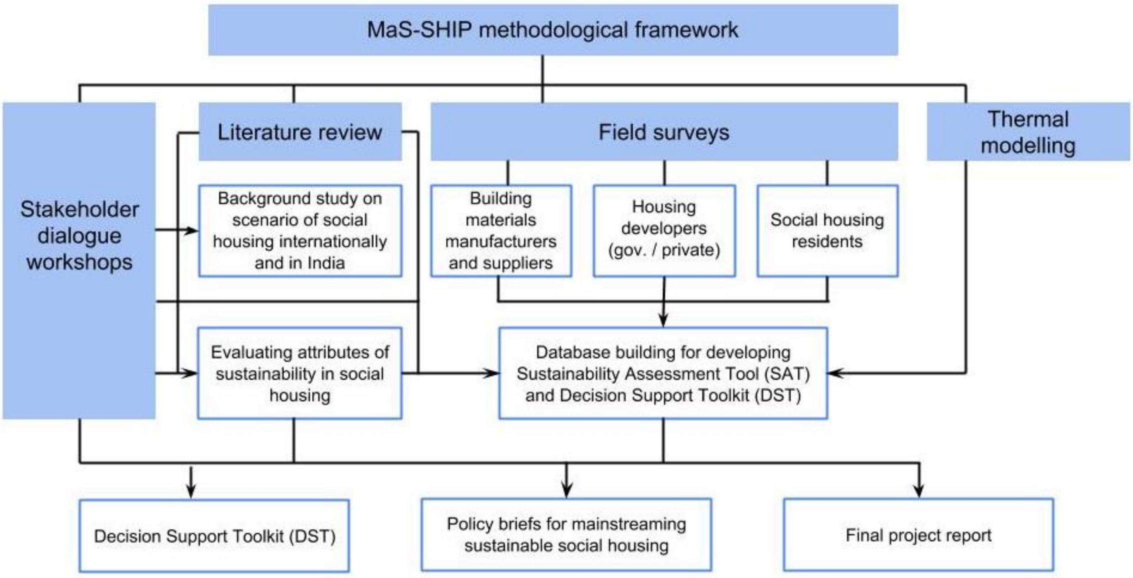

***Figure 2**: Methodological framework adopted for the research*

- **Building material manufacturers:** ACC Limited, Ambuja Cement Ltd., Supreme Petrochem Ltd.
- **Housing developers:** Adhlakha Associates Pvt. Ltd., Karnataka Slum Development Board, Mahindra Lifespace Developers Ltd.
- **Practitioners:** Aadyaaakaar & Ashok B Lall architects, Consulting Urban and Regional Planner, Bangalore, United Nations Development Programme (UNDP).
- **International agencies:** Indo-Swiss Building Energy Efficiency Project (BEEP), GIZ - Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH.
- **Voluntary sector:** GRIHA Council, Shakti Sustainable Energy Foundation.

The full list of 112 organizations that participated in the MaS-SHIP stakeholder events can be found in Annex 1.

Experts from nearly 25 state and national level policy making organizations of the country participated in seven stakeholder events. The events also saw participation from over 30 architectural firms and green building consultants and nearly 17 academic and research institutions who contributed at different stages of the project. Various organisations from voluntary sector working towards promoting sustainable practices in the Indian construction industry were also well-represented (Figure 3). Details about the purpose and outcomes of the stakeholder workshops are summarized in Annex 2.

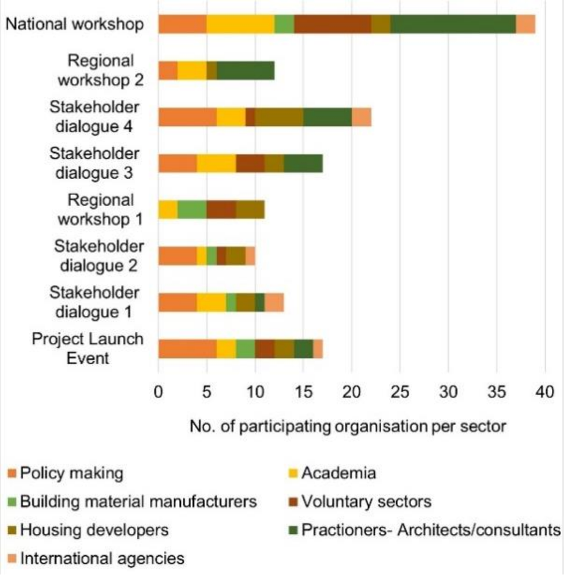

***Figure 3:*** *Level of participation at MaS-SHIP stakeholder events by different types of organizations*

## Surveys

In order to address the data gaps, primary data were gathered using interview-based questionnaire surveys to enumerate the qualitative and quantitative sustainability attributes of the selected building systems. Stakeholders included building practitioners (architects, consultants); building material manufacturers and social housing residents. An online survey of experts was also conducted to establish the relative weightings of the selected attributes of sustainability.

**Building practitioners (architects/consultants):** Seven interview-based surveys were conducted through face-to face meetings, telephonic conversations and email exchanges to collect data to populate the attributes underpinning SAT. The interview questions focused primarily on gathering data regarding the attributes - Current re-cycled content, Water usage during construction and manufacturing, durability, Ease and frequency of maintenance, Construction cost, supply chain, duration of construction and Job creation.

**Building material manufacturers:** Interview based surveys were also conducted with a total of twelve building material manufacturers to collected primary data on the attributes of critical resource use, current recycled content, construction costs, skill requirement and job creation. The manufacturers' survey went through a series of iterations based on pilot surveys conducted with fly ash brick manufacturers in Delhi and Uttar Pradesh.

**Social housing residents**: Field surveys with 723 householders were undertaken across five social housing developments (approximately 150 surveys per development) to gain insights about the experiences of residents with building systems and living environment in social housing developments. Five social housing developments in five different cities were identified for the purpose. The objective of the resident/householder survey was to gather feedback from residents about their experience of the building systems used in these dwellings and their perception of the indoor environmental conditions (indoor temperature and air quality) in their homes during summer and winter, along with aspects of maintenance and up-keep of the development familiarity with the building materials and access to basic day to day necessities around the development. The MaS-SHIP team collaborated with local architectural institutions to carry out the householder surveys. The gathered data were analysed using statistical methods to better understand the existing indoor environmental conditions in these dwellings during summer and winter periods.

**Online survey:** In order to assign relative weightings to selected attributes of sustainability, the project team conducted an online survey of experts relevant to the housing and sustainability sector in India. The respondents provided weightings to the selected attributes according to their preference or relative importance given to an attribute while selecting building materials and systems for any housing project. The survey was designed based on the Analytic Hierarchy Process (AHP), the details of while are elaborated in further in chapter 3. A total of about 200 responses were gathered, the statistical analysis of which allowed the project team to establish the relative weighting of the selected attributes. The three survey forms are available within the DST that is accessible on the MaS-SHIP website.

- **Thermal simulation**

To perform a comparative analysis of the cooling and/or heating energy savings potential of the selected building systems, thermal simulations were carried out to estimate the annual cooling or heating energy consumption (per unit area) of a case study social housing dwelling unit, for the five climatic zones in India. A dynamic thermal simulation engine - Design Builder which is based on EnergyPlus was used to perform the parametric analysis to compare the savings made in heating or cooling energy use by applying selected walling and roofing systems.

The dwelling unit was derived from one of the social housing case studies (Figure 4) and was modelled using conventional building systems (Base case), as shown in Table 1. About 16 building systems were assessed in comparison to the base case (Table 16, Annex 3).

Based on the ECBC climatic classification, five cities were chosen to represent the five climatic zones in India. The set-point for the operative room temperatures were calculated keeping in mind the higher adaptability of residents living in social housing developments and were assigned in accordance with the EN 15251 standards of adaptive thermal comfort ( Table 14, Annex 3).

A split air-conditioning HVAC system (COP-3.26) was modelled for cooling, and electric heater with efficiency of 0.9 was used for heating (Mastrucci and Rao, 2018). Occupancy and activity schedules were assumed from national standards, similar research and householders' survey data gathered as part of MaS-SHIP resident surveys (Table 15, Annex 3). Since the primary objective of the simulations was to compare the change (increase or decrease) in the cooling and/heating energy consumed due to the change in the building system (walling or roofing), the other parameters were kept constant.

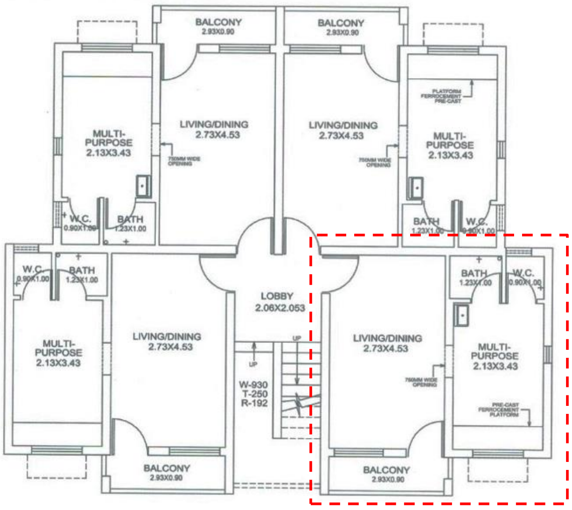

***Figure 4:*** *Layout of the dwelling unit*

***Table 1:*** *Building envelope details of the base case*

| Building orientation | North -south |
|---|---|
| **External wall** | 12.5 mm cement plaster + 225 mm burnt clay brick + 12.5 mm cement plaster<br>U-value = 2.13 W/m$^2$K |
| **Roof** | 100 mm RCC + 100 mm lime concrete<br>U-value = 2.78 W/m$^2$K |
| **Window glazing** | 6mm thk. -single glazing<br>U-value = 4.8 W/m$^2$K.<br>SHGC= 0.82 |
| **Gross WWR** | 4.85% |

## 1.4. Outputs of the research

MaS-SHIP has produced a range of outputs for different stakeholders to share the knowledge and insights that have been generated from the study. These outputs include reports, tools, technology catalogues, datasets, policy briefings and a dedicated project website, as explained below:

- **Background study report** on the scale of the problem of social housing provision in India, the response with which India has met this challenge in the past, how it translated into state level responses, and what could be learnt from national and international case studies to positively influence the Government's prerogative to provide housing for all.

- Decision Support Toolkit (DST) which not brings together all the outputs from the project in an interactive manner, but also provides design guidelines to enable the adoption of sustainable design by housing providers at the conceptual stage of housing projects.

- **Technology catalogues** have been prepared to provide empirical data for 17 selected building materials and systems against the 18 sustainability attributes identified in MaS-SHIP.

- **Sustainability Assessment Tool (SAT)** is an online excel tool in DST that performs comparative assessment of the performance of 17 building systems against the 18 sustainability attributes.

- **Case study reports** describe the findings of the resident surveys on user experience with building systems in five social housing developments.

- **Policy briefings** on mainstreaming sustainability in social housing projects.

- MaS-SHIP website which hosts the DST and policy briefings and the deliverables arising out of the project.

## 1.5. Structure of the report

The report has been structured around seven chapters. This Chapter provides the background and context of the research. It lays out the main objectives and methodological framework of the research and provides an overview of the outputs. Chapter 2 outlines the process for selecting, defining and assigning weightings to a framework of 18 attributes for measuring the performance of building systems, against four criteria, including *resource efficiency, operational performance, user experience,* and *economic impact*.

Chapter 3 describes in detail the data framework for calculating the mix of qualitative and quantitative attributes for 17 established and emerging walling and roofing systems. Chapter 4 provides insights about the *user experience* of building systems, through a field survey of 723 households in five social housing developments located in five cities across India.

Chapter 5 describes the innovative tools that have been developed in MaS-SHIP for overcoming knowledge gaps related to the design and evaluation of sustainable building systems in social housing projects. In Chapter 6, the key findings are reviewed and their implications for policy and practice are discussed. Chapter 7 provides the key conclusions of the research, especially how findings from the project can complement Government of India's efforts to promote sustainability in social housing projects.

# Chapter 2

## Attributes for assessing sustainability performance of building systems

## 2.1. Identifying sustainability attributes

A key aspect of MaS-SHIP research was to systematically select relevant attributes that can be used for characterising the sustainability performance of building materials and systems. This enabled a comparative evaluation for their application in social housing projects. This chapter describes the process for identifying and defining the attributes – and how their relative importance was assessed using a nationwide (online) survey of experts.

## 2.2. Selection of the attributes

The literature review along with deliberations with experts during the MaS-SHIP stakeholder engagement workshops enabled the development of the selected 18 attributes. Figure 5 shows the multi-step selection process, consisting of the derivation, definition and finalization of the attributes.

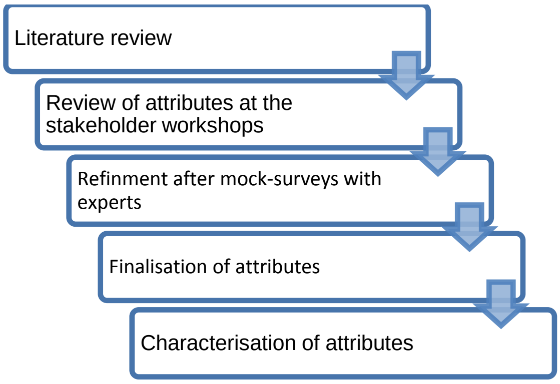

***Figure 5:** Attributes selection process*

### • Literature review

An initial list of attributes was drawn up, in line with the 'Multi-Attribute Evaluation Methodology for Selection of Emerging Housing Technologies' published by BMTPC for the Ministry of Housing & Urban Poverty Alleviation, Government of India under 'Housing for All' (Urban) mission (MoHUPA Government of India, 2015). This list comprised of 19 attributes grouped under five main criteria.

Different attributes pertaining to building materials and systems were also identified from an extensive review of literature drawing from academic papers, technical briefings and government reports. The studies showed that primarily the attributes considered for assessment included economic viability, environmental sustainability and social acceptability criteria. Most of the previous studies did not consider assessing or weighting the attributes (Amir, 2016), however a few that did, used a "multiple criteria decision making" method. It was also observed that the attributes chosen in various studies provided non-empirical recommendations for affordable housing (Mulliner, 2013).

Review of sustainability assessment tools such as BREEAM, LEED, Green Globe, NABERS, SBTool, GRIHA and CPWD Tool, identified attributes (related to building materials and systems) that are commonly used for assessing the performance of materials. It was realised that material selection mainly influences the maintenance, safety/security and responsible sourcing categories of sustainability. The well-regarded BREEAM rating system (2016b) covers health and comfort, safety and security, accessibility, stakeholder engagement and responsible sourcing of materials. Affordability in BREEAM's case falls under economic sustainability.

Based on the learning from the literature review, the number of attributes in the initial list was increased from 19 to 29.

### • Review of the attributes at the Stakeholder engagement events

The 29 attributes were discussed in the Stakeholder workshops – 1 & 2 and internal project meetings that led to re-grouping, re-naming and addition of new attributes. The revised list contained 21 attributes grouped under three criteria namely – Environment, Social and Economic.

Attributes such as Strength and Stability Requirements, Load Bearing Strength, Stability against Dynamic Forces, and Fire resistance etc. were found to be routinely considered by housing developers but are not directly indicative of the environmental quality of a building/development and therefore were not included in MaS-SHIP's list of sustainability attributes.

A RAG (Red, Amber, Green) status was assigned to each attribute where 'Red' indicated, "field surveys necessary for data collection", 'Amber' showed, "data that could be collected through desk research", and 'Green' showed that "normalized data is readily available".

The attributes which had no data sources or did not fall under any of the RAG categories were dropped. It was essential to find the indicators that are measurable in India. The issue at hand was where to obtain the data for these attributes, as there is no global framework to come up with a decision-making methodology.

These attributes included Life Cycle Embodied Energy, Water Resistance, Waste Generated, Labour Health, Design Flexibility and Design Compatibility. The attributes such as Critical Resource Use, Durability and Familiarity of a Material were difficult to measure and were not considered in the revised list of 15 attributes.

- **Refinement after the mock survey with experts**

The project team recognized that finalizing attributes was going be an iterative process and the list derived was not conclusive yet. To assign weightings to the attributes, a mock survey, based on Multi-Criteria Decision-Making method was designed to evaluate the attributes with respect to each other. This survey was circulated in order to determine relative weightings of the selected sustainability attributes against each other. The testing of the survey further refined the attributes grouped under four main criteria: *Resource Efficiency, Operational Performance, User Experience* and *Economic Impacts*.

- **Finalization of attributes**

The above process led to progressive iterations to reach the final set of 18 attributes (Figure 6) that holistically defined the sustainability character of the building material and systems being evaluated.

Their units of measurement were finalized for indicating sustainability, and categorized under four main-criteria namely:

- **Resource Efficiency:** to comprehensively account for the energy consumed and resources extracted throughout the entire life cycle of the construction process.
- **Operational Performance:** to factor in traditional efficiency metrics to ensure high quality building construction.
- **User Experience:** to factor in the role of residents and building practitioners in terms of their familiarity and experiences with existing options and sustainable alternatives.
- **Economic Impacts:** to link better environmental choices with a comprehensive set of economic indicators, including cost and job creation potential.

The list of all the attributes considered at various stages is available in Annex 4.

## 2.3. Characterization of attributes

Based on these 18 attributes, a Sustainability Assessment Tool (SAT) has been developed, (Chapter 5), to measure the relative performance of building materials and systems during the manufacturing and construction stages of social housing projects up to four stories high.

Table 3 details the finalized set of 18 attributes in terms of 'What is being measured', its measurement scale or 'Unit' and 'Calculation/ Source' of the data gathered under each attribute. This framework was created to enable data gathering for different building systems against each attribute. The 'What' explains each attribute in detail and the problem it intends to solve. The 'Unit' describes a standard of measurement for quantitative attributes and provides a natural ordering such as high, medium or low for qualitative attributes. The data collection methodology and its source are briefed under 'Calculation/ Source'.

## 2.4. Assigning relative weightings to the attributes

To avoid any bias towards an attribute, it was necessary to assess the attributes with respect to each other rather than assigning equal weightings. This helped to establish the relative importance or preference for the 18 attributes. To assign weightings to the attributes, a survey based on Multi-Criteria Decision Making (MCDM) system was designed to evaluate the attributes with respect to each other. The mathematical technique finalized for MCDM was Analytical Hierarchy Process (AHP), which was selected to assign relative weightings to the selected attributes. Complex problems or issues involving value or subjective judgements are suitable applications of the AHP approach, because of its intuitive appeal and flexibility (Viswanadhan, 2005). One key advantage of AHP is that it checks each respondent's judgment for their consistency based on a ratio known as the Consistency Ratio (CR).

- **Designing the expert survey to gather relative weightings**

An online nationwide survey based on the AHP technique was conducted to evaluate the relative

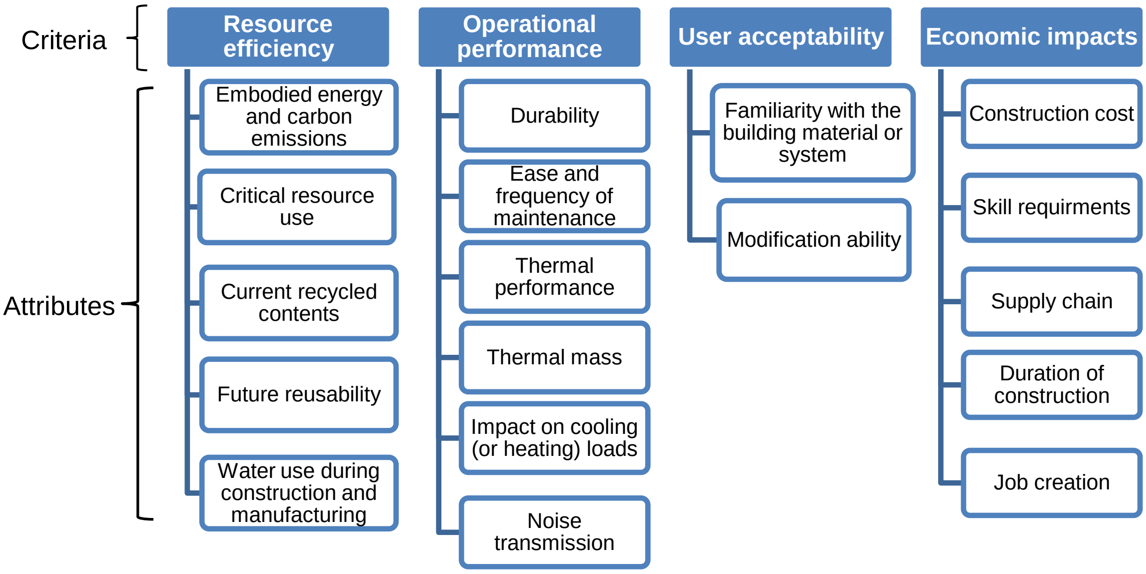

***Figure 6:*** *Final list of attributes*

importance of the 18 attributes. The following steps were involved:

- ### Defining the problem statement and creating a decision hierarchy

As part of the process, it was essential to define the goal in the problem statement. The project team had absolute clarity in terms of the desired output, however, communicating the same to the respondents was challenging. Initially, all attributes in the decision hierarchy were placed together (Figure 7).

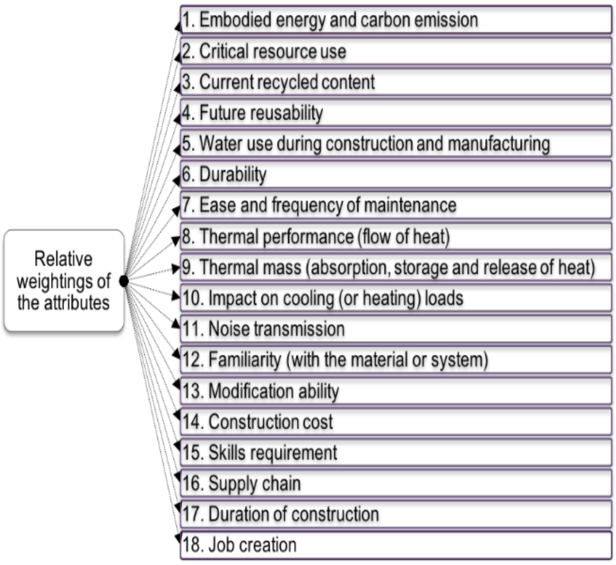

***Figure 7****: Decision hierarchy using AHP*

- ### Selecting and designing the survey questionnaire

The selection and finalization of the survey design was primarily done by reviewing similar AHP studies. Based on the rankings given by the experts as per the study, the following design was finalized (Table 2).

The nominal ratio scale of 1 to 9 (Saaty, 1990) was adopted for doing the pairwise comparisons. The formulated decision hierarchy and the above design were then tested through different MaS-SHIP stakeholder events and subsequently improved. The final decision hierarchy comprised of the four main criteria: Resource efficiency, Operational performance, User acceptability and Economic impacts. Pairwise comparison of the attributes grouped under each main criterion was followed by pairwise comparison of all the four main criteria with each other. The final decision hierarchy was the basis on which the attributes and criteria were compared for evaluating final weightings.

The Analytic Hierarchy Process is one of the pre-eminent approaches for formal decision-making techniques. It is critical to select the correct data sample size which is required for a comparative analysis to provide tangible results. The key to arriving at a statistically valid result is finalizing an appropriate sample size.

***Table 2:*** *Defining the nominal ratio scale for the AHP survey*

| | Left side scale | | | | Centre | Right side scale | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Attribute** | Very High Effect | High Effect | Moderate Effect | Slight Effect | Equal Effect | Slight Effect | Moderate Effect | High Effect | Very High Effect | **Attribute** |
| **A** | 9 | 7 | 5 | 3 | 1 | 3 | 5 | 7 | 9 | **B** |

*If A has higher effect, use left side of the scale.*
*If both, A and B have equal effect, the centre of the scale is to be selected.*
*If B has higher effect, use right side of the scale.*

- ### Determining sample size

There is no limitation on the population size that one can take up for a survey. Also, the greater number of different user groups that are represented in the survey, the better it is. For the MaS-SHIP AHP survey the different user groups are shown in Figure 8. In response to the MaS-SHIP survey, it was imperative to select the representative sample size as this would then become the population set and sampling of the responses would become a key parameter of the analysis to remove any biases from the survey results.

- ### Targeting the representative sample size from the population

***Figure 8:*** *Different user groups for the AHP survey*

Selecting the representative sample out of the population set is of utmost importance and various factors such as respondent's age, experience in sustainability, profession, qualification etc. had to be considered while sampling the responses received from the AHP Survey. To avoid any skewed results that may occur during sampling the responses, a Stratified Random Sampling process was adopted where the sampling frame was divided into smaller sub groups. Thereafter, the groups were stratified based on the relevant years of experience in sustainability.

- ### Confidence level and confidence interval

Once the required sample size was arrived at, finalizing the required confidence level of the survey and the confidence interval was essential. The confidence level is expressed as a percentage and represents how often the true percentage of the population who would pick an answer lies within the confidence interval. The confidence interval is also called margin of error.

The margin of error in a survey is approximately equal to the inverse of the square root of the sample size. However, a margin of error more than 10% is not recommended while conducting the surveys. The MaS-SHIP AHP surveys targeted an error margin in between 5% to 10%. This implied that a sample of 100 to 400 responses was desired.

## 2.5. Expert survey results

The survey helped the project team to establish relative weightings of the 18 attributes comprising the SAT. A total of 200 responses were received from leading experts in the building industry across India. All 200 responses were checked for consistency and the weightings for the attributes were eventually derived from the consistent responses of 184 experts. The 184 consistent survey respondents were categorized into user groups as per their area of expertise (Figure 9)

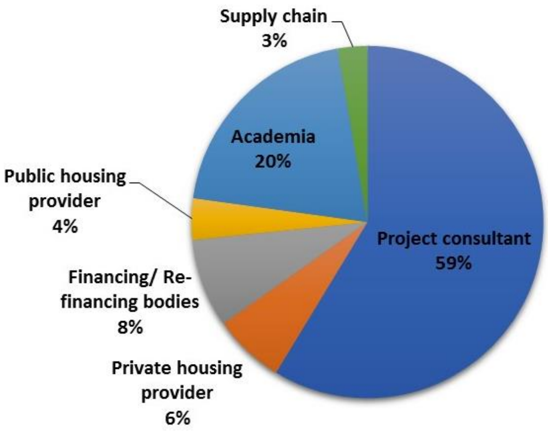

***Figure 9:*** *User groups of respondents*

About 108 respondents out of the 184 belonged to the project consultant group contributing to nearly 59% of the responses. The respondents were also assessed in terms of their experience in the field of housing sector and/or sustainability (Figure 10). The research team assessed the difference in responses of the respondents having 0-2 years (56) of experience in sustainability as opposed to the ones with experience of 3 years (52) and above. Since there were no significant disparities observed in the responses of both groups, the MaS-SHIP team decided to use all 184 responses to evaluate final weightings of the attributes.

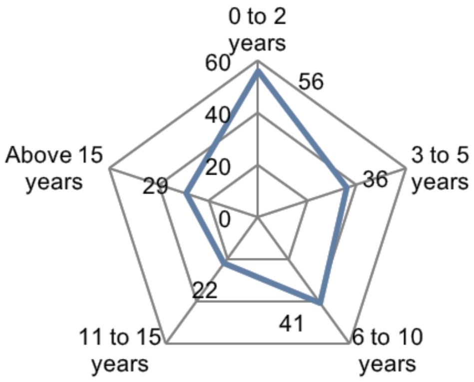

***Figure 10:*** *Experience (in years) of the survey respondents*

Based on the analysis of the survey results, weightings were obtained for the 18 attributes (Figure 11). It was evident from the AHP survey that each respondent group had their bias towards certain attributes. As expected, the private housing providers preferred 'construction cost' over all other attributes. However, it was encouraging to note that attributes such as 'familiarity', and 'modification ability' were also highly preferred. These results were no different from the overall weightings of the attributes evaluated.

Even though residents of social housing were not a part of this expert survey, it was interesting to find that attributes affecting them such as 'familiarity', and 'modification ability', came second in terms of preference, after 'construction cost'. 'Impact on cooling (or heating) loads' was also among the most preferred attributes.

It was evident that the performance of building materials and systems against the most preferred attributes (namely 'construction cost', 'familiarity', 'modification ability' and 'Impact on cooling (or heating) loads would have maximum impact on their final scores.

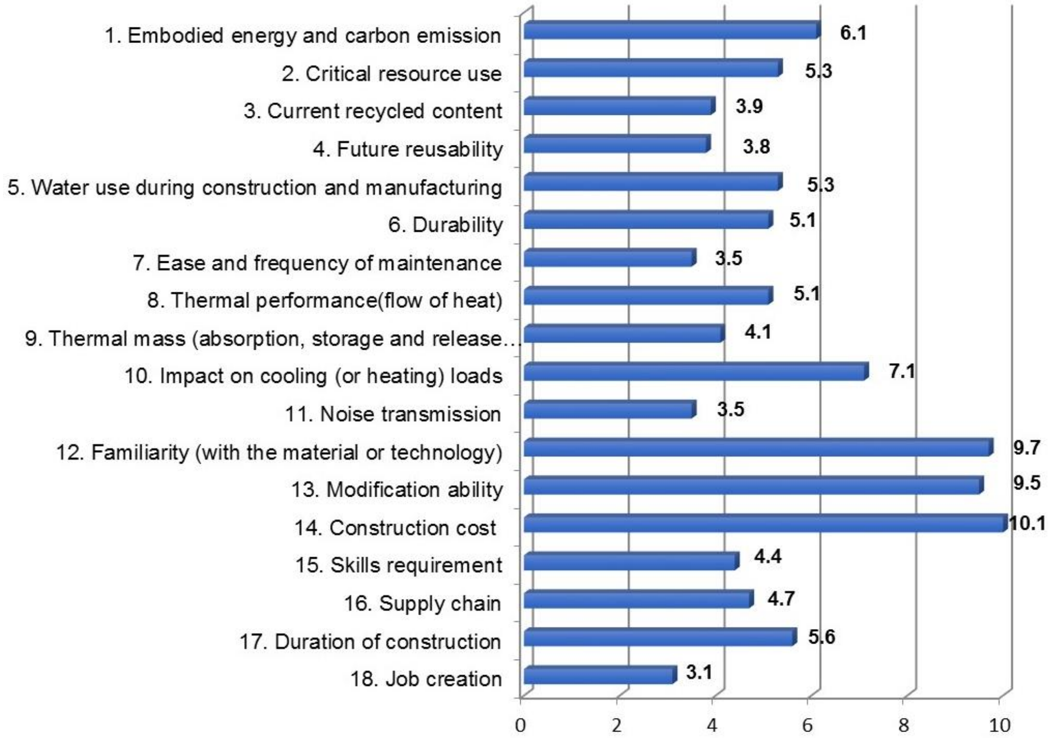

***Figure 11:*** *Final weightings of the 18 attributes*

## 2.6. Summary

An iterative and robust methodology was adopted to finalize the list of 18 attributes for defining the sustainability performance of building materials and systems for social housing sector.

Interactions with the industry experts during the various stakeholder consultations highlighted the barriers to the uptake of sustainable building materials and systems in social housing projects in India. Some of these were related to site sustainability, accessibility, design and workmanship, etc. Although, most of them were addressed and incorporated in the selected attributes, those which could not be were incorporated as part of the design guidelines and policy briefs that have come out of the project and are available from the project website.

The following chapter lays out the data framework for quantifying the performance of the selected building systems and materials against these 18 sustainability attributes.

***Table 3:*** *Detailing the 18 attributes*

| S. No. | Attribute | What is being measured | Unit | Calculation/Source |
|---|---|---|---|---|
| 1 | **Embodied Energy & Carbon Emission** | It is the total energy expended for implementing a building system, from extraction of material up until the point of installation in a building.<br>This includes energy consumed in: Manufacture of raw material (example- cement, steel); construction/ installation at site; and transportation of materials/ components from manufacturing facility/ material vendor to the construction site. | MJ/ $m^2$ of wall or roof assembly | ***Calculation:*** Normalized data readily available**.** Calculations for the embodied energy per $m^2$ of wall or roof assembly of each systems have been made in three stages:<br>Raw material → Component →System.<br>***Source:*** Tier 1 level data on embodied energy and emission factors of material on which the calculations for building components and systems are based on. |
| 2 | **Critical Resource Use** | It is the overall impact created critically from the quality of resource usage measured in terms of:<br>**A. Scarcity Index:** The creation of criticality due to impact on ecology because of the process of extraction of the various raw materials used in the product/building material (e.g. river ecology, forest ecology, mountainous ecology etc.)<br>**B. Environmental Impact (soil and water pollution):** The degree of water and soil pollution caused during the process of extraction, manufacture and construction.<br>**C. Sectorial conflicts/Conflict of use between different sectors:** The degree of criticality created due the conflict of use of raw materials in the production of building component or system (e.g. soil is important for food sector, terracotta handicrafts, etc.) | Normalized numeric index<br>Criticality score:<br>Low: 1, Medium: 2, High: 3<br>The Low-Medium-High ranking refers to severity of the three parameters of Environmental impact, Scarcity and Conflict of use. *The rankings are based on a research study conducted by Development Alternatives on Resource Efficiency in the Indian Construction Sector (2015).* | ***Calculation***: The calculations have been done using the weights of the critical resources per $m^2$ of the wall or roof assembly multiplied by the criticality score of the respective resource. These values are normalized on a 0-100 scale. The formula for calculation can be referred to in the data framework report available from the project website.<br>***Source:*** Weightings given according to Tier 1 data at primary level, with resulting calculations involving T1, T2 and T3 data at assembly level. |
| 3 | **Current Recycled Content** | Quantum of recycled content utilized in the building material which may be achieved by usage of materials which utilize, for instance, industrial waste. The intent is to reduce the dependency on virgin materials such as top soil, sand etc. or on materials with a high environmental impact such as cement. | Scale of High, Medium and Low<br>Low: 0-20%<br>Medium: 20 – 40%<br>High: > 40 – 100% | ***Calculation:*** Scale derived from percentage of recycled content in the manufacturing of the material.<br>***Source:*** Calculations based on T1 and T3 data, using inputs from manufacturer surveys and prevalent system/ material specifications. |
| 4 | **Future Reusability** | Ability of a material to be used in its second life cycle without any structural changes. The intent is to reduce the generation of C&D (Construction & Demolition) waste at source. | Scale of High, Medium and Low.<br>Low: 0-20%<br>Medium: 20 – 40%<br>High: > 40 – 100% | ***Calculation:*** The scale has been derived from percentage of constituent materials of the wall/roof, which may be reusable.<br>***Source:*** Tier 3 data from manufacturer surveys and material specifications. |

| S. No. | Attribute | What is being measured | Unit | Calculation/Source |
|---|---|---|---|---|
| 5 | **Water use (during manufacturing and construction)** | Amount of water consumed by building systems including both embodied water content of raw materials as well as process water consumed in production and construction. | Litres per $m^2$ | ***Calculation:*** Calculations are based on embodied water of raw materials, taken according to composition ratios of these materials in the final wall/roof assembly. The final amount includes water for production (on site/off-site) and curing (on-site).<br>***Source:*** Tier 1 data on embodied water in material have been used as the base for the calculations. |
| 6 | **Durability** | Time period for which the building material or system is stated to last by its manufacturer under specified conditions of use. Water resistance and compressive strength determine the durability of the material. | Scale of High, Medium and Low | ***Calculation:*** Tier 3 data was collected through material catalogues.<br>***Source:*** Tier 3 data from manufacturer surveys and material specifications. |
| 7 | **Ease & Frequency of Maintenance** | Frequency of maintenance works required (regular or occasional). Could involve the following indicators:<br>• Extra products required for the maintenance<br>• External help required<br>• Mandatory frequent services | Scale of High, Medium and Low | ***Calculation:*** Tier 3 data was collected through material specifications and catalogues regarding the maintenance of the building system. Households were questioned on the ease and frequency of maintenance required in the houses. The scale of high, medium and low comes from the responses of the householders and building practitioners towards these questions.<br>***Source:*** Tier 3 data from manufacturer surveys and material specifications. |
| 8 | **Thermal Performance (flow of heat)** | Thermal performance of a material is a measure of the thermal transmittance (also known as the U-value) which is the property of heat transmission in unit time through unit area of a building material or assembly and the boundary air films, induced by unit temperature difference between the environments on each side. The lower the U-value of a material, the better is its heat insulating capacity. | $W/m^2 K$ | ***Calculation:*** Normalized data readily available**.**<br>***Source:*** Tier 1 data from published reports and articles, Tier 2 calculations from the CEPT CARBSE Assembly U-factor calculator[1], based on the selected walling and roofing assembly |
| 9 | **Thermal Mass (absorption, storage and release of heat)** | Thermal mass or thermal admittance quantifies a material's ability to absorb and release heat from a space as the indoor temperature changes through a period of time. In climates with large diurnal swings, admittance values can be a useful tool when assessing heat flows into and out of thermal storage. | kg per $m^2$ | ***Calculation:*** The terms *heavy-weight, medium-weight* and *light-weight* are often used to describe buildings with different thermal mass strategies.<br>***Source:*** Tier 1 and Tier 3 data on material specifications, with calculation for change in unit. |

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[1] http://www.carbse.org/resource/tools/

| S. No. | Attribute | What is being measured | Unit | Calculation/Source |
|---|---|---|---|---|
| 10 | **Impact on Cooling (or heating) Loads** | Impact of the building system used in the construction of any dwelling on the energy consumed for space cooling and/or heating. The intent was to inform the user of the potential savings associated with the use of a building material or system with respect to a specific climatic zone in India. | kWh/m$^2$/year | ***Calculation:*** Simulation based results using DesignBuilder.<br>***Source:*** Tier – 2 data based on simulations |
| 11 | **Noise Transmission** | Refers to airborne insulation values of walls and airborne and impact insulation values of floors. | Decibel (dB) | ***Calculation:*** Normalized data readily available<br>Sound Transmission loss as per IS 1950:1962<br>30 dB or less – Poor<br>40 dB – Fair<br>45 dB – Good<br>50 dB - Very good<br>60 dB - Excellent<br>***Source:*** Tier 1 data from published reports and articles. |
| 12 | **Familiarity (with the material or system)** | Degree of inclination towards a building material or system based on user acceptance. | Scale of High, Medium and Low | ***Calculation:*** Tier 3 data was collected through household and building practitioner surveys. Householders were questioned on their experience with the building system used, while the building practitioners were questioned on their likeliness towards using a certain building system. The scale of high, medium and low comes directly from the responses of the householders and building practitioners towards these questions.<br>***Source:*** Tier 3 data inputs from manufacturer and household surveys. |
| 13 | **Modification Ability** | Suitability of constructed building for adopting changes after construction by occupant, including nail-ability. To be able to make changes like- Concealed piping, electrical, and plumbing services, and provision for incorporating the mechanical, electrical and plumbing services within the proposed building component thickness. | Scale of High, Medium and Low | ***Calculation:*** Qualitative tier 3 data was collected through material specifications and catalogues regarding the maintenance of the building system. Households were questioned on the modification ability of the materials used in the structures of the households.<br>***Source:*** Tier 3 data inputs from manufacturer and household surveys. |

| S. No. | Attribute | What is being measured | Unit | Calculation/Source |
|---|---|---|---|---|
| 14 | **Construction Cost** | Cost per $m^2$ of the building system (wall and/or roof). This includes primary material, labor, water and equipment charges.<br>*This is not the cost per $m^2$ of built up area.* | Cost per $m^2$ | ***Calculation:*** The cost analysis has been done first through calculation of the cost per component (e.g. solid concrete block) using rates from CPWD's Delhi Schedule of Rates 2016. The cost analysis of the final assembly is done using the above calculated costs of components.<br>***Source:*** Calculation based on combination of Tier 1 data from Delhi Schedule of Rates 2016 and Tier 3 data from practitioners and manufacturers/ suppliers. |
| 15 | **Skill Requirement** | Level of skill needed during production and construction of a building material or system. | <20%: Low;<br>20 – 40%: Medium;<br>>40%: High | **Calculation:** Percentage of skilled personnel required in the construction process.<br>***Source:*** Calculations based on Tier 3 data from practitioners and manufacturers/ suppliers. |
| 16 | **Supply Chain** | The availability of number of reliable suppliers for a particular building material or system in the very initial stage of construction of the project and in proximity to the project site. | Scale of High, Medium and Low | ***Calculation:*** GIS mapping of building materials and system suppliers<br>***Source:*** Mapping geographic locations of manufacturers and suppliers of building materials and systems (GIS mapping of building materials) |
| 17 | **Duration of Construction** | Time consumed on site in construction, assembly and installation of a building material or system. | $m^2$ of built-up area per day. | ***Calculation:*** Tier 3 values from project details, practitioners and developers.<br>***Source:*** Tier 3 values from project details, practitioners and developers. |
| 18 | **Job creation** | Quantum of jobs created per $m^2$ of wall/roof construction in terms of man-days. | Man-days per $m^2$ | ***Calculation:*** Man-days per $m^2$ have been calculated as a sum of work required per $m^2$ of wall/roof assembly by the skilled and unskilled labour in each step of the assembly process.<br>***Source:*** Calculations based on T3 data, values from projects, practitioners and developers. |

# Chapter 3

## Characterising the sustainability performance of selected building systems

The project has looked at a wide range of building system options, narrowed it to roof and wall construction materials and building systems and selected 17 options for assessment (Table 4). Based on popularity of use and level of maturity in the Indian housing market, the selected building systems for housing can broadly be divided into two categories:

- **Established Systems** that have an established evidence of development and practice in the Indian housing market. These include both the conventional building systems which are most commonly adopted and building systems which have been recognized as alternative, environment friendly in the Indian context with some evidence of performance in buildings which may or may not be for housing purpose.
- **Emerging Systems** that are being promoted by the Ministry of Housing and Urban Affairs, Government of India, through the BMTPC as prospective solutions for faster and cost-effective delivery of houses. All building systems in this category are based on a 'production' approach of housing where speed of construction is of prime importance.

## 3.1. Data availability and challenges

The extent and quality of available data pertaining to sustainability criteria for building materials and systems varies depending on its specifications and level of maturity in the Indian housing market. Broadly, the distinction in data availability is delineated by established building systems with a large evidence of use and those that are emerging such as large-scale precast systems. For established building systems, most attributes have been determined with good accuracy, whereas in the case of emerging systems, most attributes have been calculated on the basis of some, albeit limited, evidence of use. Taking this variation of data quality into account, three tiers of data have been considered, signifying varying levels of validity and accuracy of data (Table 5).

The data is reflective of the level of systems practice and its evaluation with respect to sustainability, as existing today in the Indian building sector. In particular, emerging areas of large-scale precast building solutions are currently deficient in data on sustainability parameters. However, with the introduction of new building systems, improvement in existing systems and greater disclosure of information for emerging building systems, the data presented here also has the potential of becoming more robust.

Data especially for certain attributes were not easily available and hence a tiered approach was adopted for data collection as Tier 1 (Credible published data sources), Tier 2 (Calculated data) and Tier 3 (Field survey). Further credibility of the data has been a matter of concern, stressing the significance of assumptions and methods of calculation. However, the data collected so far, and the analysis has helped in identifying the key anomalies that may exist in the data as well as future studies that will need to be conducted for gathering better quality data.

***Table 4:*** *List of selected building materials and systems*

| Established and Practiced Systems | | Emerging systems validated and promoted by BMTPC |
|---|---|---|
| **Type 1: Readily available in the market** | **Type 2: On site production based / in-situ** | **Type 3: Evidence of use in demonstration project on social housing** |
| 1. Burnt clay brickwork English bond | 7. Stone-crete blocks | 13. Glass Fibre Reinforced Gypsum (GFRG) Panel system |
| 2. Fly ash brick masonry | 8. Stabilized Compressed Earth Blocks (SCEB) | 14. Monolithic concrete building system using plastic/aluminium composite |
| 3. Rat rap bond using burnt clay bricks | 9. RCC Filler Slab roof | 15. Light Gauge Steel Frame (LGSF) system |
| 4. Solid Concrete block masonry | 10. Precast RCC Plank and Joist Roof | 16. Reinforced EPS Core Panel System |
| 5. Hollow Concrete block masonry | 11. Precast Ferro-cement channel roof | 17. Precast large Concrete Panel System |
| 6. Aerated Autoclave Concrete (AAC) blocks | 12. Reinforced Brick Panel roof | |

| Walling Systems | Roofing Systems | Integrated Systems |
|---|---|---|

***Table 5:*** *Type of data used for the DST and SAT*

| | |
|---|---|
| **Tier 1** | This data has the highest level of credibility and accuracy. It is sourced from published documents such as research papers, official government publications such as CPWD Schedule of Rates or directly measured and reported statistics from the building industry. |
| **Tier 2** | This data is calculated on the basis of standard technical specifications of building systems and often uses Tier 1 level coefficients for calculations. Some assumptions in calculations are likely to be variable in actual practice (market costs and values). |
| **Tier 3** | This data is collected from unverified sources such as manufacturer's specifications or calculations available with building practitioners based on their projects. This also includes data which has been gathered through field surveys conducted in the project. |

## 3.2. Data interpretation

The calculations for sustainability attributes involved data interpretation at three levels:

### • Material level

This includes predominantly raw materials (cement, brick, steel, aluminium, EPS, etc.) which are processed to make building materials and elements. These raw materials are manufactured in prominent large industries and their environmental performance (embodied energy, emissions, water consumption, and environmental impact) is monitored and is largely available in the public domain. Economic data in terms of cost of raw materials and cost of civil work items and manpower requirement data is also available from Central Public Works Department (CPWD) specifications and rates which are updated every year. For SAT, CPWD rates and rate analysis of civil work have been taken from Delhi Schedule of Rates (DSR) 2016. Also included at this level are standard items of construction such as different grades of concrete and mortar for which CPWD specifications have been referred. All data at this level is Tier 1 data.

### • Component level

This level pertains to building materials and elements such as concrete blocks, AAC blocks, precast RCC components, fly ash bricks, etc. Data at this level is typically an output of calculations based on standard technical specifications of a building material/ element and referring Tier 1 data of raw materials. For instance, Tier 1 data of embodied energy of cement and aggregates is used to calculate embodied energy and cost of a concrete block based on technical specifications of the concrete block. Alternatively, attribute data for some materials has been sourced from reports pertaining to alternative building systems.

### • System Level

This pertains to the final level of calculation for wall or roof system. At this level, data generated at primary and tertiary level is used to calculate attribute values on 'per $m^2$ of wall or roof. Here, most attribute calculations involve data from Tier 1 and Tier 2. For instance, Tier 1 data on cost and manpower and Tier 2 data on cost of a concrete block is integrated as per technical specifications of concrete block masonry to calculate the cost of construction of a concrete block wall. Nine attributes in the Resource Efficiency and Operational performance categories (except for Noise Transmission, Thermal Performance and Durability) have been calculated using a Tier 1 and Tier 2 data in this manner. For Noise Transmission and Thermal Performance, Tier 1 data from published research has been taken directly.

For attributes in the category of User Experience: *Familiarity with material/system* and *Modification Ability,* and *Durability*, qualitative data (Tier 3 level) has been collected at the housing level through householder survey of occupants living in social housing developments in various parts of India. Similarly, attribute values for Supply Chain and Duration of Construction, Tier 3 data was gathered through surveys of building practitioners and building material manufacturers. For the attributes under Economic Impact, data (Tier 2 and 3 level) has been complied through a combination of desk research and interviews of building professionals.

*An outline of the process of the calculation methodology adopted and the cross-linkages of Tier 1, 2 and 3 data for each attribute has been shown in Figure 12. The detailed categorization of all the data under the 17 building systems can be seen in Table 7, which shows a matrix of which tier(s) have been used under each attribute and system. The table also shows the use of tier 1 and tier 3 data at the material and component level which informs the tier 2 calculations on the system level.*

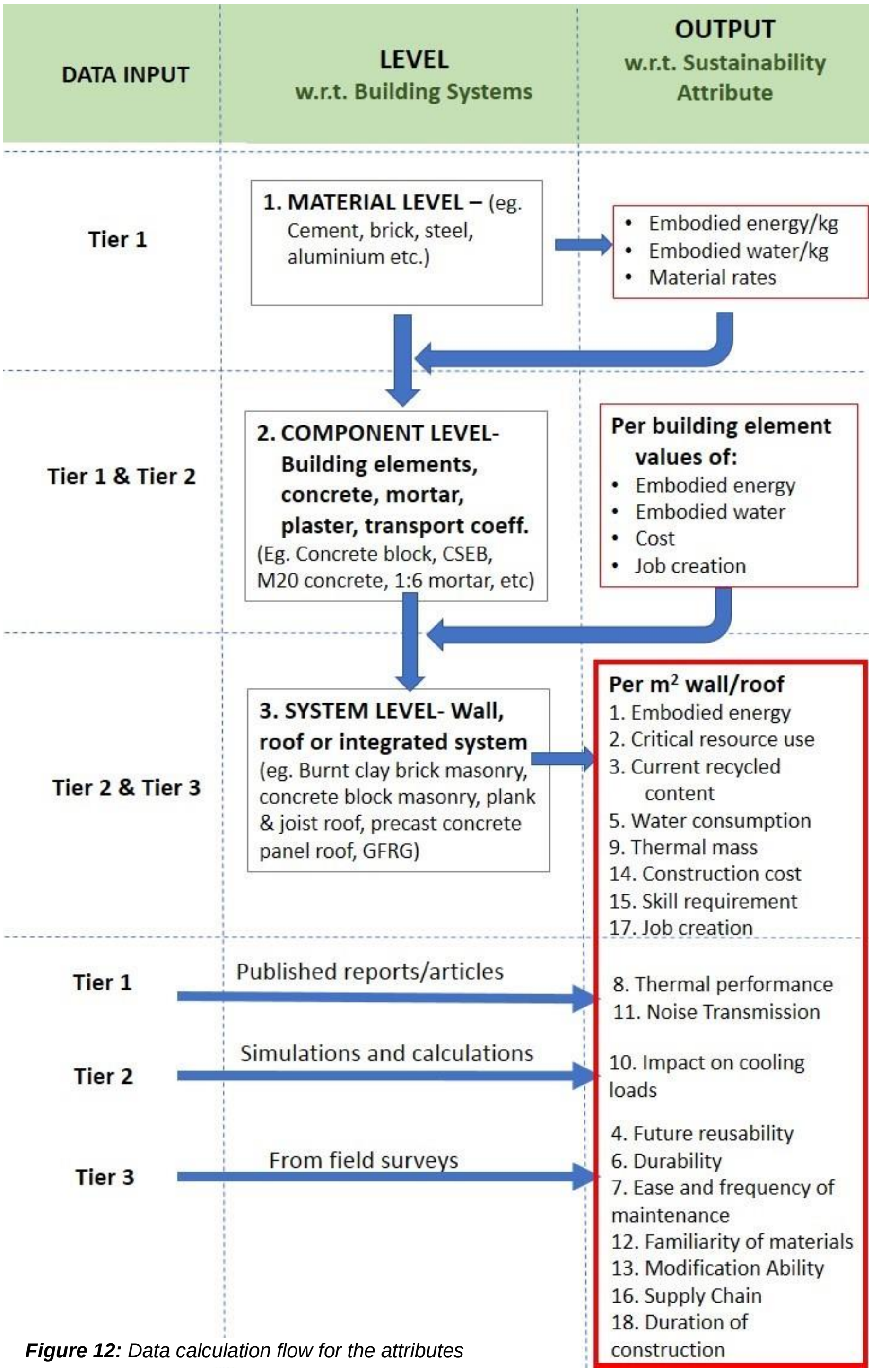

***Figure 12:*** *Data calculation flow for the attributes*

***Table 6:*** *Sources of material level data*

| | | **Resource Efficiency** | | | | | **Operational Performance** | | | | | | **User Experience** | | **Economic Impact** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Materials** | 1. Embodied energy | 2. Critical Resource use | 3. Current recycled content | 4. Future reusability | 5. Water use | 6. Durability | 7. Ease and frequency of maintenance | 8. Thermal performance | 9. Thermal mass | 10. Impact on cooling (or heating) loads | 11. Noise transmission | 12. Familiarity with the material | 13. Modification ability | 14. Construction cost | 15. Skills requirement | 16. Supply chain | 17. Duration of construction | 18. Job creation |
| | **Units** | MJ/Sq.M | Index | HML | HML | Litre/sqm | HML | HML | W/$m^2K$ | kg/$m^2$ | kW/$m^2$/Yr | dB | HML | HML | INR/Sqm | HML | HML | sqm/day | Mandays/$m^2$ |
| **Material** | Concrete, Coarse Aggregate, Sand, Steel, Aluminium, EPS, fibre board | 🟥 | ▒ | ▒ | ▒ | 🟥 | ▒ | ▒ | ▒ | ▒ | ▒ | ⬜ | ▒ | ▒ | ⬜ | ▒ | ⬜ | ▒ | ▒ |
| **Component** | Clay Brick | 🟪 | 🟪 | 🟪 | ⬜ | 🟪 | 🟧 | ⬜ | ⬜ | 🟥 | ▒ | 🟥 | 🟧 | 🟧 | 🟧 | ⬜ | 🟧 | ▒ | ⬜ |
| | Fly-Ash brick | 🟪 | 🟪 | 🟥 | ⬜ | 🟪 | 🟧 | ⬜ | ⬜ | 🟥 | ▒ | ⬜ | 🟧 | 🟧 | 🟧 | ⬜ | 🟧 | ▒ | ⬜ |
| | Solid Concrete Block | 🟪 | 🟪 | 🟪 | ⬜ | 🟪 | 🟧 | ⬜ | ⬜ | 🟥 | ▒ | ⬜ | 🟧 | 🟧 | 🟧 | ⬜ | 🟧 | ▒ | ⬜ |
| | Hollow concrete block | 🟪 | 🟪 | 🟪 | ⬜ | 🟪 | 🟧 | ⬜ | ⬜ | 🟥 | ▒ | ⬜ | 🟧 | 🟧 | 🟧 | ⬜ | 🟧 | ▒ | ⬜ |
| | AAC Block | 🟪 | 🟪 | 🟪 | ⬜ | 🟪 | 🟧 | ⬜ | ⬜ | 🟥 | ▒ | 🟥 | 🟧 | 🟧 | 🟧 | ⬜ | 🟧 | ▒ | ⬜ |
| | CSEB | 🟪 | 🟪 | 🟪 | ⬜ | 🟪 | 🟧 | ⬜ | ⬜ | 🟥 | ▒ | 🟥 | 🟧 | 🟧 | 🟧 | ⬜ | 🟧 | ▒ | 🟪 |
| | Ferrocement channel | 🟪 | 🟪 | 🟪 | ⬜ | 🟪 | 🟧 | ⬜ | ⬜ | 🟥 | ▒ | ⬜ | 🟧 | 🟧 | 🟧 | ⬜ | 🟧 | ▒ | 🟪 |
| | Stone-crete block | ⬜ | 🟪 | ⬜ | ⬜ | 🟪 | 🟧 | ⬜ | ⬜ | 🟥 | ▒ | ⬜ | 🟧 | 🟧 | 🟧 | ⬜ | 🟧 | ▒ | ⬜ |

| 🟥 Tier 1 | 🟪 Tier 2 | 🟧 Tier 3 | ⬜ No data | ▒ Not Applicable |
|---|---|---|---|---|

***Table 7:*** *Sources of component and system level data*

| | | | Resource Efficiency | | | | | Operational Performance | | | | | | User Experience | | Economic Impact | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Materials** | 1. Embodied energy | 2. Critical Resource use | 3. Current recycled content | 4. Future reusability | 5. Water use | 6. Durability | 7. Ease and frequency of maintenance | 8. Thermal performance | 9. Thermal mass | 10. Impact on cooling (or heating) loads | 11. Noise transmission | 12. Familiarity with the material | 13. Modification ability | 14. Construction cost | 15. Skills requirement | 16. Supply chain | 17. Duration of construction | 18. Job creation |
| | | **Units** | MJ/Sq. M | Index | HML | HML | Litres/sq m | HML | HML | $W/m^2 K$ | $kg/m^2$ | $kW/m^2/Yr$ | dB | HML | HML | INR/ Sqm | HML | HML | sqm/ day | $Mandays/m^2$ |
| **Building System** | Walling | English-bond brickwork (clay work) | 🟪 | 🟪 | 🟪 | 🟧 | 🟪 | 🟧 | | 🟪 | 🟪 | 🟪 | 🟪 | 🟧 | 🟧 | 🟪 | 🟪 | 🟧 | 🟧 | 🟪 |
| | | Fly-Ash brick work | 🟪 | 🟪 | 🟥 | 🟧 | 🟪 | 🟧 | 🟧 | 🟥 | 🟪 | 🟪 | 🟪 | 🟧 | 🟧 | 🟪 | 🟪 | 🟧 | 🟧 | 🟪 |
| | | Rat-trap Bond brickwork | 🟪 | 🟪 | 🟪 | 🟧 | 🟪 | 🟧 | 🟧 | 🟥 | 🟪 | 🟪 | 🟪 | 🟧 | 🟧 | 🟪 | 🟪 | 🟧 | | 🟪 |
| | | Solid concrete block masonry | 🟪 | 🟪 | 🟪 | 🟧 | 🟪 | 🟧 | 🟧 | 🟥 | 🟪 | 🟪 | 🟪 | 🟧 | 🟧 | 🟪 | 🟪 | 🟧 | 🟧 | 🟪 |
| | | Hollow concrete block masonry | 🟪 | 🟪 | 🟪 | 🟧 | 🟪 | 🟧 | 🟧 | 🟥 | 🟪 | 🟪 | 🟪 | 🟧 | 🟧 | 🟪 | 🟪 | 🟧 | 🟧 | 🟪 |
| | | *AAC block masonry* | 🟪 | 🟪 | 🟪 | 🟧 | 🟪 | 🟧 | 🟧 | 🟥 | 🟪 | 🟪 | 🟪 | 🟧 | 🟧 | 🟪 | 🟪 | 🟧 | 🟧 | 🟪 |
| | | Stone-crete blocks masonry | 🟪 | | 🟪 | 🟧 | | 🟧 | 🟧 | 🟪 | 🟪 | 🟪 | 🟪 | 🟧 | 🟧 | 🟪 | 🟪 | 🟧 | | 🟪 |
| | | CSEB walling | 🟪 | 🟪 | 🟪 | 🟧 | 🟪 | 🟧 | 🟧 | 🟥 | 🟪 | 🟪 | 🟪 | 🟧 | 🟧 | 🟧 | 🟪 | 🟧 | 🟧 | 🟪 |
| | Roofing | Ferro Cement channel roofing | 🟪 | 🟪 | 🟪 | 🟧 | 🟪 | 🟧 | 🟧 | 🟥 | 🟪 | 🟪 | 🟪 | 🟧 | 🟧 | 🟪 | 🟪 | 🟧 | 🟧 | 🟪 |
| | | RCC Filler Slab roofing | 🟪 | 🟪 | 🟥 | 🟧 | 🟪 | 🟧 | 🟧 | 🟥 | 🟪 | 🟪 | 🟪 | 🟧 | 🟧 | 🟧 | 🟪 | 🟧 | 🟧 | 🟪 |
| | | Reinforced Brick Panel roofing | 🟪 | | 🟪 | 🟧 | | 🟧 | 🟧 | 🟥 | 🟪 | 🟪 | 🟪 | 🟧 | 🟧 | 🟪 | 🟪 | 🟧 | | 🟪 |
| | | Pre-cast RCC Plank & Joist roofing | 🟪 | 🟪 | 🟪 | 🟧 | 🟪 | 🟧 | 🟧 | 🟥 | 🟪 | 🟪 | 🟪 | 🟧 | 🟧 | 🟪 | 🟪 | 🟧 | | 🟪 |
| | Integrated | Reinforced EPS Core Panel System | 🟪 | 🟪 | 🟪 | 🟧 | 🟥 | 🟧 | 🟧 | 🟪 | 🟪 | 🟪 | 🟪 | 🟧 | 🟧 | 🟪 | 🟪 | 🟧 | 🟧 | 🟪 |
| | | GFRG Panel System | 🟪 | 🟪 | 🟪 | 🟧 | 🟥 | 🟧 | 🟧 | 🟪 | 🟪 | 🟪 | 🟪 | 🟧 | 🟧 | 🟧 | 🟪 | 🟧 | 🟧 | |
| | | LGSFS-ICP | 🟪 | 🟪 | 🟪 | 🟧 | 🟥 | 🟧 | 🟧 | 🟪 | 🟪 | 🟪 | 🟪 | 🟧 | 🟧 | 🟧 | 🟪 | 🟧 | 🟧 | |
| | | Precast Large Concrete Panel system | 🟪 | 🟪 | 🟪 | 🟧 | 🟪 | 🟧 | 🟧 | 🟪 | 🟪 | 🟪 | 🟪 | 🟧 | 🟧 | | 🟪 | 🟧 | 🟧 | 🟪 |
| | | Monolithic Concrete Construction | 🟪 | 🟪 | 🟪 | 🟧 | 🟪 | 🟧 | | 🟪 | 🟪 | 🟪 | 🟪 | 🟧 | 🟧 | 🟧 | 🟪 | 🟧 | 🟧 | 🟪 |

## 3.3. Data calculation for different attributes

This section outlines the data calculation and comparison of the selected building systems against some of the attributes of sustainability. The detailed data calculation framework and comparative performance of building systems against all the 18 attributes is available through the DST.

### Embodied energy

'Embodied energy' is one of the main criteria pertaining to Resource Efficiency of a building system. It has been taken as summation of four components: Primary energy of materials like cement, steel, sand, etc; processing energy for manufacture of building components; construction/installation energy and transportation energy (assumed from common practice) for primary materials to manufacturing plant and finished goods to construction site. The fuel used by lifting and placing equipment, such as cranes has not been considered for precast systems.

There is clear distinction in energy consumption between some of the masonry-based walling systems and emerging systems which involve large scale pre-casting in large factories. For instance, precast large concrete panels consume 8 times the energy consumed by CSEBs (Figure 13). The CSEB system has the lowest embodied energy among the masonry-based options because of significantly lower use of industrial processed material and reduced transportation because of the possibility of production being close to the source of soil and construction site. Which is to say that in the above case, building systems with on-site production have lower embodied energy than pre-fabricated systems. An exception to this is monolithic concrete construction using aluminium formwork, which is cast on-site but has a high embodied energy due to the use of aluminium formwork.

The emerging systems have a significantly higher energy requirement for their large-scale manufacturing facilities. Electricity consumption in these facilities, typically needed for an assembly line of production processes, is a predominant consumer of energy. For instance, in the LGSFS-ICP building system, the energy consumed by batching plants, slip forming machines and cutters is almost 2/3rd of the total embodied energy. Similarly, Monolithic Concrete construction using aluminium or plastic frames consumes significant process energy for high level mechanization and thermal energy for drying of panels (Figure 14).

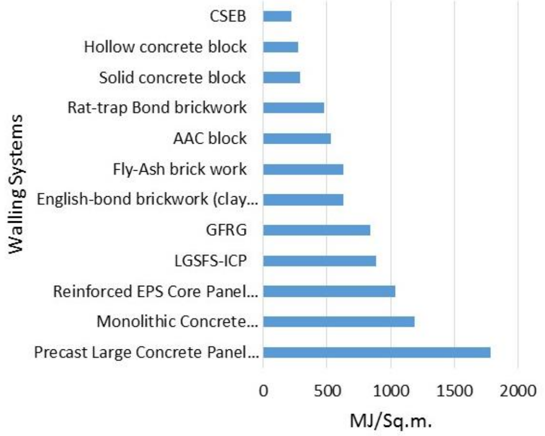

***Figure 13:*** *Embodied energy of selected walling systems*

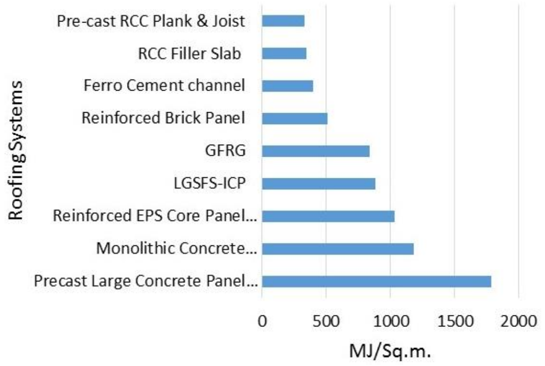

***Figure 14****: Embodied energy of selected roofing systems*

### Critical resource use

Critical resource use is understood from the point of view of minimizing the negative impact of natural resource exploitation which is inevitable in the case of some primary materials that are commonly needed across building systems. The following seven natural resources were identified for the critical resource use index. The criticality of each of these resources *(mentioned for each resource in the list below)* is taken as average of their ranking on three parameters - Scarcity, Environmental impact and Conflict of use – on a 1 (low), 2 (medium), 3 (high) scale.

- Top soil - 2.67
- Sub soil - 2.33
- Sand - 1.67
- Stone aggregate - 2.33
- Steel (Iron) - 1.67
- Cement (Limestone) - 2.0
- Petroleum - 2.0

Weight of the critical resource (as per specifications of the given building system) is calculated per m$^2$ of the wall assembly and its proportion in regard to total weight of wall assembly is calculated. This proportion is multiplied by the respective resource criticality to arrive at a normalized index. A simple average of indices for all applicable critical resources is calculated for the final Critical Resource Use Index for the building system. The index that emerged ranges from 0 to 100, with the lower value being better.

A lower value of this index would be possible through technology improvement measures such as more efficient use of natural resources per quantum of the building technology; part-replacement of critical resources with complimentary materials or industrial wastes and/or ensuring recyclability/re-use of building elements.

Amongst walling systems, English bond brickwork has a considerably high index value of 93 as a result of the predominant requirement of top-soil and also riverbed sand in its brick production and masonry work (Figure 15). Solid concrete block is the highest due to high amount of sand, limestone (cement) and aggregate used. Fly-ash brickwork, precast large concrete panel and CSEB perform well because of a rationalized quantity of cement which is offset by high usage of sand and stone aggregates. Fly ash brickwork performs well because of high usage of non-critical fly ash and no stone aggregates used. Despite containing petroleum-based Styrofoam, EPS core panels have one of the lowest criticality values as the total quantum of material used is low.

Overall for roof systems, the variation in critical resource index is less than in the case of walls, with the range being 0 to 79. It is important to note that the reinforced EPS Core Panel system fares amongst the best for the same reasons as described above. RCC filler slab rationalizes the usage of resources like steel and cement and uses almost 30% of waste material as filler. It can be compared to RCC plank and joist roofing where the overall thickness is rationalized across the span. Ferrocement channel roofing rates highest among roofing systems when the whole assembly of the roofing system is considered, with sand, aggregate and brickbat filling and screed cover, thus resulting in an overall high amount to critical resource use (Figure 16).

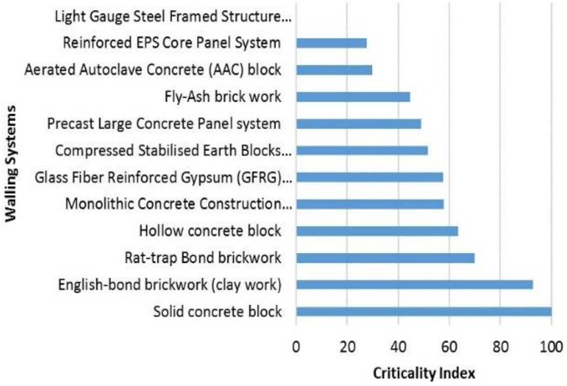

***Figure 15:*** *Critical resource use in selected walling systems*

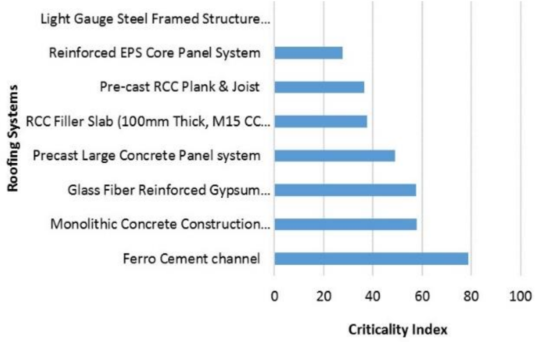

***Figure 16:*** *Critical resource use in selected roofing systems*

### Water use during construction and manufacturing

The water consumption during construction and manufacturing has been calculated on the basis of embodied water co-efficient in different building materials: cement, steel, aluminum, precast concrete and process water for mixing and curing of concrete.

There is a clear distinction between masonry-based technologies and precast technologies. However, it is noteworthy that fly ash brick masonry also needs 1928L/m$^2$ of water for mixing and curing processes (for instance, fly ash bricks are cured for 24 hours in a 66°C steam bath) as compared to, 429L/m2 for burnt clay bricks and 683L/m2 for CSEB (Figure 17). GFRG has the lowest water use as it is produced in a controlled environment and requires no curing on-site. In comparison, LGSFS-ICP has higher water use during construction and manufacturing due to the embodied water in the steel production (Figure 18).

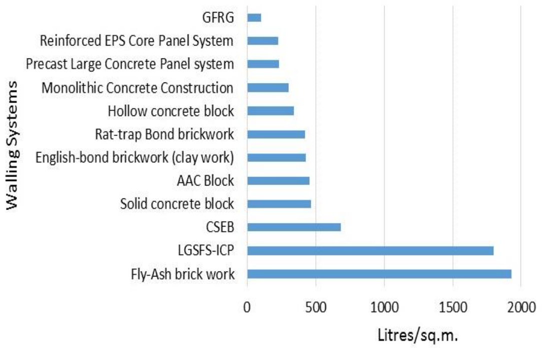

***Figure 17:*** *Water use during construction and manufacturing of selected walling systems*

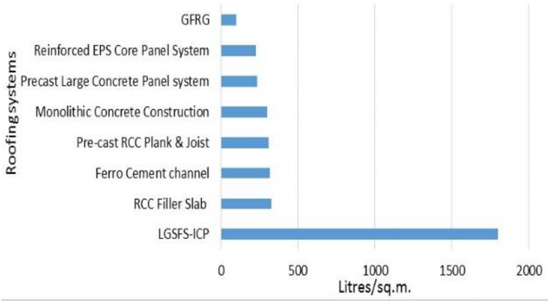

***Figure 18:*** *Water use during construction and manufacturing of selected roofing systems*

## - Thermal performance

Thermal performance of a material is a measure of the thermal transmittance (also known as the U-value) which is the property of heat transmission in time through unit area of a building material or assembly, induced by unit temperature difference between the environments on each side. The lower the U-value of a material, the better is its capacity to resist flow of heat through it.

Monolithic concrete constructions of 100mm RCC walls and roofs have a higher thermal transmittance value (U-value = 3.59 W/m$^2$k) as compared to traditional English bond brickwork (U-value = 2.11 W/m$^2$k) and even lesser for AAC blocks, which for a 200mm thick wall has a U-value of 0.7 W/m$^2$k (Figure 19). However, surveys with several AAC brick manufacturers and developers have indicated that increase in moisture content in these bricks, due to humidity, has resulted in cracks and breakages in the brickwork. In the case of standard rat-trap bond brickwork and hollow concrete blocks, they perform similarly because of the presence of the cavity in both cases.

The thermal performance of LGSFS- ICP it ranks low with a high U-value of 3.87 W/m$^2$k as compared to Reinforced EPS Core panels that have a much greater heat insulating factor with the U-value being low (0.58 W/m$^2$k) as a result of a 70mm thick EPS in the centre which acts as insulation (Figure 20). The thermal performance of LGSFS- ICP depends on the infill panel and not on the framing itself. Therefore, U-value could vary in range.

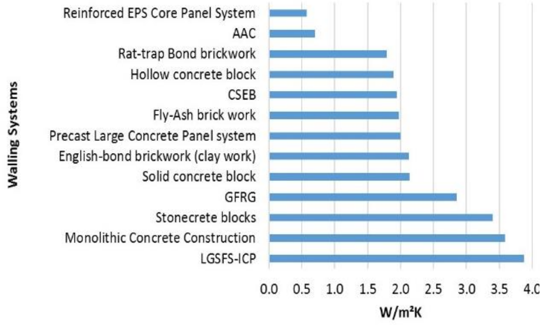

***Figure 19****: Thermal performance of selected walling systems*

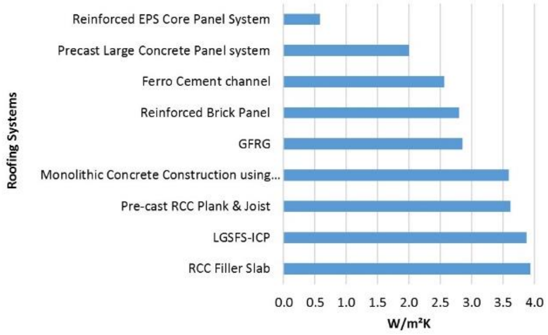

***Figure 20:*** *Thermal performance of selected roofing systems*

## - Construction cost

Construction cost refers to the costs incurred in production of building components and construction process at site. These vary based on the Schedule of Rates of States, but also largely based on the skill requirement as well as availability of labour. However, it is anticipated that with the rising demand in the social housing market and the need for higher speed of construction, the cost of emerging systems will considerably reduce, thus making them affordable.

In the case of CSEB, the construction cost is relatively less, as the production is usually done on site, thus saving on the transportation. Fly ash bricks have for many years been competing with the burnt clay bricks in terms of cost, and with several incentives as well as the implementation of bye-laws, fly ash bricks now have a comparative advantage over burnt clay bricks. In the case of both walling and roofing systems, GFRG to date has the highest construction cost, as the market for emerging, prefabricated building systems is still at the nascent stage.

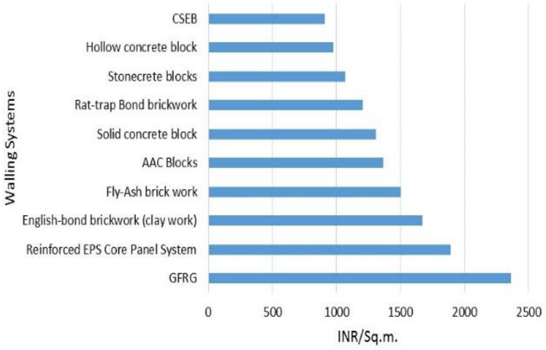

**Figure 21:** *Construction cost of selected walling systems*

**Figure 22:** *Construction cost of selected roofing systems*

## • Job creation

Job creation refers to the amount of employment generated both skilled and unskilled in terms of man-days (8hours) per sq. m of the built-up area. With the data provided on number of manpower required for the manufacturing as well as on-site construction, the job creation potential was calculated for each of the building materials and systems.

As is observed from the graph, English bond brick work and rat-trap bond brickwork generate the maximum number of man-days/m$^2$ thus ensuring that there is a large labour force that is employed. This in comparison of large, highly prefabricated building systems like precast large concrete panels that generate 0.08 man-days/m$^2$. There is a trade-off that needs to be made in terms of speed of construction as well as local unskilled/semi-skilled employment generation. The difference ranges from the scale of production and construction to the kind of skill that is required. In the case of CSEBs, as the blocks are produced on-site, a large work force is required for production of blocks and consequently for construction purposes.

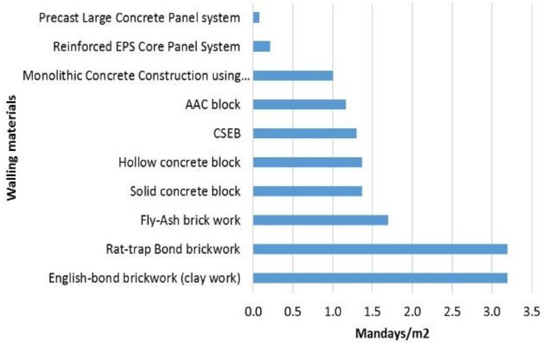

**Figure 23:** *Job creating potential of selected walling systems*

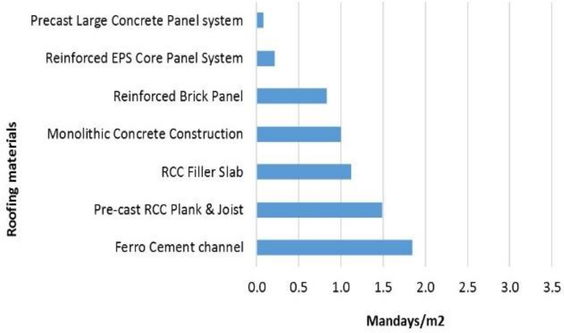

**Figure 24:** *Job creating potential of selected roofing systems*

## • Impact of building systems on cooling and heating energy consumption

Thermal simulations were carried out using the 17 building systems as per the methodology described in chapter 1. The purpose of the exercise was to calculate and compare the heating and/or cooling energy required to provide optimum indoor temperatures for a dwelling unit constructed using conventional building systems (walling and roofing) vis-a-vis the selected alternate building systems (listed in this chapter). Figure 25 and Figure 26 show the potential energy savings associated with the use of the 17 building systems in the five climatic zones of India (Refer Annex 5 for energy savings in kWh/m$^2$/yr).

Since the simulation only tested the impact of change in roofing and/or walling system, the results obtained were as expected. The building systems with lower U-values (AAC blocks wall system and Reinforced EPS Core Panel System) showed more energy saving potential across all climatic zones. However, the exercise was imperative in the context of the project, as it provided quantitative data for developing the Sustainability Assessment Tool (SAT) described in the following chapters.

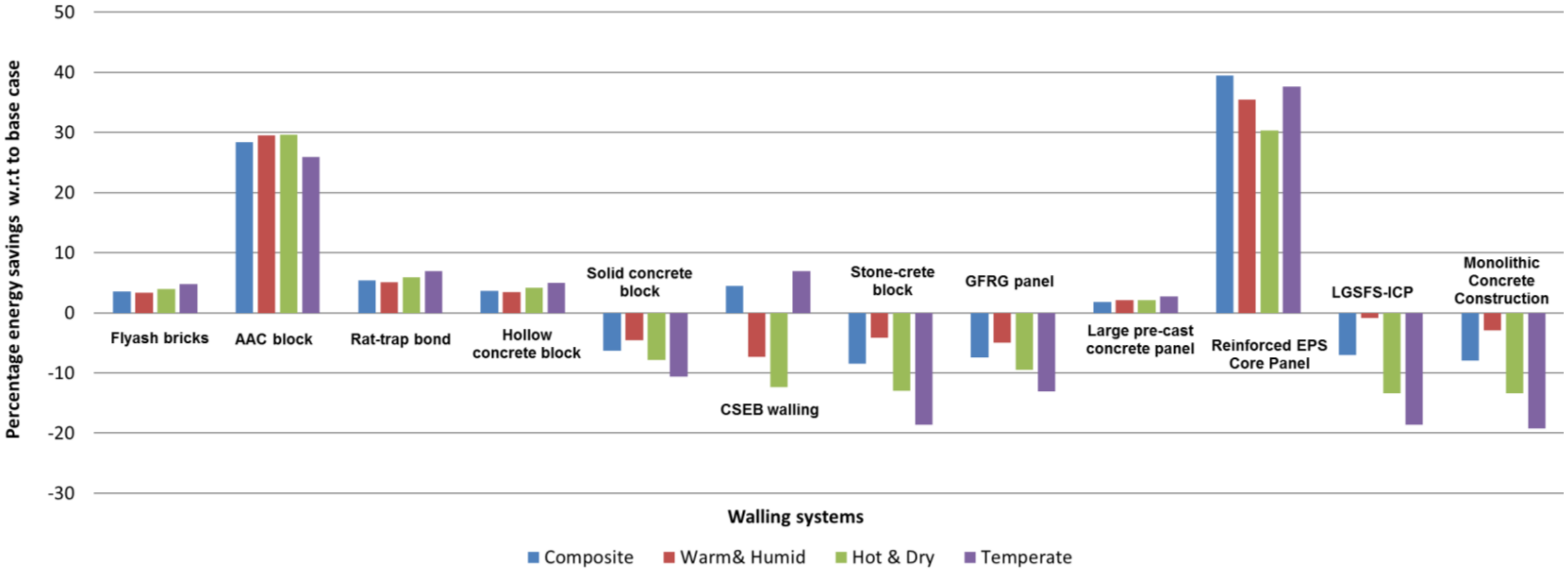

***Figure 25****: Impact of walling systems on cooling energy consumption w.r.t to the base case*

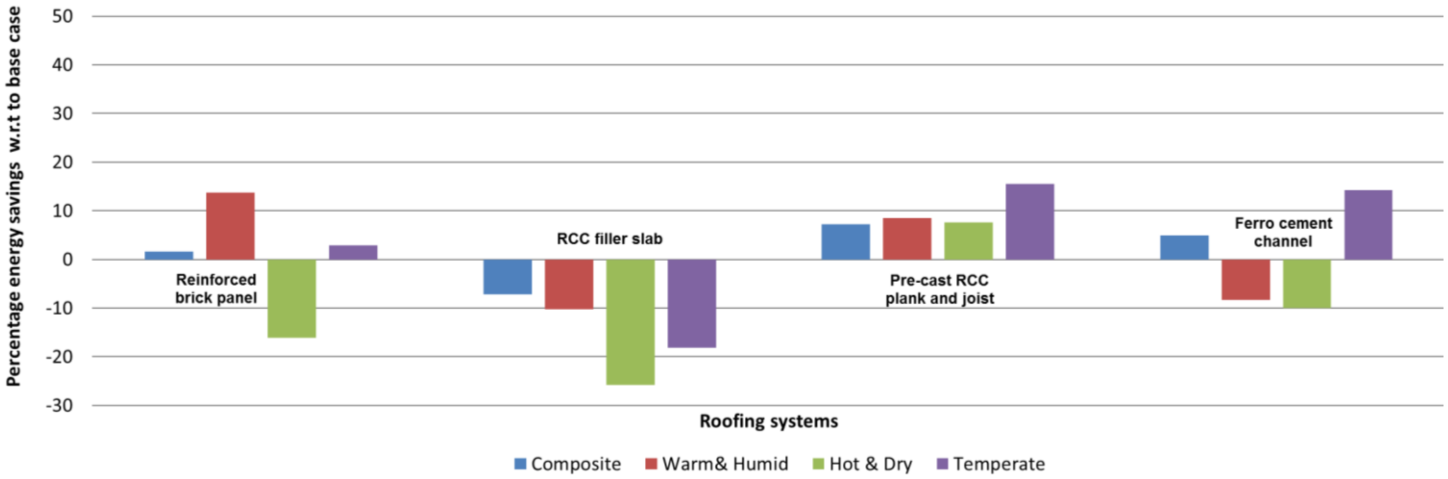

***Figure 26:*** *Impact of roofing systems on cooling energy consumption w.r.t to the base case*

## 3.4. Summary

Preferences under the sustainability criteria play a major role in the selection of appropriate building materials and systems for social housing projects. With the emergence of new and emerging systems in the Indian construction market, there have been several contentious views on their use and sustainability, especially in the context of social housing.

However, the above comparison suggests that a building system that performs well with respect to resource efficiency may not perform as well with respect to operational performance or cost economics. Building systems were found to perform at different levels across the defined attributes, for example a system that performs well with respect to embodied energy may not necessarily perform very well with respect to material resource input; and one that performs well with respect to cost of construction may not have a high job creation potential.

A holistic outlook needs to be embedded in the decision-making processes when visualising future housing needs in the time of extreme natural resource depletion and climatic uncertainties. The Sustainability Assessment Tool (SAT) of the Decision Support Toolkit has therefore been built for this purpose to provide the targeted beneficiaries with evidence-based performance information, for selecting appropriate building materials and systems for the social housing sector.

# Chapter 4

# Resident experiences of building systems and living in social housing developments

This chapter describes the methodology and lessons learnt from the resident survey of nearly 723 social housing dwellings located in five case study developments. There is limited empirical evidence regarding the experiences of EWS or LIG residents, including the extent to which they view their homes as adequate, and their perspectives on various building materials and systems. The resident survey was conducted to gather feedback from residents about their perception of the indoor environmental conditions (indoor temperature and air quality) in their homes during summer and winter, along with aspects of maintenance and upkeep of the development, familiarity with the building materials, and access to basic day to day necessities around the development.

Resident experiences were enumerated as an attribute of the "User Experience" criterion explained in Chapter 2. Data was gathered from, five social housing developments, located in five cities, representing three climatic zones of India. These social housing developments were selected based on the following criteria:

- Geographical location (climatic zone).
- Type and scale of the cities in which they are located
- Share of urban housing shortage and the Average Annual Exponential Growth Rate in the state.

The base data along with the details of building materials and systems used were collected for all the selected social housing developments. Basic details of all the case study developments are available in Annex 6.

Of the five case study developments, the housing in Bangalore and Dehradun had been developed by the Building Materials and Technology Promotion Council (BMTPC) to demonstrate and promote the use of cost-effective materials and systems for use in social housing projects in India. Alternative environmentally friendly materials and systems had also been adopted in the Bawana Industrial workers housing to construct energy efficient and cost-effective dwellings. Through desk research the details of various building materials used in the selected social housing developments were also gathered (Table 8).

## 4.1. Methodology for conducting resident surveys

The following methods were adopted to collect data from the residents of social housing developments: (1) Interview based questionnaire survey (2) Observations of researchers and (3) Photographic survey of the dwellings and surroundings to capture the existing conditions.

- ### Questionnaire survey

The survey questionnaire was designed based on Likert scale and consisted of questions on aspects of indoor environmental conditions; daylight and ventilation; experience with the building materials and system; maintenance and up-keep of the common areas and accessibility to basic public facilities. Although the three climatic zones covered in this study differ in their seasonal temperature variations there are transition periods where outdoor conditions are more comfortable. The survey, therefore, focused on gaining feedback on a general perception during the hot and cold seasons (summer and winter) only, thereby also allowing for the universal applicability of the questionnaire survey across all the selected locations. Additionally, the questionnaire design was deliberated based on the sociological and educational background of the respondents. To assess householder perception of indoor environment, easy-to-understand questions on the perception of ‘indoor temperature and indoor air’ were included, and the rating scale was limited to a scale of three. It is to be noted at the outset that in this study, *‘bearable’* is assumed to relate with the capacity of residents to extend their comfort range over a period of time. The quality of building materials used and the general comfort conditions and well-being of the residents living in the development were assessed by inquiring about the physical condition of the building (presence of dampness) and the maintenance and cleanliness regime of the surroundings.

For easy comprehension the questionnaires were translated into the local languages (Delhi, Dehradun and Jaipur – Hindi; Vijayawada- Telugu; Bangalore-Kannada) and the householder responses were later translated back to English for analysis. The survey was conducted by students (researchers) trained by the MaS-SHIP team, from local educational institutions. The students were trained through training workshops and mock

***Table 8:*** *Building materials and systems used in the five case study social housing developments*

| Category | Foundation | Superstructure | Roof / Floor | Doors and windows |
|---|---|---|---|---|
| **Delhi** | - Under-reamed pile foundation | - Single brick thick load bearing wall using combination of modular FalG & mechanised modular perforated bricks<br>- Precast Ferro cement steps for stairs and kitchen shelves<br>- Precast R.C. sunshade<br>- Use of fly ash with cement mortars | - Precast RC Plank and Joists.<br>- Cast in-situ RCC waist slab. | - Second class Teak wood door and window frames and flush door<br>- Pre-cast lintel |
| **Jaipur** | - | - Fly ash brick<br>- RCC plinth and roof level band | - RCC slab | - Timber |
| **Dehradun** | - Step footing in solid concrete blocks | - Solid/Hollow Concrete Blocks<br>- RCC plinth, lintel, roof level band, vertical reinforcement in corners for earthquake resistance | - RCC planks and joists<br>- IPS flooring | - Pre-cast RCC door frames<br>- Coir polymer door shutters<br>- Clay jalli in ventilators |
| **Bangalore** | - Random rubble stone masonry | - Solid concrete blocks for 200 mm thick walls<br>- Clay bricks for partition walls<br>- RCC plinth band for earthquake resistance | - RC filler slab using clay bricks as fillers in ground and first floors<br>- IPS flooring | - Pre-cast RCC door frames<br>- Coir polymer door shutters<br>- Clay jalli in ventilators |
| **Vijayawada** | - | - Fly ash brick | - RCC slab | - |

surveys conducted by the MaS-SHIP team. A batch of 10 students took 4 days to complete the survey of about 150 households at each location.

Households were selected through random sampling and were generally suggestive of the availability of the members in the house as well as their eagerness to participate in the survey. While conducting the surveys, the responses were gathered from the available adult at home, and the feedback was assumed to be the general perception for that household. Therefore, each survey response represents a single dwelling unit in the respective development. The householder survey questionnaire can be accessed from the 'For Whom' tab under the DST.

- ### Photographic survey

After seeking permission from the resident/s, the researchers conducting the survey took digital pictures of the interiors of the dwellings and the surrounding areas to provide contextual data about the physical environment.

- ### Researcher observations

The researchers also recorded their experience of conducting the survey and observations about the development, by completing two personal logs - one at the end of day one of the survey, and the second after completing the survey for the development. The information derived from the student logs generally helped to triangulate the findings from the questionnaire survey, and at places also provided additional feedback regarding various aspects for that particular development. Some of the conclusions made in this study were also derived from the students' observations.

## 4.2. Survey analysis

- ### Perceived indoor environmental conditions

The survey revealed that overall of the 723 surveyed households across the five case study locations, only 16% (118 out of 723) *perceived indoor temperature* to be *satisfactory* during summer, whereas during winter 18% of households perceived indoor temperature to be *unsatisfactory.* During winter the number of households perceiving indoor temperatures as *bearable* increased only marginally compared to during the summer, but the number of households satisfied with the indoor temperature nearly doubled (Table 9).

Due to the extreme external temperatures during summer and winter, a similar proportion of households across the three social housing developments located in composite climatic zone perceived indoor temperatures to be *unsatisfactory* during summer. In winter in four of the five case study locations majority of the residents perceived indoor temperature to be 'just' *bearable* (Table 9). The exception was in Jaipur, where majority of the households perceived indoor temperature to be *satisfactory*. Despite the relatively moderate external temperatures in the Temperate and Warm & Humid climatic zones for the two case study developments located in these zones, majority of the residents perceived indoor temperature to be 'just' *bearable* during both summer and winter. Interestingly, in Bangalore (temperate climate), the number of households *unsatisfied* with the indoor temperature, were found to be highest for both summer and winter period. This can be attributed to the higher U-value (2.70 W/m$^2$K) of the walling system (solid concrete blocks) used in the dwellings in Bangalore.

The survey results for householders' perception of indoor air quality showed that regardless of their geographical location, residents across the five social housing developments largely perceived air quality in their dwellings to be 'just' *bearable* during both summer and winter. However, during summer the majority of households perceived indoor air quality to be *bearable*, with the exception of the case study development in Dehradun, where the majority of surveyed households perceived air quality in their dwellings to be *stuffy*. The highest numbers of households reporting stuffy indoor air quality during summer were found in the two surveyed developments in the composite climatic zones (Delhi, and Dehradun). Consequently, the number of households perceiving indoor air quality as *fresh* were found to be lowest in these developments. It is worth noting that for the social housing developments located in the Temperate and Warm & Humid climatic zones, a nearly similar number of households perceived air quality in their dwellings to be either *stuffy* or *fresh* during the summer. In winter, the perception of indoor air quality seemingly improved, but became only more *bearable* across the five case studies: as the number of households perceiving stuffy indoor air quality reduced, *bearable* perception increased (Table 10).

Although actual monitored data for air quality is required to validate these findings, the relatively 'poor' perception of indoor air quality in these dwellings can be attributed to the poor design and planning of the window openings as well as unhygienic surroundings around the dwellings. In the surveyed development in Vijayawada, though the dwelling units were provided with adequate windows and ventilators in each room, these opened into the central access corridor or the staircase area, and therefore had to be kept closed due to privacy and security issues (Figure 27). Similarly, many surveyed households in Bangalore reported keeping the windows closed due to privacy issues. Some of them were also forced to keep their windows closed to avoid mosquitoes from entering their homes.

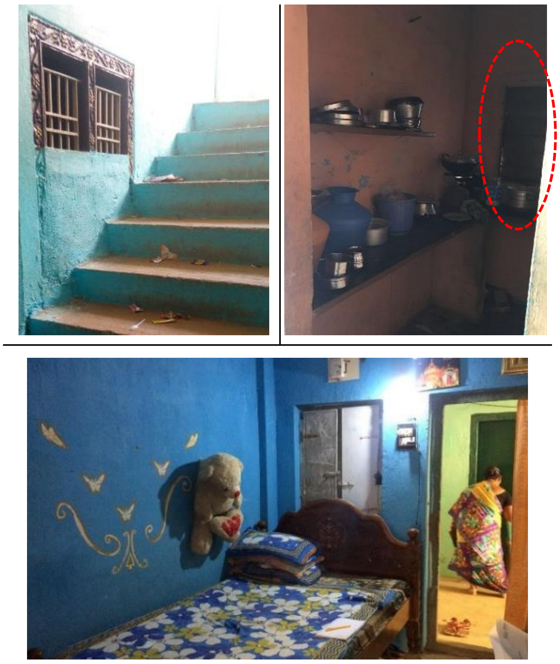

***Figure 27:*** *Window location in dwelling units in Vijayawada (top left and bottom) and Bangalore (top right)*

**Table 9:** Perceived indoor temperature across five case studies

| Climatic zone | Case study location | Summer | | | | Winter | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Unsatisfactory | Bearable | Satisfactory | Total responses | Unsatisfactory | Bearable | Satisfactory | Total responses |
| **Composite** | **Delhi** | 56 | **73** | 19 | 148 | 20 | **94** | 32 | 146 |
| | **Jaipur** | **59** | **58** | 33 | 150 | 20 | 59 | **71** | 150 |
| | **Dehradun** | **54** | **52** | 14 | 120 | 25 | **59** | 36 | 120 |
| **Temperate** | **Bangalore** | 66 | **71** | 18 | 155 | 49 | **81** | 25 | 155 |
| **Warm-humid** | **Vijayawada** | 37 | **81** | 34 | 152 | 16 | **74** | 62 | 152 |
| **Total responses** | | **272** | **335** | **118** | 723 | **130** | **367** | **226** | 723 |

This in turn also reflected in the poor levels of natural (day) lighting in these dwellings. The highest percentage of households reporting the need to use electrical lighting during the day were found in the surveyed development in Vijayawada (58%), followed by households in Bangalore (52%) and Delhi (38%) (Figure 28).

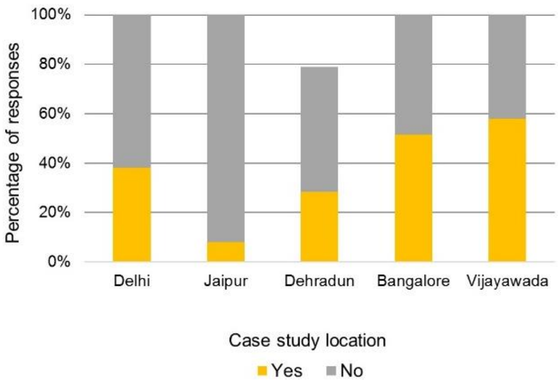

***Figure 28:*** *Householders' response regarding need to use artificial lighting during the day*

Interestingly, the flawed window locations did not seem to have any significant impact on the residents' perception of indoor air movement in their dwellings during summer and winter. Also, the effect of climatic conditions on the residents' perception/need to use ventilation for achieving thermal comfort was evident from the highest number of households perceiving their dwellings to be well-ventilated during both summer and winter found in the surveyed developments in Vijayawada and Bangalore (Table 11). For two of the three the developments located in the composite climatic zone (Delhi and Jaipur), the majority of the householders perceived their dwellings to be *well-ventilated* during summer. In Dehradun, however, the majority of the households perceived *still* air inside their dwellings.

When asked about their overall perception of indoor environment in their homes, residents across the three climatic zones seemed more forgiving as they possibly adapted to their existing conditions. Despite perceiving indoor temperature and air to be 'just' bearable, the majority of householders in the surveyed development in Vijayawada reported overall perception as satisfactory during both summer and winter, whereas the majority of residents at the remaining four surveyed developments felt only bearable with their overall experience of the indoor environment during summer. Similarly, during winter in three locations (Delhi, Dehradun and Bangalore), the number of households experiencing overall bearable indoor conditions was found to be highest even in winters. However, in the case study development in Jaipur, the majority of households reported feeling satisfied with their overall experience. Regardless of their geographical locations/climatic conditions, a similar number of households in Delhi, Jaipur, Dehradun and Bangalore reported feeling unsatisfied with their overall experience during summer. However, the level of dissatisfaction seemed to be much less in winter, with the number of unsatisfied households reducing to less than half compared to summer across the five case study developments (Table 12).

Overall, across the three climatic zones, nearly one third of the surveyed households reported experiencing 'only' bearable indoor environmental conditions in their dwellings during both summer and winter. However, the number of households that were completely unsatisfied with their overall experience of the indoor environment in summer was found to be nearly twice of that during winter. Likewise, the number of households with satisfactory overall experience in summer was nearly two thirds of that in winter.

***Table 10:*** *Perceived indoor air quality across five case studies*

| **Climatic zone** | **Case study location** | **Summer** | | | **Total responses** | **Winter** | | | **Total responses** |
|---|---|---|---|---|---|---|---|---|---|
| | | **Stuffy** | **Bearable** | **Fresh** | | **Stuffy** | **Bearable** | **Fresh** | |
| **Composite** | **Delhi** | 68 | **73** | 7 | 148 | 25 | **112** | 9 | 146 |
| | **Jaipur** | 37 | **85** | 28 | 150 | 18 | **111** | 32 | 150 |
| | **Dehradun** | **52** | 42 | 26 | 120 | 25 | **57** | 38 | 120 |
| **Temperate** | **Bangalore** | 41 | **74** | 40 | 155 | 26 | **96** | 33 | 155 |
| **Warm-humid** | **Vijayawada** | 49 | **55** | 48 | 152 | 25 | **65** | 62 | 152 |
| **Total responses** | | **247** | **329** | **149** | 723 | **119** | **441** | **163** | 723 |

***Table 11:*** *Perceived indoor air movement across five case studies*

| Climatic zone | Case study location | Summer | | | Total responses | Winter | | | Total responses |
|---|---|---|---|---|---|---|---|---|---|
| | | Draughty DW | Still | Well-ventilated | | Draughty DW | Still | Well-ventilated | |
| Composite | **Delhi** | 2 | 59 | **87** | 148 | 30 | **59** | 57 | 146 |
| | **Jaipur** | 29 | 50 | **71** | 150 | 2 | 70 | **78** | 150 |
| | **Dehradun** | **9** | **65** | 46 | 120 | 4 | 50 | **66** | 120 |
| Temperate | **Bangalore** | 4 | 46 | **105** | 155 | 3 | 36 | **116** | 155 |
| Warm-humid | **Vijayawada** | 0 | 52 | **100** | 152 | 0 | 24 | **128** | 152 |
| Total responses | | **44** | **272** | **409** | 723 | **39** | **239** | **445** | 723 |

***Table 12:*** *Overall experience in summer and winter across five case studies*

| Climatic zone | Case study location | Summer | | | Total responses | Winter | | | Total responses |
|---|---|---|---|---|---|---|---|---|---|
| | | Unsatisfactory | Bearable | Satisfactory | | Unsatisfactory | Bearable | Satisfactory | |
| Composite | **Delhi** | 49 | **81** | 18 | 148 | 16 | **100** | 30 | 146 |
| | **Jaipur** | 40 | **71** | 39 | 150 | 12 | **67** | **71** | 150 |
| | **Dehradun** | 43 | **68** | 9 | 120 | 15 | **68** | 37 | 120 |
| Temperate | **Bangalore** | 47 | **72** | 36 | 155 | 32 | **80** | 43 | 155 |
| Warm-humid | **Vijayawada** | 14 | 67 | **71** | 152 | 9 | 49 | **94** | 152 |
| Total responses | | **193** | **359** | **173** | 723 | **84** | **364** | **275** | 723 |

- ### Experience of building systems

The study also focused on visually analysing the quality of construction and building materials used in the surveyed developments and sought the residents' perception of it through the survey questionnaire. During the interview the researchers inquired about the presence of dampness in that particular dwelling and its specific location. They then prompted the respondents to choose one or multiple responses from the given options as to what they perceived the cause of it to be. The use of materials like modular Fal-G brick, fly ash bricks, solid/hollow concrete blocks, clay bricks etc may have proven to be cost effective, but the state of the dwellings revealed the poor quality of construction workmanship and materials in the form of dampness inside many surveyed households. It was observed that of the 726 responses gathered across the five different locations, 50% householders reported the presence of dampness in their dwelling. The highest proportion of dwellings experiencing dampness were found in Dehradun, followed by dwellings in Delhi (Gupta et al., 2018) (Figure 29). The residents in these locations mainly perceived leaking pipes (poor plumbing) and building materials not being water resistant as the primary reason for the occurrence of dampness (Figure 30). The higher incidence of dampness in Dehradun can also be ascribed to a higher rainfall and poor maintenance of the dwellings which are nearly 12 years old and one of the oldest among the five case studies.

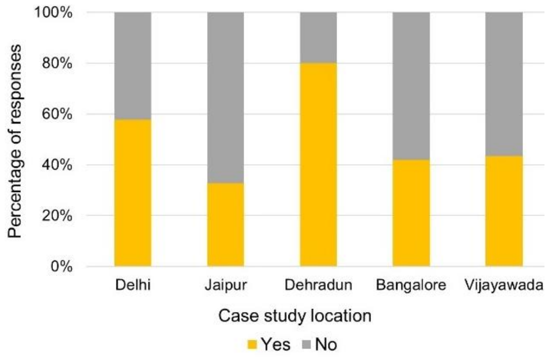

***Figure 29:*** *Presence of dampness in households as per location*

The survey questionnaire also focused on gathering feedback from the residents regarding their experience with the building materials used in the dwellings. The survey question asked in this context prompted the responders to choose one or more response/s from the given options. Figure 30 shows the distribution of the survey responses across the five case study developments.

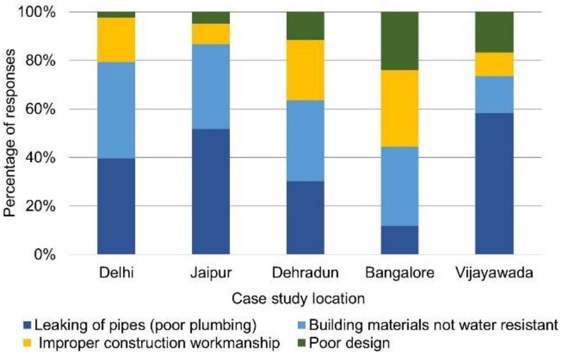

***Figure 30:*** *Perceived causes of dampness by householders at the five surveyed locations*

With the exception of surveyed households in Vijaywada (where nearly 41% of residents reported satisfaction) very few households were found to be satisfied with the building materials used in their dwellings. Nail-ability (i.e. the ability [of a wall] to be nailed) emerged as a reason of dissatisfaction among the majority of the residents across all the surveyed developments. A substantial number of residents in the surveyed developments in Delhi, Bangalore and Vijayawada also expressed problems in altering the location of electrical points on the walls as an issue. Overall across the five surveyed social housing developments, only 22% of the residents expressed satisfaction with the building materials. 36% expressed nail-ability of the walls as an issue, while 17% cited difficulty in adding/changing electrical points.

- **Maintenance and up-keep**

The researchers also asked the householders about the maintenance and repair mechanisms in place for the development and if they paid any charges for maintaining the common areas of the building and its surroundings. The survey revealed that such mechanism was absent in all surveyed developments, except for the housing development in Vijayawada which had a Residents' Welfare Association that carried out the cleaning and maintenance of the site. The impact of this could be clearly seen during the site visits to housing developments in Delhi, Jaipur, Dehradun and Bangalore. Garbage accumulation along the streets and water logging due to poor drainage systems were a common sight across the five surveyed social housing developments. In Bangalore, the residents also expressed their dissatisfaction about the incomplete roadworks in the development, which also contributed to water logging during monsoons. A few residents reported cleaning the immediate surroundings of their dwellings, but the developments at large lacked cleanliness and hygiene (Figure 31).

***Figure 31:*** *View of street in surveyed developments in Delhi (top left), Jaipur (top right) and Bangalore (bottom)*

- **Location and accessibility to the basic public facilities**

The significance of availability of basic services at convenient vicinity from a housing development has been recognised by various recent researchers as well as green building certification bodies in India (Kumar et al, 2018 and IGBC Rating System for Green Affordable Housing: Pilot Version, 2017). This was reinforced by the survey findings regarding aspects related to the location of the developments. The distance of the housing development from the city centre (Table 13) had a direct impact on the resident's satisfaction or dissatisfaction with the connectivity to the various facilities around the surveyed developments.

***Table 13:*** *Distance of the case study developments from the city centre*

| Case study location (city) | Distance from city centre (km) |
|---|---|
| **Delhi** | 30 |
| **Jaipur** | 19 |
| **Dehradun** | 1 |
| **Bangalore** | 13 |
| **Vijayawada** | 11 |

In terms of convenient proximity to their work place, except for Jaipur[2], the residents at all the other locations reported that their work place was at a convenient distance from the development. However, in the case of the surveyed development in Delhi, though the majority of the residents reported that their place of work was at a convenient distance from the development, it is worth noting that majority of these residents were living in homes that had been rented from the original owners, who had moved back to locations closer to their workplace.

Since the social housing developments in Dehradun, Bangalore and Vijayawada, are relatively close to the main city centre, higher percentages (43-48%) of residents reported having access to public transport to commute to their place of work, compared to only 20-25% of the residents in Delhi and Jaipur. Consequently, a higher percentage (14%) of households in Jaipur reported facing issues with the availability of conveyance (Figure 32).

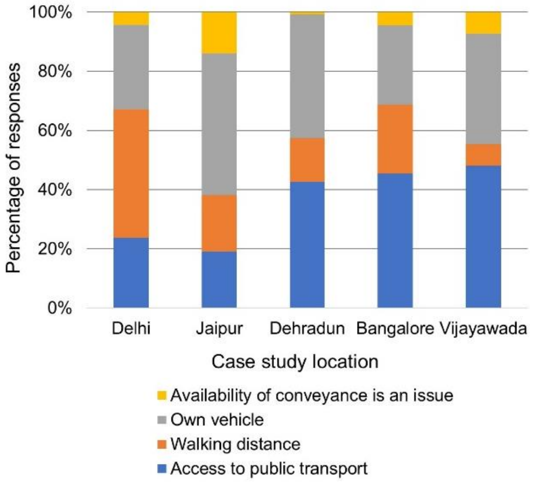

***Figure 32:*** *Mode of travel to work as per location*

Similarly, when asked about the ease of access to basic facilities like hospitals, nearly 51% of the surveyed households in Jaipur reported that availability of conveyance to travel to hospital was an issue. A substantial percentage of residents (21%) in Delhi also reported availability of conveyance as an issue to travel to hospitals and other places of necessities. For the social housing developments surveyed in Bangalore and Vijayawada, the majority of residents reported that basic amenities were within walking distance of the development (Figure 33).

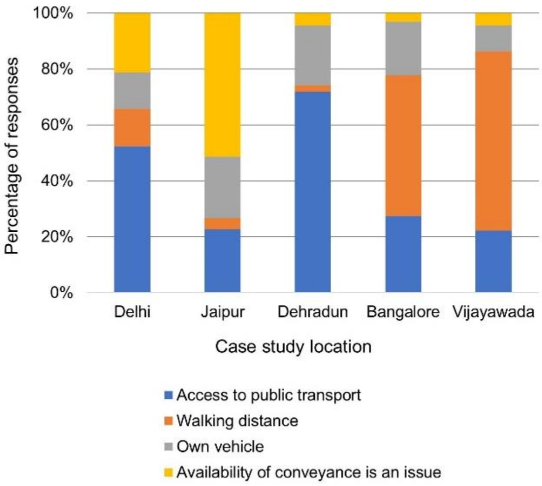

***Figure 33:*** *Mode of travel to hospitals as per location*

## 4.3. Key findings

The survey results revealed that regardless of the geographical location or the materiality of the dwellings, the dwellings were unable to provide a comfortable indoor environment. Across the three climatic zones covered in this study, the majority of householders perceived indoor temperature and air quality to be ‘just’ bearable during both summer and winter. However, the level of dissatisfaction with the indoor temperature was found to be much higher in summer compared to that in winter across the five case study locations, indicating the inability of the building envelope to keep the heat out when it is most required. During winter, however, higher levels of adaptation occur wherein residents resort to warm clothing and blankets, along with a reduced heat loss due to small size/exposure of the dwelling units.

Despite the poor window design and orientation, residents across the five surveyed developments reported their dwellings to be well-ventilated during both summer and winter. Interestingly, this did not help improve their perception of ‘indoor air quality’ since the majority of residents across the five case studies perceived air quality to be ‘just’ bearable during both summer and winter. Natural ventilation in buildings, though, depends on various factors like wind speed and direction, building orientation and fenestration design etc. It also depends on the occupant behaviour, especially in naturally ventilated buildings. Since the residents of these dwellings rely largely on natural ventilation to

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[2] *The housing development was developed to provide housing for daily wage works and vendors working in the local farmer’s market. The location of the development though away from the city centre is at close proximity for the residents from their place of work.*

enhance indoor comfort during both summer and winter, they make use of the available fenestrations (including doors) to allow for air movement. Apart from improving the building envelope to reduce heat gain in summers, providing passive cooling measures therefore becomes an important aspect of design for these dwellings.

Inadequate levels of daylight seem to have worsened the comfort levels of the residents across the five case studies. This has happened due to the poor configuration of the blocks and design of dwelling units wherein windows sometimes open into the staircase or communal area. Due to privacy issues, windows cannot be then used for airing the dwelling. Poor levels of workmanship and construction quality have led to ingress of dampness in the dwellings. The residents across the five case studies largely seemed to have concerns regarding the building materials used in the construction of these dwellings. The attribute ‘modification ability’, the nail-ability of the walls and the difficulty in making basic alterations to the interiors due to the poor quality of the plaster, or brittleness of the bricks, emerged as their reasons of dissatisfaction with the building material. Proper maintenance regime was found missing across the case studies, resulting in unhygienic conditions in and around the developments. There was no garbage disposal or maintenance system in place and inappropriate planning of drainage systems resulted in water logging on the streets creating unhygienic conditions and posing a health hazard to residents of these developments.

## 4.4. Summary

This study has revealed, for the first time, resident perception and experiences of inhabiting social housing developments in India and helped the project team to gather qualitative data under the criteria of ‘User experience’. The findings reveal that the attribute of ‘modification ability’ of a building material/system greatly influences the user’s perception of it. Additionally, the results also showed that the quality of indoor environment, quality of the interiors, the maintenance and up-keep of the surroundings and availability of job opportunities at convenient vicinity are important factors in determining the level of ‘satisfaction’ of the residents.

It is evident that selection of appropriate building materials and systems at the design stage is not enough for achieving sustainable social housing. Much more needs to be done during the design, construction and operation stages if these developments are to be truly sustainable and livable for the residents. This is what the MaS-SHIP Decision Support Tooklit (DST) is seeking to achieve, as described in the following chapter.

# Chapter 5

## Tools for informing design and performance of building systems in social housing

The data and knowledge assimilated in the research was brought together in the form of a web-based Decision Support Toolkit (DST) with embedded tools, to enable practitioners, housing developers and policy-makers for integrating sustainability concepts in the planning, design and selection of building systems in social housing projects. This chapter describes the scope, application and pilot testing of the DST and its key tools – Sustainability Assessment Tool (SAT) and Materials Mapping.

## 5.1. Decision Support Toolkit (DST)

The Decision Support Toolkit (DST) is an interactive web-based toolkit that not only helps to bring together the outputs and insights from the project, but also provides a unique platform in the social housing sector with data and knowledge on various aspects of sustainable (social) housing. The DST is developed with an aim to enable developers, practitioners and policy-makers to integrate sustainability concepts in the planning, design and specification of social housing projects in India.

The DST, which is accessible from the MaS-SHIP project website is designed to address the requirements of different stakeholders involved in the social housing sector. It is organised around the following key questions:

### Why should sustainability be integrated in social housing projects?

Before delving into ways of incorporating sustainability measures in housing, the DST helps the user understand why this should be done. This section helps the users of the toolkit to familiarise themselves with the social housing sector through its realities today, national policy scenario, best practice examples and opportunities for sustainability in the Indian housing sector.

### How should sustainability be integrated into the design of social housing across different climatic zones in India?

The practice of sustainability is still at an early stage in the Indian housing sector. The most efficient way for achieving sustainability is to incorporate its principles in the planning and design stage of the project. There is information available to guide practitioners in this aspect, but this is largely fragmented and available in different versions pertaining to different sources. This section of the toolkit collates the principal design guidelines for sustainable housing in five climatic zones in India. These guidelines drawn from existing literature in the Indian context, data collected in the project as well as findings from the resident's experiences gathered from surveys of housing projects. The guidelines provide an overview of different aspects to be addressed at project conception stage, including passive design strategies, material use and its impact on energy consumption for indoor comfort, maintenance and up-keep of the site and water conservation measures. The guidelines though brief, serve the purpose of directing the user's thoughts towards different aspects and ways of integrating sustainability in social housing projects.

### What sustainable building materials and systems are appropriate for social housing projects? What criteria should be used to evaluate their performance?

This section is the core part of the DST and brings together all data collected on building materials and systems which can be considered for social housing. The data for each building system is organized as pertaining to a set of attributes identified and defined by the project. This is intended to assist the user in making an informed choice of building materials and systems by evaluating their sustainability through multiple criteria. The following information is available in this section:

- Sustainability attributes for evaluating building materials and systems,
- 17 catalogues for building materials and systems providing data on their performance against the framework of 18 sustainability attributes,
- Analysis of comparative performance of these building systems with respect to sustainability,
- A User guide to using the Sustainability Assessment Tool (SAT),
- The Sustainability Assessment Tool (refer section 5.2).

### Where are these sustainable building materials available?

The construction sector in India is very diverse and unorganised in nature. About 98% of the construction companies are small and medium scale enterprises. Unlike the manufacturing industry, it is not always repetitive and is project specific and

MaS-SHIP Mainstreaming Sustainable Social Housing in India Project

MaS-SHIP- Decision Support Toolkit

*Integrating sustainability in social housing in India*

| WHY | HOW | WHAT | WHERE | FOR WHOM |
|---|---|---|---|---|
| *Why should sustainability be integrated in social housing projects? Why does this matter?* | *How should sustainability be integrated into the design of social housing across different climatic zones in India?* | *What sustainable building materials and technologies are appropriate for social housing projects? What criteria should be used to evaluate their performance?* | *Where are these sustainable building materials available?* | *Who are the residents of social housing and what are their experiences of living in such developments?* |

Policy measures for mainstreaming sustainable social housing

Decision making using the sustainability assessment tool

Institutional mechanisms for adopting DST

***Figure 34**: Snapshot of Decision Support Toolkit (DST)*

dependent on the source of the local material. A key aspect which governs selection of building materials and systems is transportation distance for delivering materials to construction site and the associated transportation cost. This section provides a guide to the user to locate existing building material manufacturers across the country, with basic information given on each manufacturer for ease of communication. Thus, the user can make an informed decision on the choice of material or system to be used, based on the estimated distance and scale of supply of the manufacturing unit to the proposed construction site.

Also given in this section are formats for recording basic information about building material/system and for specific details of a social housing project. This is to enable the addition of new materials to the DST and to the GIS-based database to maintain the dynamic nature

### Who are the residents of social housing and what are their experiences of living in such developments?

This section provides the users, access to the findings from the case study of the five social housing developments (discussed in Chapter 4) in different climatic zones. The case studies are based on surveys of 723 residents belonging to the five housing developments. The resident surveys gather user experience with indoor environment (air temperature, air quality, air movement, overall experience), natural light, problems of dampness, quality of construction and accessibility to amenities.

## 5.2. Sustainability Assessment Tool (SAT)

The Sustainability Assessment Tool (SAT) is one of the key components of DST (Figure 35) and was developed using a Multi-Criteria Decision Making (MCDM) method to enable developers and designers make informed decisions regarding the selection of building materials and systems for walling and roofing, for deploying in social housing projects in India. Presently SAT evaluates 12 established and 5 emerging building materials and systems against the 18 attributes described in Chapter 3. SAT is an easy-to-use, interactive excel tool that is available through the DST.

This section describes the development and potential application of (SAT) using the results of the AHP survey conducted among 200 experts. This was combined with the data gathered for the 17 building systems against each of the 18 attributes using the tiered approach as described in the Chapter 3.

- ### Methodology underpinning SAT

Given the difference in the nature of the data gathered against the 18 attributes (qualitative and quantitative), their units of measurements and gaps in the data, it was important to select a methodology that would capacitate both qualitative and

MaS-SHIP Mainstreaming Sustainable Social Housing in India Project

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*Integrating sustainability in social housing in India*

***Figure 35**: SAT embedded in the DST*

quantitative datasets and cater for data gaps while evaluating building systems. All the attributes and the building materials and systems had to be assessed on a level plane to achieve precise scores.

The Multi Criteria Decision Making (MCDM) approach was selected to bring together the quantitative and qualitative data to derive the relative weightings of the attributes for each of the 17 building systems. The approach and methodology were developed so that they provide tangible outcomes and trade-offs as a measure of sustainability.

An extensive literature review was carried out to identify a Multi Criteria Decision Making (MCDM) method which would address all the above challenges to give credible results. MCDM methods such as Analytic Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Multi-Attribute Utility Theory (MAUT), Preference Ranking Organization METHod for Enrichment Evaluation (PROMETHEE) and Weighted Sum Model (WSM) were studied. While some of these could help in overcoming the above challenge, most of them were unable to address the issue of missing data under different attributes.

The MCDM problem considered at the building material and system level in SAT was categorized as a non-classical MCDM problem as it accounts for the missing data under the attributes. The non-classical MCDM method used in SAT is Belief Function based TOPSIS. The Analytic Hierarchy Process (AHP) was selected as the MCDM method to evaluate the attributes and as a result, relative weightings were ascribed to them, to determine the order of preference at criteria level. The data collected for the 17 building materials and systems against the 18 attributes defined the problem statement to select a suitable method for evaluating them under the existing challenges.

The proposed Belief Function based TOPSIS was classified as MCDM tool (Han, 2016) as its purpose is to help the ‘User’ to choose a building material or systems among a known set of 17 based on their numerical scores calculated with respect to data collected under 18 attributes.

This new approach offered the advantage to deal directly with negative, zero and positive data values, missing data values, and unreliable sources of information related to each attribute as well. This process assigned belief, plausibility and uncertainty for the missing data values to which TOPSIS was applied subsequently to obtain final scores of the building materials and systems.

Although this MCDM problem was easily formulated, there were difficulties in solving it because the data under various attributes was expressed in different units and scales. Such differences in the unit and scale of data gathered necessitated a normalization step that could have yielded further problems like rank reversal. A rank reversal is a change in rank ordering due to addition or deletion of a building material or systems from the list.

The process for developing SAT calculations involved creating a ‘base matrix’ comprising of 18 attributes with data populated for 17 building systems. The matrix had both qualitative and quantitative sets of data. The missing values in the matrix were denoted by ‘NA’. These missing values were addressed by adopting a theory of belief functions or the Dempster Shafer’s Theory which involves assigning probabilistic values of belief, plausibility and uncertainty to data values. After calculating the belief, plausibility and uncertainty, TOPSIS method is applied to the matrix to arrive at the final scores of the building systems.

The step-wise process for developing the SAT calculations is explained in Annex 7.

- ### Interpretation of SAT scores

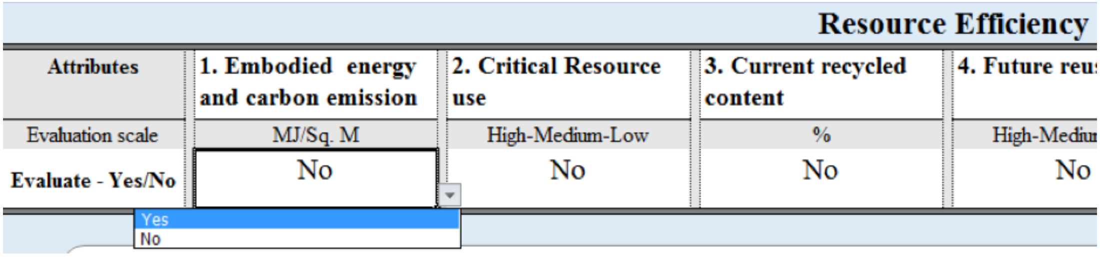
The SAT enables the user to make an informed choice by providing the order of preference of the 17 walling & roofing systems against all 18 attributes.

The user can select the attribute or attributes grouped under the four main criteria (Resource Efficiency, Operational Performance, User Experience and Economic Impacts) to evaluate a total of 17 walling and roofing systems. The selection can be completed by picking a ‘Yes’ from the dropdown list placed under each attribute (Figure 36).

Figure 37 shows the walling and roofing systems evaluated for the selected attributes (‘Critical resource use’, ‘Future reusability’ and ‘Water use’) under the criterion ‘Resource efficiency’. The relative performance of the building materials and systems against each other across the attributes in each criterion could be seen in the form of graphs below the attributes.

Higher score of a building material or systems with respect to others is an indicator of its better performance. A high score is better and independent of the nature of the attribute. For instance, a high score of a building material or system for an attribute ‘Embodied energy and carbon emissions’ indicates that it has a low absolute value (MJ/ $m^2$) which has led to its high score. In simpler terms, the higher the graph spikes, the better the score gets, hence the better the performance. Similarly, results for other criteria (Operational performance, User experience and Economic impacts) can be evaluated using SAT. The holistic score across all or selected attributes is also displayed towards the bottom of the SAT under ‘Sustainability Assessment – Holistic’ (Figure 38). A detailed guidance document on ‘how-to-use’ SAT is available as part of the DST.

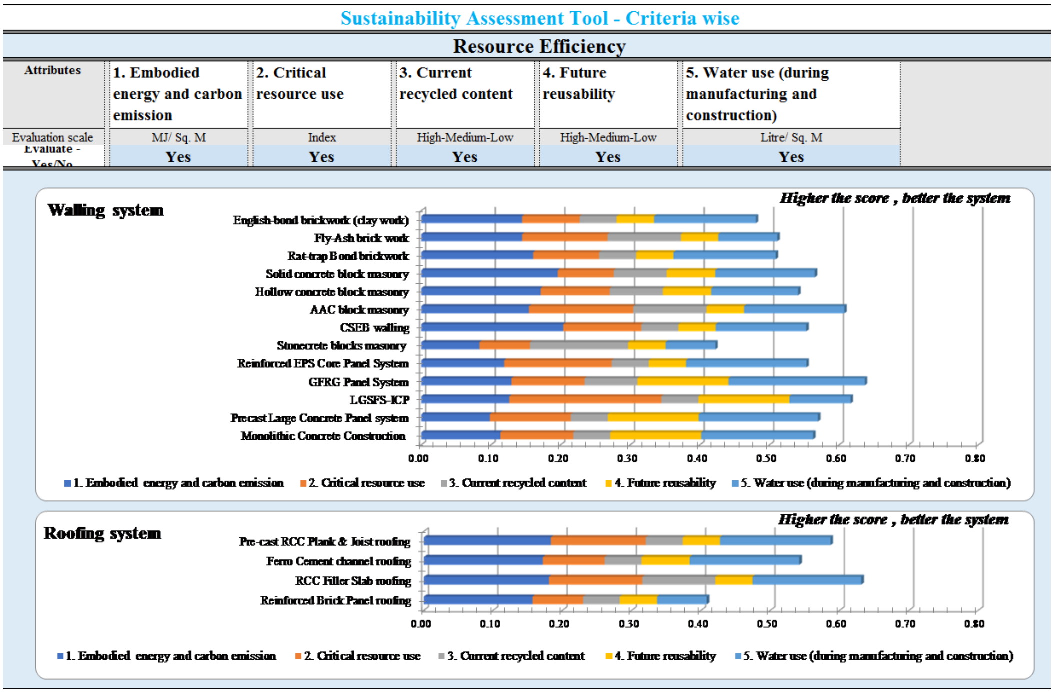
While SAT is a novel tool for appraising the performance of building systems against a wide range of attributes, it is important to remember that presently, it provides comparative analysis of 17 selected building systems against the 18 attributes of sustainability identified for housing units up to G+4. Also, SAT does not give absolute data or values for the building systems evaluated by it under 18 attributes. It only provides a score which has been calculated using the absolute data for building systems under weighted attributes. The ‘score’ calculated for any particular building system against the 18 attributes is the ‘relative weighting’ of that particular building system against the other 16 building systems listed in SAT.



Resource Efficiency

| Attributes | 1. Embodied energy and carbon emission | 2. Critical Resource use | 3. Current recycled content | 4. Future reu |
|---|---|---|---|---|
| Evaluation scale | MJ/Sq. M | High-Medium-Low | % | High-Mediu |
| Evaluate - Yes/No | No | No | No | No |

***Figure 36:*** *Selection of attributes to evaluate the building materials and systems*



Sustainability Assessment Tool - Criteria wise

Resource Efficiency

| Attributes | 1. Embodied energy and carbon emission | 2. Critical resource use | 3. Current recycled content | 4. Future reusability | 5. Water use (during manufacturing and construction) |
|---|---|---|---|---|---|
| Evaluation scale | MJ/ Sq. M | Index | High-Medium-Low | High-Medium-Low | Litre/ Sq. M |
| Evaluate - Yes/No | Yes | Yes | Yes | Yes | Yes |

***Figure 37:*** *Order of preference across all attributes under 'Resource efficiency'*

Sustainability Assessment Tool- Holistic

***Figure 38:*** *Holistic sustainability assessment of the given building system using SAT*

## 5.3. Material mapping

As part of the efforts to ensure informed decision making for choice of (off-site) building materials or systems, a key aspect that is always considered is distance from the project site and transportation cost of raw material or finished product. The key purpose of the Material mapping is to ensure an active engagement between the manufacturer and the building practitioner in choosing the appropriate building material and technology for any social housing project.

The Material mapping developed based on the Geographical Information System (GIS) is an application aimed at helping developers and practitioners to spatially locate existing building material manufacturers across the country, with basic information given for each manufacturer. This will help them make an informed decision based on the estimated distance of the manufacturing unit to the proposed construction site.

Based on interviews conducted with building material manufacturers and information collected from marketing teams of specific manufacturers, the Material mapping application provides information about: name of product; location of manufacturing unit (city); name of manufacturing company and contact details. Given the nature of certain building systems (i.e., constructed off-site or on-site), only materials that are manufactured off-site have been mapped. The link to the Material mapping is embedded within the DST (under 'Where') along with a brief guide on its usage and user interface.

***Figure 39**: Material mapping using GIS*

The following building materials have been mapped-

- Fly ash source
- Autoclaved Aerated Concrete Blocks (AAC)
- Glass Fibre Reinforced Gypsum (GFRG)
- Light Gauge Steel Frame Structure (LGSFS)
- Monolithic Concrete
- Reinforced EPS Core Panel
- Precast Concrete Panel

### • Mapping established building systems

These are systems which have an established evidence of development and practice in the Indian housing market. These include, both the conventional systems which are most commonly adopted and a few which have been recognized as alternative, environment friendly systems in the Indian context with some evidence of performance in buildings which may or may not be for housing purposes. Depending on their application process, these systems can be further categorized as materials available in the market (such as fly ash bricks, AAC blocks, etc.) or systems used through on-site production mostly through semi-mechanized process (such as Compressed Earth blocks, precast RCC plank and joist for roofing, etc.).

Established materials such as fly ash bricks, hollow/concrete blocks etc., are commonly used materials and a strong market already exists with numerous small manufacturing units setup across the country. Hence these have not been mapped. However, a data point incorporated as a part of the GIS application is that of thermal power plants in India. A waste material from thermal power plants is fly-ash. Fly ash has a number of applications in the construction industry, and thus the location of manufacturing units of fly ash bricks as well as the distance from source of fly ash is an important factor. Hence as an indicator for fly ash as a raw material, thermal power plants have been mapped.

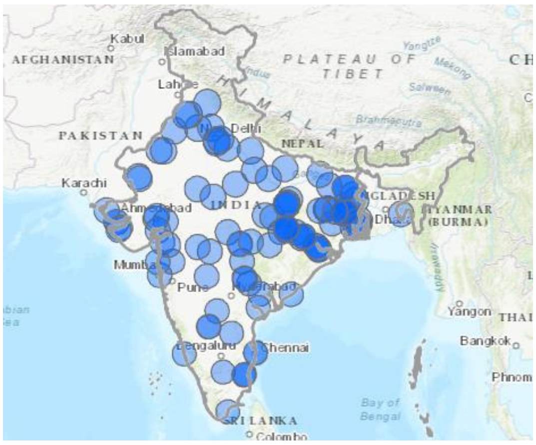


***Figure 40**: Location of thermal power plants for fly ash availability*

### • Mapping emerging building systems

These are largely technologies which are being promoted by the Ministry of Housing and Urban Affairs, Government of India, through the BMTPC, as prospective solutions for faster and cost-effective delivery of houses. All systems in this category are based on a 'production' approach of housing where speed of construction is of prime importance. Hence, the technologies in this category are based on either precast component assembled at site (such as reinforced EPS core panels, large precast concrete panels, etc.) or rapid in-situ processes where large formwork systems are installed at site for rapid construction of houses through casting the entire house in one go.

## 5.4. Pilot testing DST

DST was tested through an interactive working session with the design team of Adlakha Associates Pvt. Ltd. and Mahindra Lifespaces. The purpose of the exercise was to assess the working of the DST and its constituent outputs and tools, in terms of usability of the interface, capability to present scenarios with different building system options, and steer decision making.

A brief presentation covering the structure of DST, key tools within DST (SAT, Material mapping) and overview of the sustainability attributes, was made by the MaS-SHIP team to the design team of Adlakha Associates. The design team was then requested to navigate through the toolkit with guidance from MaS-SHIP team (if needed). The MaS-SHIP team provided assistance with respect to familiarizing the design team with the purpose and scope of different tools (SAT and Material mapping) and various other outputs available within the DST. The MaS-SHIP team members also helped the users navigate through the DST.

In order to assess the influence that the SAT 'scores' can have on the choice of building materials and systems in a social housing project, the design team was asked to refer to one of their housing projects at the design stage for which, the walling and roofing system selected were fly ash brick wall and pre-cast joist roof. The design team had previously made conscious choices on the kind of building materials to be used, namely based on sustainable building concepts of climate-based design, use of adaptable technology innovations, precast and prefab indigenous technologies, reduced consumption of energy intensive and costly materials, low cost maintenance etc. The results from SAT helped to validate their choice of materials. The design team were also interested to consider resident's experience in greater detail in future projects.

Similarly, the design team at Mahindra Lifespaces, assessed the buildings materials chosen for one of their housing projects, using SAT. AAC block walling system and RCC filler slab for roofing system were assessed on all the attributes except familiarity with material, skill requirement and job creation. The team felt that the SAT results can be used as a strong means of communication between different teams representing different aspects of the project, such as design, sustainability, marketing, procurement and investors. This allows an interdisciplinary team to view and assess different options together in the decision-making process. They expressed that SAT could also help in explaining the reasoning behind certain material choices.

While most of the sustainability attributes shown in the SAT were already being considered by the Mahindra Lifespaces, the attribute of job creation could be considered in future projects. Skills development is promoted by the Mahindra group, so preference for materials which have low skill requirement was not necessary. The team felt that the resident experiences given in the DST as well as the survey forms can be used as a reference for assessing residences experience during post occupancy studies for their previous and present projects. The manufacturer survey can be used as a reference for collection of information on new materials. The pilot testing also provided useful feedback on how the DST tools could be made even more user friendly and intuitive.

## 5.5. Wider application of DST

It is clear that DST can function as a common reference point to overcome such knowledge gaps. It can help prospective users meet their individual priorities while factoring into their decision making, broader systemic goals when selecting building materials, making housing design decisions, and understanding why it is important to mainstream sustainable social housing. For example, decision makers have lacked an appropriate framework to measure the performance of existing and new building materials against its socio-economic and operational benefits and environmental risks. To address this gap, SAT was developed as part of the DST. The tool consists of four broad criteria, some of which were missing in the various earlier sustainability assessment tools, including *resource efficiency, operational performance, user experience* and *economic impact*.

The DST also contributes to filling the current lack of data that has inhibited decision makers from making informed policies and investments related to sustainable construction practices. For example, the SAT is populated with the performance of 17 building materials and systems to compare available options. Lack of available information has also affected the development of the green materials supply chain. To this end, a GIS mapping of materials offers a platform to promote the location and performance of materials that are not widely known.

The limited availability of high quality, educational materials has also inhibited the implementation of sustainable design and construction practices. The DST's climate specific design guidelines help ensure sustainable material selection is grounded in construction practices that strengthen the quality and adequacy of the home.

In addition, the DST's backgrounder on the policy context for housing in India provides important insights into the institutional environment within which sustainability can be mainstreamed. Its documentation of resident experience can also help refine policies to better incorporate the preferences and concerns of the consumer.

## 5.6. Users of DST

Mainstreaming sustainable social housing will require a coordinated effort from multiple actors who may have individual and sometimes, conflicting priorities. What is common among most construction stakeholders is that they lack an appreciation for the concept of sustainable social housing. As consumer preferences and building standards and rules evolve to mandate adoption of more sustainable building materials, social housing developers will need to adjust their practices accordingly.

In this context, the DST can assist **developers** in calculating the costs of sustainable alternatives and locate the requisite suppliers. As such, the DST could conceivably help capital constrained developers efficiently manage costs and adhere to sustainability criteria. By extension, the tool could be used by developers to promote their commitment to high sustainability standards. In addition, materials manufacturers and suppliers could leverage the materials map to promote their products, form linkages with prospective clients and strengthen the supply chain.

**Building practitioners** could also benefit from the DST in terms of making incremental, but important, improvements to their design practices. This, in turn would enhance resident comfort. Given that many practitioners train their workers on site, with no consistent approach, the DST could also enable a more systemic way of monitoring workers' performance. This has the potential of realizing construction standards delivered by a largely unskilled cohort of construction workers.

Public sector **housing finance** and alternative finance institutions, seeking to make impact investments in green, affordable housing, could use the DST to structure their funds. The data on costs and sustainability of various materials can be used to make linkages between returns on investments with socio-economic and environmental impacts.

For **universities** and students involved in architecture, planning, and civil engineering, DST can function as an important educational tool by establishing an important framework to understand sustainability in social housing. The listing of the attributes can be used by educators as an entry point in developing lessons that explore issues that range from sustainable water practices to supply chain management.

The DST can also potentially assist **local government bodies** by functioning as a supplementary guide for monitoring and evaluating the quality of buildings. Its free design guidelines, in particular, provide a useful basis for officials with limited technical resources to make informed decisions. The DST can also be used by state housing agencies planning to incorporate sustainability criteria into procurement guidelines to induce greater adoption of sustainable building materials.

Numerous **central government ministries** could also find utility in the DST. The potential of the DST in supporting the Building Materials and Technology Promotion Council's (BMTPC) research and promotional endeavours is indicative. For example, the DST could assist in refining the BMTPC's third party "Performance Appraisal Certification Scheme (PACS)." PACS is a voluntary program that evaluates the performance of emerging materials based on traditional metrics pertaining to cost effectiveness and efficiency. The certified products are promoted to help them gain a foothold in the market. In addition, PACS assist the Central Public Works Department (CPWD) in incorporating findings into its procurement guidelines for building materials. They also support the Bureau of Indian Standards (BIS) such that findings help in reviewing or formulating relevant Indian Standards (BMTPC, 2016). As such, incorporating the DST's evaluation framework could widen the basis of performance and potentially influence codification.

# Chapter 6

## Policy implications for mainstreaming sustainable social housing

It is clear from the preceding chapters that MaS-SHIP has made considerable progress in addressing the challenges of making social housing in India sustainable. In particular it has aided in the development and testing of the DST, enabling developers and practitioners in the housing construction ecosystem to make informed decisions for integrating sustainability in the design and specification of building systems in social housing projects.

The DST's multiple benefits warrant a detailed assessment of the institutional environment in which it can be advanced. MaS-SHIP presented a variety of pathways, including the BMTPC, through which the DST could be adopted. Importantly, for the DST to be used by key stakeholders such as developers, it is assumed that interventions, such as improvements in building standards, will also be made. Indeed, the effectiveness of the DST in mainstreaming sustainable social housing is contingent upon a well-developed policy framework, a coherent data collection strategy, and ongoing support for capacity building, research, and awareness campaigns. Based on the knowledge gathered in MaS-SHIP, the following sections layout some key policy implications that need to be addressed for mainstreaming sustainable social housing in India.

## 6.1. Revisiting the housing policy framework

There remains a need to develop a comprehensive housing policy, situated within an urban context. Such a policy needs to be supported with a defined strategy to decouple environmental externalities from the socio-economic benefits of access to housing. Current housing policy frameworks create an enabling environment for the private sector to supply housing, with incorporation of some components of sustainability. For example, the importance of extracting locally sourced materials for construction is clearly articulated (Hingorani, 2011).

Ongoing deliberations over developing the National Urban Policy present an opportunity to position housing at the centre of cities. However, resource extraction has been part of a separate strategy development initiative for resource efficient practices, carried out by the Indian Natural Resources Panel (InRP), housed within the Ministry of Environment, Forests & Climate Change (MoEF&CC) (GIZ, 2017). It is important to evaluate the extent to which such initiatives converge, and the feasibility of further integration or coordination.

## 6.2. Updating sustainability standards and rules

A targeted strategy to develop sustainability standards for social housing must also be considered. For example, the Bureau of Energy Efficiency (BEE) has an established reputation for enhancing building efficiency. This is reflected in its development of Energy Conservation Building Code (ECBC) first introduced in 2007 for commercial buildings. A version of the code - which earlier set energy efficiency requirements for five building systems, including building envelopes, lighting, power, heating, service water heating, and ventilation and cooling – is in the process of being applied to residential units (BEE, 2018). However, the potential short-term cost increases associated with higher standards require a cost-benefit analysis to substantiate a strategy targeted at social housing units.

The Ministry of Housing and Urban Affairs (MoHUA) has also developed Model Building Byelaws as guidance for states and local governments to implement. In its most recent revisions in 2016, it included "Green Buildings and Sustainability Provisions," for example, for the suitable use of supplementary building materials that are "derived or processed waste" and utilisation of factory produced options, such as fly ash bricks. Importantly, the provisions note that the "sustainable use of building materials shall be encouraged which may combine certain mandatory provisions and incentives" (MoUD, 2016). However, the breakdown of what should be made mandatory and what should be incentivised is not articulated.

The role of the Bureau of Indian Standards, in charge of formulating the National Building Code, is also important in advancing sustainability in housing. In its most recent iteration of the Code in 2016, Chapter 11 developed an "Approach to Sustainability," which, inter alia, proposed strategies to merge resource and energy efficiency, from design to construction and maintenance in housing (BIS, 2016). The BIS's comprehensive approach to buildings, combined with the provisions made for in the ECBC and Building Bye-Laws warrant a thorough review, based off of which the broader costs and benefits of codifying sustainability specifically into social housing can be assessed.

In addition, there are no specifications that mandate procurement of sustainable building materials for constructing social housing. That is, state housing boards support the implementation of social housing projects through devising various incentives for private developers (Herda et al., 2017). However, they do not tie the benefits to sustainability requirements. It is important to consider mandatory options because there is evidence of greater adoption of sustainable practices in social housing construction following such an intervention. For example, the MoEF&CC issued a Fly Ash Notification in 1999, encouraging adoption of the raw material for brick making. In addition, restrictions were placed on the traditional practice of using topsoil. Many states have followed suit (Caleb et al., 2017). In this context, MaS-SHIP surveys clearly showed significant use of fly ash bricks in a number of social housing units.

## 6.3. Strengthening implementation

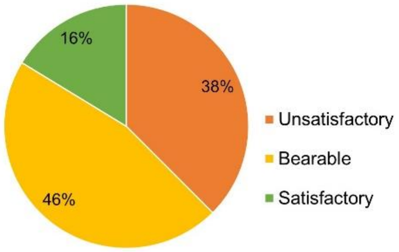
Mandatory rules can only be monitored and enforced if local government capacity is strengthened. MaS-SHIP case studies found that the composition of the material use, and by extension the quality of construction of a number of houses, was poor (Figure 41). Local governments have limited personnel to perform the requisite function. In addition, existing personnel are not equipped with and trained to use complex evaluation frameworks to make informed decisions (Niti Aayog, 2015). Such shortcomings can also inhibit the application and development, modification of nationally crafted rules, such as the Model Building Byelaws, to local conditions. The implication is for central and state governments to work with educational and other relevant agencies to develop the necessary technical support and arrange sustainable sources of funding to improve the capacity of local governments.

***Figure 41:*** *Dwelling unit at Bawana housing, Delhi*

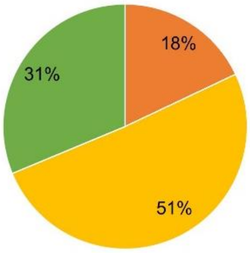
Secondly, the poor quality of construction is because many construction workers are unskilled and operate in informal settings and require more training. MaS-SHIP surveys demonstrated that such individuals were trained on site by the building practitioner and/or mason. There is limited understanding amongst such workers to adopt practices that may either require more rigorous quality assurance or the use of more complex building technologies. As such, there is a need to provide simple training modules for such actors, detailing strategies for incremental enhancements in design and construction.

## 6.4. Incorporating resident experiences into policy development and implementation

The surveys of nearly 723 residents across five Indian cities, about their experiences of living in social housing units revealed that measures are needed to improve the adequacy of social housing. Persistent dampness in walls illustrated a common grievance among residents, and indicative of the poor quality of construction. Others expressed dissatisfaction at their homes being located away from employment opportunities. This reflects poor incorporation of livelihood considerations in planning for homes. A number of residents complained about discomfort during hot or cold seasons (Figure 42). This suggested that simple design interventions, such as shading and ventilation, were not appropriately factored in. These concerns imply that the policy development process, planning, and design of housing require more resident participation.



Summer



Winter

***Figure 42:*** *Householders' perception of indoor temperature across the five cases studies*

MaS-SHIP case studies also showed that residents preferred to live in houses built with the least environmentally friendly system – English-bond brickwork – because it afforded them the flexibility to make modifications to their walls. Greater resident engagement can therefore also help build awareness amongst such prospects about the importance of sustainability. That is, engagement could conceivably involve building resident awareness and capacity building initiatives to utilise and demand more sustainable building material and design alternatives.

## 6.5. Incentives and conditions to engage social housing developers

There is a need to balance incentives provided to developers with imposing stricter conditions to deliver sustainable housing. MaS-SHIP demonstrated that for developers, cost and profit remained a priority. In the absence of direct public investments, incentives and regulatory relaxations, such as with Floor Area Ratios (FARs), have been created to meet private developers' priorities (Herda et al., 2017). In addition, many social housing developers have been known to skirt the approval process because it is time consuming and costly (FSG, 2018). However, failure to acquire the requisite permits precludes them from securing more capital from formal channels to continue with further construction. To overcome noncompliance, financial shortfalls and meet policy priorities to expedite construction, "Single Window Clearance Mechanisms" are being proposed, developed and experimented with across the country (MoHUA, 2016, BIS, 2016; KPMG, 2012).

However, there is limited evidence of tying such incentives and regulatory relaxations to meeting basic standards of adequacy or sustainability. For example, resident discomfort indicates neglect amongst developers in making or instructing designers to design interventions to incorporate higher standards. In some states, there is some evidence of relaxation of FAR regulations in exchange for housing projects that have registered for Green Ratings for Integrated Habitat Assessment (GRIHA) (an Indian measurement tool that rates the predicted performance of a building against various sustainability parameters) (Herda et al., 2017). However, this arrangement does not factor in the potential negative effects of resource extraction that arise from increases in density (Gopalan & Venkataraman, 2015). In essence, the costs and benefits of tying supply side subsidies and incentives to stricter conditions have not been given careful attention. Given that housing for low income groups is also financed by private firms such as AHFCs, it is important for these groups to test models that can tie returns on investment with socio-economic impact and environmental management.

## 6.6. Strengthening the supply chain

A study found that adopting "greener" measures adds an average of 10% to the cost of construction in India (World Bank, 2011). Specifically, this increase was attributed to increased transportation, labour, and incremental costs associated with adopting enhanced energy efficiency standards. However, no similar studies exist for potential costs associated with adopting sustainable building systems.

Such a study is needed to inform strategies to balance incentives with mandatory rules to strengthen the supply chain. First, a strong evidence base is needed to develop sound policies and strategies for housing that can more accurately account for trade-offs such as potential jobs foregone when choosing a more sustainable building system. However, MaS-SHIP found data gaps with criteria such as labour requirements and resource related information. This may partly be because developers and manufacturers are not mandated to disclose information. To address this gap, a rigorous data collection strategy would be needed. Specifically, there is a need for a well-funded initiative that maps out existing resources, collects primary data where gaps exist, models cost and projections, and develops a centralized database to facilitate aggregation.

More data is also needed to support initiatives that promote small, sustainable building system companies with a small client base. For example, the Building Materials and Technology Promotion Council (BMTPC), housed within the Ministry of Housing and Urban Affairs (MoHUA) studies and showcases innovative building systems. It is also responsible for a Technology Sub-Mission, which is involved in such pursuits as part of the PMAY. However, the current focus on materials and systems tend to focus on cost and speed. Missing data on criteria such as a building system's job creation potential inhibits systematic efforts to promote such options against broader metrics. Resolving this shortfall could enable evidence based promotional campaigns, to build awareness and induce demand for more sustainable alternatives amongst prospective clients.

# Chapter 7

## Conclusions and recommendations

## 7.1. Conclusions

As the Government of India aims to construct 12 million social housing dwelling units through the Housing for All by 2022 programme, the pressure to deliver in a timely and cost-effective way will increase. It is vital to identify what the impacts and benefits of housing production at such a massive scale and speed could be, especially when there is limited evidence of coherent strategies to decouple the socio-economic benefits arising from housing construction and provision from its negative environmental impacts, such as the deleterious effects of resource extraction. In particular, this shortfall applies to how building materials and systems are not selected in a sustainable manner. Research from MaS-SHIP has produced a comprehensive data framework, datasets, tools, evidence-based knowledge and insights for mainstreaming sustainable social housing in India.

First, MaS-SHIP created systematically a framework of 18 attributes grouped under four criteria, including resource efficiency, operational performance, user experience, and economic impact in collaboration with developers, practitioners and academics to measure the sustainability performance of 17 established and emerging building materials and systems. Second, it studied the construction and policy ecosystem to identify barriers and opportunities in adopting sustainable materials and related design and construction practices.

Previous public and private efforts to develop measurement tools have been constrained by data gaps to populate the instruments. In particular, newer building material alternatives lack sufficient detailing to enable informed decisions. MaS-SHIP made progress by collecting new data on 17 building materials and systems. The findings have been collated into catalogues for each material. The granularity of available data and methodology for calculating the mix of qualitative and quantitative attributes are provided as part of a data framework.

Importantly new information was presented on the user's experience with building systems. Large-scale surveys revealed that residents also influence the demand for sustainable materials. For example, in the case study housing developments, residents were found to prefer less resource and operationally inefficient materials such as English-bond brickwork because such an option affords them greater flexibility to make in house adjustments such as nailing wall-hangings. Many residents raised grievances about factors such as discomfort because of inadequate ventilation, and their homes being located away from employment opportunities. This indicates negligence amongst practitioners and policymakers in incorporating resident needs into planning and design to ensure socially inclusive and environmentally-friendly social housing.

A key output from MaS-SHIP research has been the creation of the DST, an interactive and online toolkit comprising a range of outputs, datasets, tools and insights that can help prospective users in choosing sustainable building materials and making and monitoring sustainable design interventions and construction practices in social housing projects. The DST not only addresses the absence of a comprehensive measurement framework to assess sustainable materials, through the development of SAT it fills missing data that is needed to quantify the performance, and using Material mapping application, spatially maps the availability of sustainable building systems options. DST also includes design guidelines to ensure sustainability is embedded at the conception stage of a housing project. Filling these knowledge gaps can also assist in prioritising sustainability considerations in housing policy and implementation.

SAT as a key component of the DST has the capability to measure the relative performance of building materials and systems for social housing projects that do not exceed four stories, using the framework of 18 attributes. The multiplicity of attributes requires rationalized valuations relative to each other. SAT establishes consistency by drawing on the inputs of a representative sample of housing experts in India to weigh each attribute. That is, a widely accepted "Analytic Hierarchy Process (AHP)" was applied to survey 200 experts including project consultants, private and public housing providers, academics, manufacturers, and building practitioners. A weighting process affords a rigorous evidence base for prospective users to prioritize their interventions, appropriately allocate resources, and potentially mitigate preconceived biases.

The results of analysing the performance of Autoclave Aerated Concrete (AAC) Blocks using SAT is indicative of its capability. The ACC blocks option stood out as being resource efficient and scored well in terms of operational performance. With respect to economic impact, this option is cost effective, allows for quick construction, and has some potential for creating jobs for semi-skilled workers. In fact, AAC blocks have demonstrated some success in the market. However, they are generally limited to high-rise buildings, atypical of the three-story units that are characteristic of most social housing projects. Part of the reason for its limited adoption in social housing is due to its poor performance in terms of user experience, reflected in developers' limited familiarity with the material.

## 7.2. Recommendations

Creative interventions are needed to strengthen the supply chain and improve construction practices to mainstream sustainability into social housing. To enable this to happen, the following recommendations are made based on the research findings:

- Develop an Overarching Sustainable Housing Policy Framework that integrates resource and energy efficiency considerations with socio-economic parameters in urban contexts. The framework can build on existing policies with an implementation strategy and monitoring provisions to ensure efficacy.
- Develop a Data Collection Strategy to fill missing information on factors such as job creation potential for new technologies, based on interventions such as:
    - Instituting mandatory disclosures,
    - Funding primary data collection efforts,
    - Developing a centralized, open source database for constant updating.
- Incorporate sustainability requirements in state procurement guidelines as conditions for developers to win social housing contracts. Standards and specifications need to be developed for architects and engineers to adopt and for public officials to use for compliance checks.
- Secure resources to improve local government capacity by developing collaborations between state and union governments, educational institutions and other relevant agencies for technical support. Training programs and educational materials on sustainability should be systematically developed and made available to urban local bodies.
- Develop awareness programs for developers with a focus on sensitizing such actors to potential convergences between cost and efficiency considerations, with environmental benefits. Identify key materials and design practices that achieve such goals and link them to its potential benefit for their prospective customers – the resident of social housing dwellings.
- Develop training modules for developers, masons and unskilled construction workers to adopt better construction practices with a focus on ensuring basic design factors are implemented for resident comfort.
- Engage residents in design and planning through:
    - Awareness programs to sensitize residents to the value of sustainability and influence them to demand sustainable options from housing providers,
    - Studying resident needs in order to apply design changes to enhance comfort, and potentially allocate additional resources to empower residents in more sustainably managing their homes,
    - Collaborating during the planning and design phase of housing to secure long term buy-in and ensure resident satisfaction.

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# Annexes

# Annex 1: List of organizations that participated in MaS-SHIP Stakeholder events

| Sector | Sr. No. | Name of participating organization |
|---|---|---|
| **Policy makers** | 1 | Delhi Development Authority (DDA) |
| | 2 | Building Materials and Technology Promotion Council (BMTPC) |
| | 3 | Central Public Works Department (CPWD) |
| | 4 | Ministry of Housing and Urban Poverty Alleviation (MoHUA) |
| | 5 | Housing and Urban Development Corporation (HUDCO) |
| | 6 | National Housing Bank |
| | 7 | Bureau of Energy Efficiency |
| | 8 | Central Public Works Department |
| | 9 | Human Settlement Management Institute (Housing and Urban Development Corporation) |
| | 10 | National Housing Bank |
| | 11 | Urban Development & Housing Department, Sikkim |
| | 12 | Andhra Pradesh Urban Finance & Infrastructure Development Corporation |
| | 13 | SNPUPR, Ministry of Housing and Urban Poverty Alleviation |
| | 14 | Central Pollution Control Board |
| | 15 | Town and Country Planning Organisation, MoUD |
| | 16 | National Buildings Construction Corporation |
| | 17 | Punjab Energy Development Agency |
| | 18 | Council of Architecture |
| | 19 | Energy Efficiency Services Limited |
| | 20 | RAHDA, Rajasthan Housing Board |
| | 21 | Ministry of Home Affairs |
| | 22 | Dept of Science and Technology, Government of Bihar |
| | 23 | Ministry of Environment forest and climate change |
| | 24 | Ministry of External Affairs |
| | 25 | iCED, (An institute of CAG of India) |
| **Academia and research** | 26 | IIT Delhi |
| | 27 | Amity School of Architecture & Planning |
| | 28 | School of Planning and Architecture |
| | 29 | RMIT University |
| | 30 | Tata Institute of Social Sciences |
| | 31 | Rachana Sansad Institute Of Environmental Architecture |
| | 32 | School of Planning and Architecture |
| | 33 | DIT, Dehradun |
| | 34 | Indira Gandhi National Open University, IGNOU |
| | 35 | Deenbandhu Chhotu Ram University of Science and Technology |
| | 36 | Bhagalpur village of Engineering |
| | 37 | Central University Rajasthan |
| | 38 | MNIT, Jaipur |
| | 39 | Jamia Millia Islamia Central University |
| | 40 | DCR University of science & Technology, Murthal |
| | 41 | Dr Bhanuben Nanavati College of Architecture for Women |
| | 42 | University of Science and Technology, Murthal, Sonipat |
| | 43 | Institute for Human Development |
| | 44 | National Institute of Urban Affairs |
| | 45 | Construction Research Centre |
| | 46 | World Resource Institute (WRI) |
| | 47 | National Environmental Engineering Research Institute |
| | 48 | Shakti Sustainable Energy Foundation |
| **Building material manufacturers** | 49 | Ambuja Cement Ltd. |
| | 50 | ACC Limited |
| | 51 | Supreme Petrochem Ltd. |
| | 52 | Armacell India Pvt Ltd |
| | 53 | H&R Johnson India |
| | 54 | Saint Gobain |
| | 55 | Everest |
| **Sector** | **Sr. No.** | **Name of participating organization** |

| | | |
|---|---|---|
| **Voluntary sector, Networks, Associations** | 56 | GRIHA Council, Delhi |
| | 57 | Indian Housing Federation (IHF) |
| | 58 | Confederation of Construction Products and Services |
| | 59 | Italian Chamber of Commerce |
| | 60 | Indo Italian Chamber |
| | 61 | IEMQ India |
| | 62 | Samarasa |
| | 63 | Auroville Earth Institute, UNESCO Chair Earthen Architecture |
| | 64 | Habitat Technology Group |
| | 65 | Habitat for Humanity |
| | 66 | Confederation of Indian Industry (CII) |
| | 67 | Tilothu Mahila Mandal |
| **Housing developers** | 68 | Adhlakha Associates Pvt. Ltd. |
| | 69 | Mahindra Lifespace Developers Ltd. |
| | 70 | Karnataka Slum Development Board |
| | 71 | B3B Group |
| | 72 | Supertech |
| | 73 | IREO Pvt. Ltd. |
| | 74 | Yaduvanshi Developers ltd |
| | 75 | Partnerships for Sustainable India |
| | 76 | Space design consultants |
| | 77 | SHiFT |
| | 78 | Greentech |
| **Practitioners-Architects/consultants** | 79 | Manoj Misra & Associates |
| | 80 | Anuj Mehta & Associates |
| | 81 | Consulting Urban and Regional Planner, Bangalore |
| | 82 | Sprout - Greening Ideas |
| | 83 | Knowledge Works |
| | 84 | ADW Developments |
| | 85 | Plaksa Solutions Pvt. Ltd. |
| | 86 | Partnerships for Sustainable India |
| | 87 | Skyline |
| | 88 | Tushar Sogani Designs Pvt. Ltd. |
| | 89 | Athenos Design |
| | 90 | Vivacious designs |
| | 91 | MA Architects |
| | 92 | Rihaish Properties |
| | 93 | Uflex Ltd |
| | 94 | Bhagat Video P Ltd |
| | 95 | Finance - IIFL- India Infoline Home Loan |
| | 96 | Descon India |
| | 97 | Anuj Mehta Architects |
| | 98 | Ashok B Lall Architects |
| | 99 | Ashok & Associates |
| | 100 | Sudha Technical Consultant P. Ltd |
| | 101 | KPMG |
| | 102 | TATA Consultancy Services |
| | 103 | EarthenHive Architects |
| | 104 | In-Sans |
| | 105 | Development & Environment Consulting Services |
| **International agencies** | 106 | Indo-Swiss Building Energy Efficiency Project (BEEP) |
| | 107 | Swiss Agency for Development & Cooperation |
| | 108 | GIZ - Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH |
| | 109 | Climate Change & Urbanization, UN - United Nations |
| | 110 | United Nations Development Programme |
| | 111 | UN Habitat |
| | 112 | UN Environment |

# Annex 2: Stakeholder events: purpose and learnings

| Event no. | Name | Date | Location | No. of participating organizations | Purpose | Outcomes |
|---|---|---|---|---|---|---|
| ***SE 1** | Project Launch | 4 Oct 2016 | New Delhi | 18 | Introduce the project and gain interest of experts to participate in the project through the project Advisory Committee and Technical Peer reviewers. | The event provided an opportunity to gain early insights from various experts and stakeholders on the project plan, its objectives, outcomes and areas of impact. |
| ***SE2** | Stakeholder dialogue 1 | 8 Feb 2017 | New Delhi | 13 | Discussion on defining 'social housing' in the Indian context, selecting sustainability attributes and the need for developing a Decision Support Toolkit (DST) | The feedback helped to incorporate social aspects in terms of employment generation, while selecting the sustainability attributes of building materials and/or systems. The scope of DST as a 'support mechanism' to enable decision makers make informed choices, was also discussed. |
| ***SE3** | Stakeholder dialogue 2 | 4 May 2017 | New Delhi | 10 | Gain feedback on the 27 sustainability attributes (underpinning SAT) and methods of data collection for the different materials against these attributes. | The discussion provided useful insights to rationalise the list of selected attributes. The aspect of local climatic conditions in the selection process for sustainable materials was added to the list of attributes.<br>The feedback also led to improvements in the survey questionnaire designed to collect data for the attributes. |
| ***SE4** | Regional workshop 1 | 21 Aug 2017 | Mumbai | 11 | Obtain feedback from the experts (primarily building material manufacturers and housing developers) on the revised set of attributes. | The discussions revealed factors that hinder uptake of new, alternate sustainable materials such as cost implications, unavailability of skills etc.<br>The feedback led to further refinement in the list of attributes and in removing ambiguities about the selected attributes by adding working definitions for all the attributes. |
| ***SE5** | Stakeholder dialogue 3 | 6 Nov 2017 | New Delhi | 17 | Share insights from surveys of building material manufacturers, developers and residents of social housing developments.<br>Mock survey to test the methodology adopted for assigning weightings to the attributes. | Discussions led to further revisions in the list of sustainability attributes. 'Job creation' and 'Critical resource use' were added to the list of attributes of sustainable building materials and/systems.<br>The feedback on the mock survey to assign weightings to attributes helped in further refinement in the ranking format and overall layout of the survey, making it more intuitive for the respondents. |

| Event no. | Name | Date | Location | No. of participating organisations | Purpose | Outcomes |
|---|---|---|---|---|---|---|
| ***SE6** | Stakeholder dialogue 4 | 1 Feb 2018 | New Delhi | 22 | Gather inputs on how the policy briefings from the project can complement the Indian government's various, current and future projects in social housing projects. | The experts pointed that access job opportunities as well as basic services like public transport, hospitals etc. should also form an integral part when discussing social housing projects in India. These suggestions have been incorporated in the design guidelines for sustainable social housing.<br>A key aspect in mainstreaming sustainable building and design practices and relevant policy measures, could be through engaging and educating the architects, building practitioners, and local, state ministry as well as through engagements with academic institutes. |
| ***SE7** | Regional workshop 2 | 3 Apr 2018 | Jaipur | 12 | To present the data collected for the selected building materials and/or systems against the sustainability attributes and gain insights on the methodology adopted for assigning weightings to the attributes. | The discussions were focused on the importance of passive strategies, planning, orientation and use of locally available materials. Some of these aspects have been incorporated in the design guidelines for social housing projects.<br>The experts also highlighted the importance of spreading awareness and capacity building for promoting sustainability in the building sector. |
| ***SE8** | National workshop | 9 Oct 2018 | New Delhi | 39 | Launch the Decision Support Toolkit (DST) and obtain feedback from the experts on the DST and Sat interface, as well as other outputs from the project (Building materials and systems catalogues, case study data collection reports and GIS mapping). | Overall the feedback received on the Material mapping, DST and SAT were positive, however, the participants highlighted the need to simplify the representation of scores in the SAT, to make it more intuitive.<br>The data collected for the selected building systems received many critical comments from the experts. This helped the team to further improve the data through extensive research, calculations and validation by experts.<br>The design guidelines for sustainable social housing in the five climatic zones as well residents' perception of living in social housing developments were well received. Many academics expressed their interest in carrying out works to build similar data in future. |

SE= Stakeholder event

# Annex 3: Thermal simulation details

***Table 14:*** *Set point temperature as per climatic zones*

| | | Mean Temp (deg. C) | | Setpoint (deg. C) | |
|---|---|---|---|---|---|
| **City** | **Climate** | **Annual Min.** | **Annual Max** | **Min** | **Max** |
| **New Delhi** | Composite | 19 | 31.4 | 25 | 29 |
| **Chennai** | Hot and Humid | 24.8 | 33.1 | 27 | 30 |
| **Ahmedabad** | Hot and Dry | 21 | 34.4 | 26 | 30 |
| **Bengaluru** | Temperate | 19.2 | 29.6 | 25 | 29 |
| **Sundernagar** | Cold | - | - | 20 | - |

***Table 15:*** *Activity schedules*

| | Living Room | Bedroom |
|---|---|---|
| **Occupancy** | W: 8:00–18:00 (50%); 18:00–22:00 (100%) WE: 8:00–22:00 (100%) | 22:00–08:00 (100%) |
| **Lighting** | 18:00 - 06:00 | 18:00 - 06:00 |
| **Cooling (March to September)** | W: 18:00–22:00<br>WE: 13:00–22:00 | 22:00–08:00 |
| **Heating (December to March)** | - | 22:00–08:00 |

***Table 16:*** *Materials tested*

| Options | Material | Assembly | U-value $W/m^2K$ |
|---|---|---|---|
| **Base case** | Burnt clay brick | 12.5 mm cement plaster + 225 mm brick + 12.5 mm cement plaster | 2.13 |
| **Option 1** | Fly Ash brick | 200mm fly-ash brick (density – 1240), 12.5mm plaster on both sides. | 1.90 |
| **Option 2** | AAC Block | 200mm masonry with plaster on both sides | 0.7 |
| **Option 3** | Rat-trap bond | 230mm masonry, plaster on both sides | 1.79 |
| **Option 4** | Hollow concrete block masonry | 200mm blocks, 12.5mm plaster on both sides | 1.89 |
| **Option 5** | Solid concrete block masonry | 200mm blocks, 12.5mm plaster on both sides | 2.70 |
| **Option 6** | CSEB walling | 230mm masonry, plaster on both sides | 1.94 |
| **Option 7** | Stone-crete blocks masonry | 100mm sandstone, 100mm concrete, 12.5mm plaster on inside face. | 3.40 |
| **Option 8** | GFRG Panel System | Standard 124mm thick GFRG panel filled with cellular concrete (94mm thick cavity). | 2.85 |
| **Option 9** | Precast Large Concrete Panel system | 100mm thick wall with plaster on both sides | 2.00 |
| **Option 10** | Reinforced EPS Core Panel System | 150mm thick single panel, incl. 70mm EPS core and 40mm shortcrete on both sides. | 0.58 |
| **Option 11** | LGSFS-ICP | Cold formed LGS frame with 20mm thick M20 precast concrete panel, 10mm plaster on external face. | 3.87 |
| **Option 12** | Monolithic Concrete Construction | 100mm RCC wall or roof | 3.59 |
| **Option 13** | Reinforced Brick Panel roofing | 75mm clay brick with 35mm thick cement mortar on both sides | 2.8 |
| **Option 14** | RCC Filler Slab roofing | 100mm thick, 12mm plaster on both sides. Filler: mangalore clay tiles of effective thickness of 62mm. | 3.94 |
| **Option 15** | Pre-cast RCC Plank & Joist roofing | 60mm thick RCC plank | 2 |
| **Option 16** | Ferro Cement channel roofing | 25mm channel roof with 75mm brickbat concrete and 30mm cement screed | 2.56 |

# Annex 4: List of attributes considered at different stages

| | Initial list of 29-attributes (Literature review) | | Abridged to 27, after Stakeholder Dialogue - 2 | | Abridged - 21 | | Abridged -15 | | RAG Status |
|---|---|---|---|---|---|---|---|---|---|
| Environmental | 1 | Embodied energy | 1 | **Life cycle** embodied energy | 1 | **Embodied energy** | 1 | Embodied energy | 🟥 |
| | 2 | Carbon Emissions | 2 | Carbon Emissions | 2 | Carbon Emissions | 2 | Carbon Emissions | 🟨 |
| | 3 | Water Efficiency | 3 | Water Efficiency | 3 | Water Efficiency | 3 | Water Efficiency | 🟥 |
| | 4 | Water Resistance | 4 | Water Resistance | | ***Water Resistance*** | | | |
| | 5 | Critical Resource Use | 5 | Critical Resource Use | 4 | Critical Resource Use | | ***Critical Resource Use*** | |
| | 6 | Reusability | 6 | Reusability | 5 | **Future** reusability | 4 | Future reusability | 🟨 |
| | 7 | Recyclability | 7 | Recyclability | 6 | **Current Recycled content** | 5 | Current Recycled content | 🟨 |
| | 8 | Local Availability | | ***Local Availability*** | | | | | |
| | 9 | Waste Generated | 8 | Waste Generated | | ***Waste Generated*** | | | |
| | 10 | Impact on Cooling Loads | 9 | Impact on Cooling Loads | 7 | Impact on Cooling Loads | 6 | Impact on Cooling Loads | 🟥 |
| | 11 | Durability | 10 | Durability | 8 | Durability | | ***Durability*** | |
| | 12 | Acoustic Performance | 11 | Acoustic Performance | 9 | Acoustic Performance | 7 | **Noise Transmission** | 🟥 |
| | | | | | 10 | ***Thermal Performance*** | 8 | Thermal Performance | 🟩 |
| | | | | | | | 9 | ***Thermal Mass*** | 🟨 |

| | Re-grouping of the abridged - 19 | |
|---|---|---|
| **Environmental performance** | 1 | Embodied energy |
| | 2 | Carbon Emission |
| **Resource efficiency** | 3 | ***Critical Resource Use*** |
| | 4 | Current Recycled content |
| | 5 | Future reusability |
| | 6 | Water **use (during manufacturing and construction)** |
| **Operational performance** | 7 | ***Durability*** |
| | 8 | Ease & frequency of maintenance |
| | 9 | Thermal Performance **(flow of heat)** |

| | Final list of 18 attributes | |
|---|---|---|
| **Resource efficiency** | **1** | **Embodied energy** |
| | **2** | **Carbon Emission** |
| | **3** | **Critical Resource Use** |
| | **4** | **Current Recycled content** |
| | **5** | **Future reusability** |
| | **6** | **Water use (during manufacturing and construction)** |
| **Operational performance** | **7** | **Durability** |
| | **8** | **Ease & frequency of maintenance** |
| | **9** | **Thermal Performance (flow of heat)** |
| | **10** | **Thermal mass (absorption, storage and release of heat)** |
| | **11** | **Impact on cooling (or heating) loads** |
| | **12** | **Noise Transmission** |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Social | 13 | Thermal Performance | 12 | Thermal Performance | | | | | |
| | 14 | Labour Health | 13 | Labour Health | | ***Labour Health*** | | | |
| | 15 | End-user Friendliness | 14 | End-user Friendliness | 11 | **Alteration & Modification ability** | 10 | **Modification ability** | 🟥 |
| | 16 | Design Flexibility | 15 | Design Flexibility | | ***Design Flexibility*** | | | |
| | 17 | Design Compatibility | 16 | Design Compatibility | | ***Design Compatibility*** | | | |
| | 18 | Restriction on number of Floors | 17 | Restriction on number of Floors | 12 | Restriction on number of Floors | | ***Restriction on number of Floors*** | |
| | 19 | Acceptance/ Familiarity of a Material | 18 | Acceptance/ Familiarity of a Material | 13 | Acceptance/ Familiarity of a Material | | ***Acceptance/ Familiarity of a Material*** | |
| | 20 | Skilled Labour | 19 | Skilled Labour | 14 | Skilled Labour | | ***Skilled Labour*** | |
| | 21 | Ease of Maintenance | 20 | Ease of Maintenance | 15 | Ease of Maintenance | 11 | **Ease & frequency of maintenance** | 🟥 |
| | 22 | Frequency of maintenance | 21 | Frequency of maintenance | 16 | Frequency of maintenance | | | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Economic | 23 | Initial Cost | 22 | **Cost per Sq. M** | 17 | Cost per Sq. M | 12 | Cost per Sq. M | 🟩 |
| | 24 | Maintenance Cost | 23 | Maintenance Cost | | ***Maintenance Cost*** | | | |
| | 25 | Time of Construction | 24 | Time of Construction | 18 | Time of Construction | 13 | Time of Construction | 🟥 |
| | 26 | Supply Chain | 25 | Supply Chain | 19 | Supply Chain | 14 | Supply Chain | 🟨 |

| | | |
|---|---|---|
| | 10 | Thermal mass **(absorption, storage and release of heat)** |
| | 11 | Impact on cooling **(or heating)** loads |
| | 12 | Noise Transmission |

| | | |
|---|---|---|
| User acceptability | 13 | ***Familiarity with a building material or system*** |
| | 14 | Modification ability |

| | | |
|---|---|---|
| Economic impacts | 16 | **Construction cost** |
| | 16 | Skill requirement |
| | 17 | Supply Chain |
| | 18 | **Duration** of construction |
| | 19 | ***Job creation*** |

| | | |
|---|---|---|
| **User acceptability** | **13** | **Familiarity with a building material or system** |
| | **14** | **Modification ability** |

| | | |
|---|---|---|
| **Economic impacts** | **16** | **Construction cost** |
| | **17** | **Supply Chain** |
| | **18** | **Duration of construction** |
| | **19** | **Job creation** |

|  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|
|  | 27 | Scalability |  | *Scalability* |  |  |  |  |  |
|  | 28 | Impact on Carpet Area | 26 | **Least functional thickness** | 20 | Least functional thickness |  | ***Least functional thickness*** |  |
|  | 29 | Impact on local economy | 27 | Impact on local economy | 21 | Impact on local economy |  | ***Impact on local economy*** |  |
|  |  |  |  |  |  |  | 15 | ***Skill requirement*** |  |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| **Nomenclature changed** |  | ▨ | *Dropped* | 🟩 | ***Added*** |
| 🟩 | Tier 1- Normalized Data readily available | 🟨 | Tier 2- Data can be gathered through desk research | 🟥 | Tier 3- Field surveys necessary |

# Annex 5: Cooling and/or heating energy saving potential of building systems

|  | U-Value W/m$^2$-K | Composite |  | Warm & Humid |  | Hot & Dry |  | Temperate |  | Cold |  |
|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | Cooling energy (kWh/m$^2$/yr) |  |  |  |  |  |  |  | Heating energy (kWh/m$^2$/yr) |  |
| **Base Case** |  | 50.19 |  | 44.85 |  | 46.47 |  | 15.24 |  | 42.32 |  |
| Walling (12.5 mm cement plaster + 225 mm brick + 12.5 mm cement plaster) | 2.13 |  |  |  |  |  |  |  |  |  |  |
| Roofing (100 mm RCC + 100 mm lime concrete) | 2.78 |  |  |  |  |  |  |  |  |  |  |
| **Walling systems** | **U-Value W/m$^2$-K** | **Savings from Base Case (kWh/m$^2$/yr)** | **Savings (%)** | **Savings from Base Case (kWh/m$^2$/yr)** | **Savings (%)** | **Savings from Base Case (kWh/m$^2$/yr)** | **Savings (%)** | **Savings from Base Case (kWh/m$^2$/yr)** | **Savings (%)** | **Savings from Base Case (kWh/m$^2$/yr)** | **Savings (%)** |
| 1. Fly ash brick work | 1.90 | 1.77 | 4 | 1.48 | 3 | 1.84 | 4 | 0.73 | 5 | 1.63 | 4 |
| **2. AAC block masonry** | **0.80** | **14.22** | **28** | **13.23** | **29** | **13.75** | **30** | **3.95** | **26** | **5.31** | **13** |
| 3. Rat-trap Bond brickwork | 1.79 | 2.68 | 5 | 2.30 | 5 | 2.75 | 6 | 1.06 | 7 | 2.18 | 5 |
| 4. Hollow concrete block masonry | 1.89 | 1.85 | 4 | 1.52 | 3 | 1.92 | 4 | 0.76 | 5 | 1.68 | 4 |
| 5. Solid concrete block masonry | 2.70 | -3.17 | -6 | -2.07 | -5 | -3.64 | -8 | -1.62 | -11 | -6.83 | -16 |
| 6. CSEB walling | 1.94 | 2.25 | 4 | -3.29 | -7 | -5.76 | -12 | 1.06 | 7 | 1.41 | 3 |
| 7. Stone-crete blocks masonry | 3.40 | -4.24 | -8 | -1.85 | -4 | -6.03 | -13 | -2.83 | -19 | -19.16 | -45 |
| 8. GFRG Panel System | 2.85 | -3.74 | -7 | -2.24 | -5 | -4.39 | -9 | -1.99 | -13 | -9.22 | -22 |
| 9. Precast Large Concrete Panel system | 2.00 | 0.90 | 2 | 0.93 | 2 | 0.97 | 2 | 0.41 | 3 | 0.98 | 2 |
| **10. Reinforced EPS Core Panel System** | **0.58** | **19.78** | **39** | **15.89** | **35** | **14.11** | **30** | **5.73** | **38** | **6.41** | **15** |
| 11. LGSFS-ICP | 3.87 | -3.53 | -7 | -0.40 | -1 | -6.21 | -13 | -2.84 | -19 | -28.11 | -66 |
| 12. Monolithic Concrete Construction | 3.59 | -4.01 | -8 | -1.31 | -3 | -6.22 | -13 | -2.92 | -19 | -22.81 | -54 |

|  | U-Value W/m$^2$-K | Composite |  | Warm & Humid |  | Hot & Dry |  | Temperate |  | Cold |  |
|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | Cooling energy (kWh/m$^2$/yr) |  |  |  |  |  |  |  | Heating energy (kWh/m$^2$/yr) |  |
| **Base Case** |  | 50.19 |  | 44.85 |  | 46.47 |  | 15.24 |  | 42.32 |  |
| Walling (12.5 mm cement plaster + 225 mm brick + 12.5 mm cement plaster) | 2.13 |  |  |  |  |  |  |  |  |  |  |
| Roofing (100 mm RCC + 100 mm lime concrete) | 2.78 |  |  |  |  |  |  |  |  |  |  |
| **Roofing systems** | **U-Value W/m$^2$-K** | **Savings from Base Case (kWh/m$^2$/yr)** | **Savings (%)** | **Savings from Base Case (kWh/m$^2$/yr)** | **Savings (%)** | **Savings from Base Case (kWh/m$^2$/yr)** | **Savings (%)** | **Savings from Base Case (kWh/m$^2$/yr)** | **Savings (%)** | **Savings from Base Case (kWh/m$^2$/yr)** | **Savings (%)** |
|  |  |  |  |  |  |  |  |  |  |  |  |
| 13. Reinforced Brick Panel roofing | 2.80 | 0.78 | 2 | 6.16 | 14 | -7.50 | -16 | 0.43 | 3 | -0.15 | 0 |
| 14. RCC Filler Slab roofing | 3.94 | -3.61 | -7 | -4.59 | -10 | -11.98 | -26 | -2.76 | -18 | -5.09 | -12 |
| 15. Pre-cast RCC Plank & Joist roofing | 2.00 | 3.61 | 7 | 3.82 | 9 | 3.55 | 8 | 2.37 | 16 | 3.59 | 8 |
| 16. Ferro Cement channel roofing | 2.56 | 2.48 | 5 | -3.73 | -8 | -4.63 | -10 | 2.17 | 14 | 4.47 | 11 |

# Annex 6: Case studies overview

## Delhi

The Bawana housing scheme, developed by DSIIDC (Delhi State Industrial and Infrastructure Development Corporation Ltd.) was constructed as a part of the Rajiv Gandhi Housing scheme primarily to provide shelter for industrial workers and other Economically Weaker Sections (EWS). The housing development is spread across 37 acres (~15 hectares) having a high density - about 300 dwelling units per hectare. A mix of 2, 3 and 4 storey exposed brick buildings, housing a total of 4348 dwelling units, are spread across in a rectangular layout separated by paved pathways and courtyards.

Cluster planning was adopted in the housing development, to provide organised open spaces and green areas in the form of courtyards, but proper maintenance and upkeep of these spaces is missing. All the dwelling units comprise of minimum two rooms and confirm with the minimum standards of area prescribed by the government for EWS housing. Each unit is provided with a covered balcony and the required minimum fenestrations. The building blocks were oriented so as to reduce heat gains from direct solar radiation and enhance natural ventilation

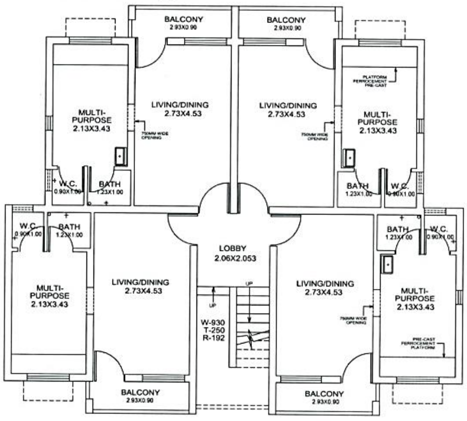


***Figure 43:*** *Typical floor plan-DU type -I*

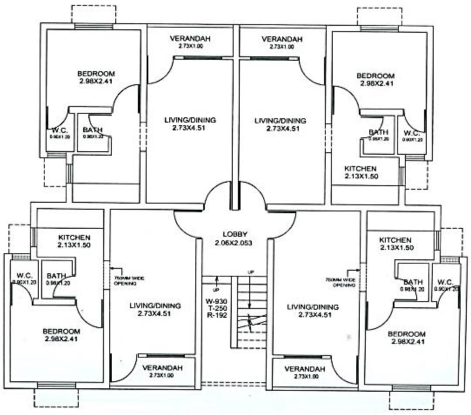


***Figure 44:*** *Typical floor plan-DU type -II*

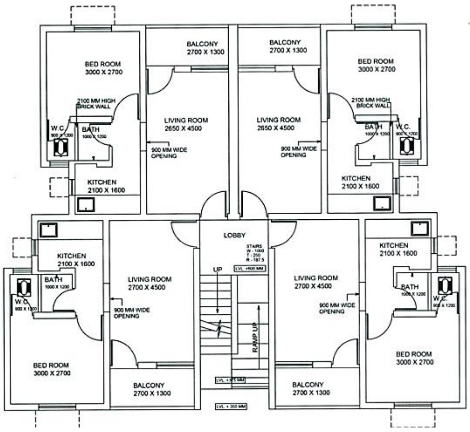


***Figure 45: Typical floor plan-DU type -III***

## About the households

At the time of the survey the houses had been occupied for up to 11 years with only a few of the original residents still living there. Over the years the industrial workers moved to different location and put up the houses on rent. Most of the residents surveyed were living on rent. In terms of number of residents, the survey revealed maximum households having about four members However, a significant number of dwellings were also found having occupancy of five or more members, making the living congested

***Table 17:*** *Case study -base details: Delhi*

| Category | Case study |
|---|---|
| **Name of the development** | Bawana Industrial workers housing |
| **Government scheme** | The Rajiv Gandhi Housing Scheme |
| **Occupancy** | 11 years |
| **Target group** | Economically Weaker Section and Industrial workers |
| **Number of dwelling units** | 4348 |
| **Carpet area of each dwelling (sq. ft.)** | Type I = 263; Type II = 297; Type III = 311 |

## Jaipur

The Kiron Ki Dhani housing project developed under the Rajeev Awaas Yojana was constructed to rehabilitate the local workers and slum dwellers in the area. It is situated near a wholesale vegetable market called Muhana mandi about 19km from the city centre of Jaipur. The community comprises of daily wage earners, most of them working in Muhana mandi. The project was undertaken and constructed by the Jaipur Development authority (JDA) along with support from the union government and the Government of Rajasthan. The project was handed over in 2015. This housing project comprises of 1104 dwelling units with 100% EWS as the target group.

The development consists of G+2 storey structures housing about 1104 dwelling units. A typical floor layout consists of four dwelling units laid out around a central service core on each floor. All units are identical and consist of two rooms, one separate kitchen, one WC and a separate shower area and a balcony (Figure 46). The central spaces provided in the development which were originally meant to be developed as green landscape areas, have been left barren and unfinished. The occupants have been known to use these as a dumping ground (Figure 47), severely impacting the health and hygiene of the area.

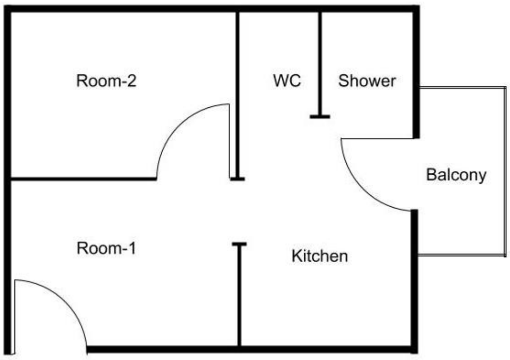


**Figure 46:** typical layout of the dwelling units

***Figure 47:*** *View of the central spaces left unfinished*

### About the households

At the time of the survey the houses had been occupied for up to 4 years with most of the original occupants still living there. Of the 150 surveyed households about 93% had been occupied for up to 3 years. About the 4% had been occupied in between for less than 1 year and the remaining 3% of the households had been occupied for more than 3 years. In terms of number of residents, the survey revealed maximum households having about 4 to 5 members (Figure 48). A significant number of dwellings were also found having occupancy of more than 6 members which made the living congested.

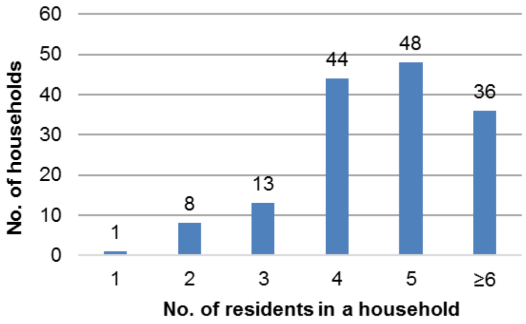


***Figure 48:*** *No. of residents in a household*

***Table 18****: Case study -base details: Jaipur*

| Category | Case study |
|---|---|
| **Name of the development** | Kiron Ki Dhani |
| **Government scheme** | Rajeev Awaas Yojana |
| **Occupancy** | 4 years |
| **Target group** | Slum dwellers and Economically Weaker Section |
| **Distance from city centre** | 19 km |
| **Number of dwelling units** | 1104 |
| **Built-up area of each dwelling (sq. ft.)** | 328 |
| **Cost of construction (INR per sq. ft.)** | 1100-1200 |

## Dehradun

The housing society in a collection of several small colonies redeveloped in-situ under the “Valmiki Ambedkar Awas Yojana.” This is the first social housing project developed in Dehradun under a scheme. The colonies include, Ram Kusth Ashram, Rotary Club Kusth Ashram, Bhagat Singh Colony, Shanti Kusth Ashram, and Indrapuram Phase I. As a result of being a BMTPC demonstration project, several cost effective and disaster resilient technologies have been used.

The development consists of ground floor structures housing about 100 dwelling units. All units are identical and consist of one room, kitchen space, one WC and shower area (Figure 49). The housing units being on the ground floor have access to plenty of open spaces. This area originally housed shanty constructions of these inhabitants that covered most of the space. After the construction was completed, green cover and community spaces were developed in these open areas.

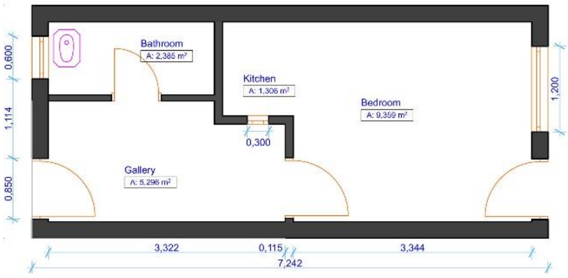


**Figure 49:** *Typical layout of Shanti Kusth Ashram*

### About the households

At the time of the survey the houses had been occupied for more than 9 years with most of the original residents still living there. Of the 120 surveyed households about 59% (52%+7%) had been occupied for 9 years or more. About 16% houses had been occupied in between 3.1 to 5 years and 15% of the households had been occupied as little as 1.1 to 3 years.

**Figure 50:** *Rotary club colony*

In terms of number of residents, the survey revealed maximum households having about four members (Figure 51). However, a significant number of dwellings were also found having occupancy of five or more members which made the living congested inside these dwellings (Figure 6).

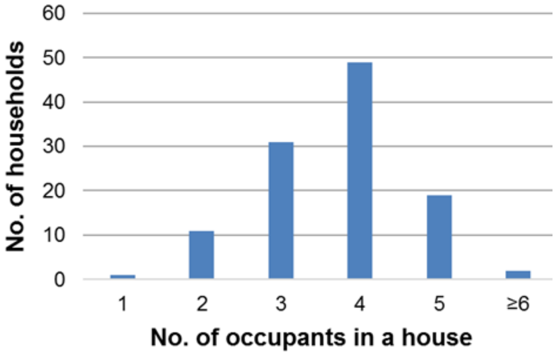


**Figure 51:** *No. of residents in a household*

***Table 19****: Case study -base details: Dehradun*

| Category | Case study |
|---|---|
| **Name of the development** | Shanti Kusth Ashram, Bhagat Singh colony |
| **Government scheme** | Valmiki Ambedkar Awas Yojana (VAMBAY) |
| **Occupancy** | 9years |
| **Target group** | Economically Weaker Section/Slum dwellers |
| **Distance from city centre** | 1 km |
| **Number of dwelling units** | 100 |
| **Built-up area of each dwelling (sq. ft.)** | 181 |
| **Cost of construction (INR per sq. ft.)** | 250 |

## Bangalore

The first model demonstration housing, constructed under the Valmiki Ambedkar Awas Yojana (VAMBAY), is located at Laggere, in the North-west outer rim of Bangalore. The housing project is one of the many social housing developments by the Karnataka Slum Development Board, constructed with an aim to upgrade the dwelling units and improve living conditions for the slum dwellers of the Laggere area. Designed and constructed by Building Materials and Technology Promotion Council (BMTPC), the slum rehabilitation housing project at Laggare demonstrates the use of cost-effective materials and technologies for use in social housing projects in India.

The development consists of G+2 storey structures housing 252 dwelling units. The 125 houses under VAMBAY and the 127 additional houses by the Karnataka Slum Clearance Board were designed to share maximum common walls. A typical floor layout comprises of four dwelling units accessed by a centrally located staircase and lobby provided at each level. With a built-up area of about 275 sq. ft. the dwelling units consists of two rooms, a kitchen, one WC and a separate shower area. Windows have been provided on the two longer façades, such that each unit has window openings only on one external wall; reducing the possibility of cross ventilation (Figure 52).

### About the households

At the time of the survey the houses had been occupied for more than 10 years with most of the original residents still living there. Of the 154 surveyed households about 28% had been occupied for more than 9 years. About the same percentage of houses (29%) had been occupied in between 7 to 9 years. An almost equal number of surveyed households had been occupied for a period of 3 to 7 years. Whereas less than one quarter of the surveyed dwellings were found to have been recently occupied within the past three years.

In terms of number of residents, the survey revealed maximum households having about four members However, a significant number of dwellings were also found having occupancy of five or more members which made the living congested.

***Figure 52:*** *Typical building block layout*

***Table 20:*** *Case study -base details: Bangalore*

| Category | Case study |
|---|---|
| **Name of the development** | Laggere slum rehabilitation |
| **Government scheme** | Valmiki Ambedkar Awas Yojana |
| **Occupancy** | 10 years |
| **Target group** | Economically Weaker Section (slum dwellers) |
| **Distance from city centre** | 13 km |
| **Number of dwelling units** | 252 |
| **Built-up area of each dwelling (sq. ft.)** | 275 |
| **Cost of construction (INR per sq. ft.)** | 218 |

## Vijayawada

The Jakkampudi colony in Vijayawada is a social housing project developed under the Jawaharlal Nehru National Urban Renewal Mission (JNNURM) to provide affordable and improved housing for the Economically Weaker Sections (EWS) of the society living in the city. The project located around 11km from the city centre, was made on land pooling basis with 60% land from the inhabitants and 40% from the government. A screening process was established to identify the beneficiaries of the scheme. Through an online application system and physical visits, households were selected based on their original house location, number of family members and annual income. About 1000 units were left midway of construction due to funding issues from the government, 7104 have been completed and are occupied.

The development consists of G+3 storey structures housing about 7104 dwelling units. A typical floor layout consists of eight dwelling units and a central corridor with two staircases located at either ends of the corridor. With four dwelling units on either side the long central corridor is interrupted midway by a cut out equal to the length of a dwelling unit, to allow for daylight and natural ventilation into the building. All units are identical and consist of two rooms, one combined WC and shower area and a balcony. Except for the windows and ventilators provided in the balcony area, all the other windows of any dwelling unit open onto to the central corridor and/or the staircases, making them redundant to use due to privacy issues (Figure 53).

### About the households

At the time of the survey the houses had been occupied for more than 5 years. Of the 152 surveyed households about 32% had been occupied for up to 3 years. About the same percentage of houses (29%) had been occupied in between 3.1 to 5 years. Only 20% of the households had been occupied for 5 years or more.

In terms of number of residents, the survey revealed maximum households having about four members However, a significant number of dwellings were also found having occupancy of two and three members. The number of households with occupancy more than five or six was found to be less.

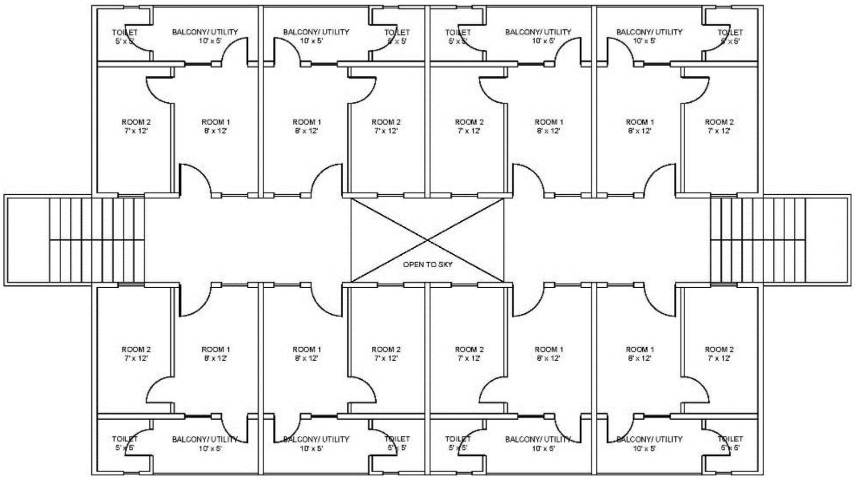


***Figure 53:*** *Typical layout of a building block at Jakkampudi colony*

***Table 21****: Case study -base details: Vijayawada*

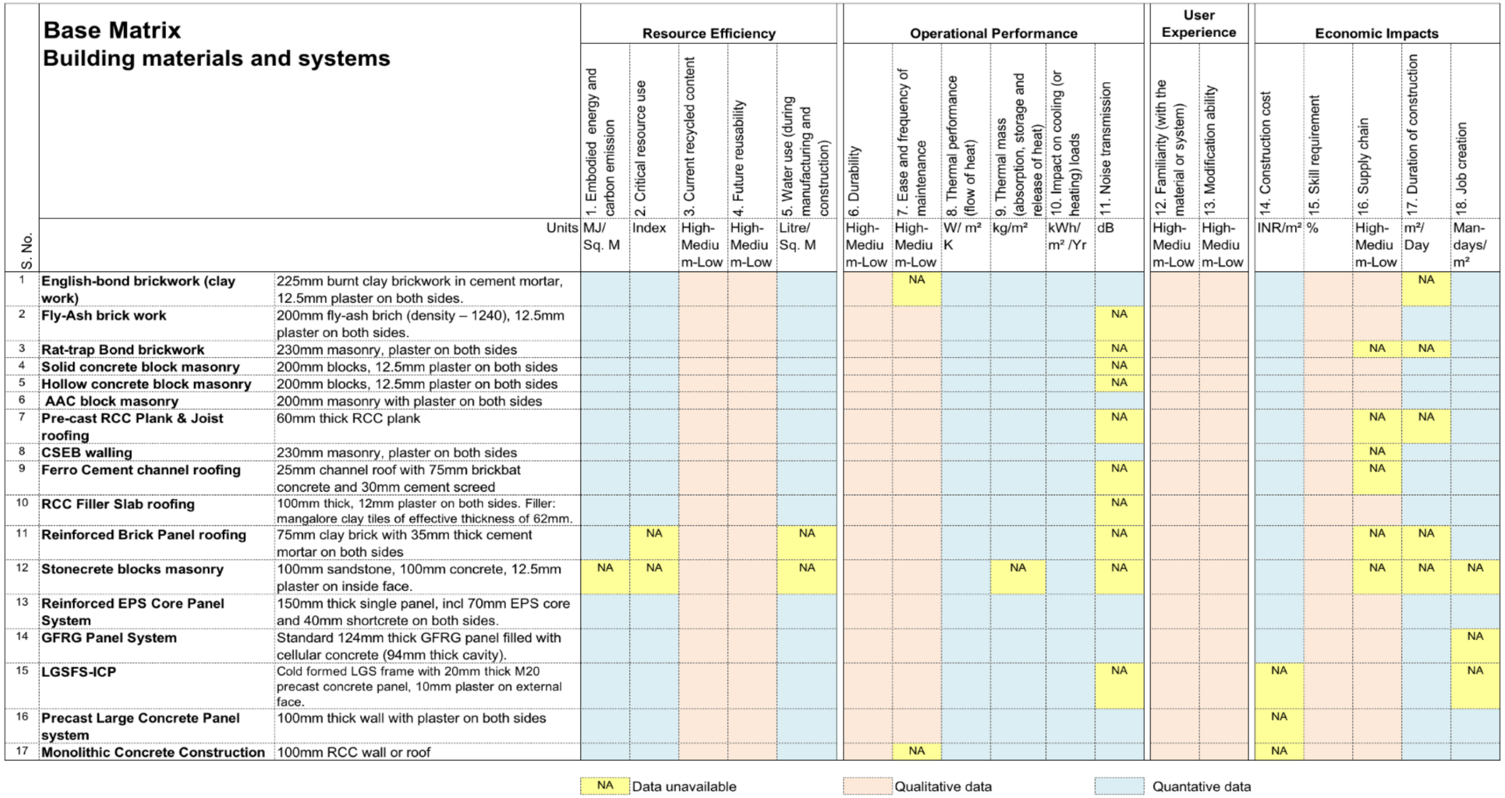
| Category | Case study |
|---|---|
| **Name of the development** | Jakkampudi colony |
| **Government scheme** | Jawaharlal Nehru National Urban Renewal Mission (JNNURM) |
| **Occupancy** | 8 years |
| **Target group** | Economically Weaker Section |
| **Distance from city centre** | 11 km |
| **Number of dwelling units** | 7104 |
| **Built-up area of each dwelling (sq. ft.)** | 275 |
| **Cost of construction (INR per sq. ft.)** | - |

# Annex 7: SAT calculations

The step-wise process for developing the SAT calculations is explained below.

## Formulating the MCDM

There were 17 building systems scored against 18 attributes for their relative assessment of sustainability against each other. This led to formulation of a 17*18 'Base Matrix'. Data for 9 attributes among 18, was quantitative and for the other 9 was qualitative which was quantified. All the 18 attributes had different metric of measurement. For 8 attributes amongst 18, a lesser value was better and for the remaining 10, higher was better. This data was corrected into a uniform order by making lower values better for all attributes. Over that, of the 17*18 data values in the matrix, some of the data values were missing. These missing values were denoted by 'NA'.



| S. No. | **Base Matrix**<br>**Building materials and systems** | | Resource Efficiency | | | | | Operational Performance | | | | | | User Experience | | Economic Impacts | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1. Embodied energy and carbon emission | 2. Critical resource use | 3. Current recycled content | 4. Future reusability | 5. Water use (during manufacturing and construction) | 6. Durability | 7. Ease and frequency of maintenance | 8. Thermal performance (flow of heat) | 9. Thermal mass (absorption, storage and release of heat) | 10. Impact on cooling (or heating) loads | 11. Noise transmission | 12. Familiarity (with the material or system) | 13. Modification ability | 14. Construction cost | 15. Skill requirement | 16. Supply chain | 17. Duration of construction | 18. Job creation |
| | | Units | MJ/ Sq. M | Index | High-Medium-Low | High-Medium-Low | Litre/ Sq. M | High-Medium-Low | High-Medium-Low | W/ m² K | kg/m² | kWh/ m² /Yr | dB | High-Medium-Low | High-Medium-Low | INR/m² | % | High-Medium-Low | m²/ Day | Man-days/ m² |
| 1 | **English-bond brickwork (clay work)** | 225mm burnt clay brickwork in cement mortar, 12.5mm plaster on both sides. | | | | | | | NA | | | | | | | | | | NA | |
| 2 | **Fly-Ash brick work** | 200mm fly-ash brich (density – 1240), 12.5mm plaster on both sides. | | | | | | | | | | | NA | | | | | | | |
| 3 | **Rat-trap Bond brickwork** | 230mm masonry, plaster on both sides | | | | | | | | | | | NA | | | | | NA | NA | |
| 4 | **Solid concrete block masonry** | 200mm blocks, 12.5mm plaster on both sides | | | | | | | | | | | NA | | | | | | | |
| 5 | **Hollow concrete block masonry** | 200mm blocks, 12.5mm plaster on both sides | | | | | | | | | | | NA | | | | | | | |
| 6 | **AAC block masonry** | 200mm masonry with plaster on both sides | | | | | | | | | | | | | | | | | | |
| 7 | **Pre-cast RCC Plank & Joist roofing** | 60mm thick RCC plank | | | | | | | | | | | NA | | | | | NA | NA | |
| 8 | **CSEB walling** | 230mm masonry, plaster on both sides | | | | | | | | | | | | | | | | NA | | |
| 9 | **Ferro Cement channel roofing** | 25mm channel roof with 75mm brickbat concrete and 30mm cement screed | | | | | | | | | | | NA | | | | | NA | | |
| 10 | **RCC Filler Slab roofing** | 100mm thick, 12mm plaster on both sides. Filler: mangalore clay tiles of effective thickness of 62mm. | | | | | | | | | | | NA | | | | | | | |
| 11 | **Reinforced Brick Panel roofing** | 75mm clay brick with 35mm thick cement mortar on both sides | | NA | | | NA | | | | | | NA | | | | | NA | NA | |
| 12 | **Stonecrete blocks masonry** | 100mm sandstone, 100mm concrete, 12.5mm plaster on inside face. | NA | NA | | | NA | | | | NA | | NA | | | | | NA | NA | NA |
| 13 | **Reinforced EPS Core Panel System** | 150mm thick single panel, incl 70mm EPS core and 40mm shortcrete on both sides. | | | | | | | | | | | | | | | | | | |
| 14 | **GFRG Panel System** | Standard 124mm thick GFRG panel filled with cellular concrete (94mm thick cavity). | | | | | | | | | | | | | | | | | | NA |
| 15 | **LGSFS-ICP** | Cold formed LGS frame with 20mm thick M20 precast concrete panel, 10mm plaster on external face. | | | | | | | | | | | NA | | | NA | | | | NA |
| 16 | **Precast Large Concrete Panel system** | 100mm thick wall with plaster on both sides | | | | | | | | | | | | | | NA | | | | |
| 17 | **Monolithic Concrete Construction** | 100mm RCC wall or roof | | | | | | | NA | | | | | | | NA | | | | |

NA Data unavailable

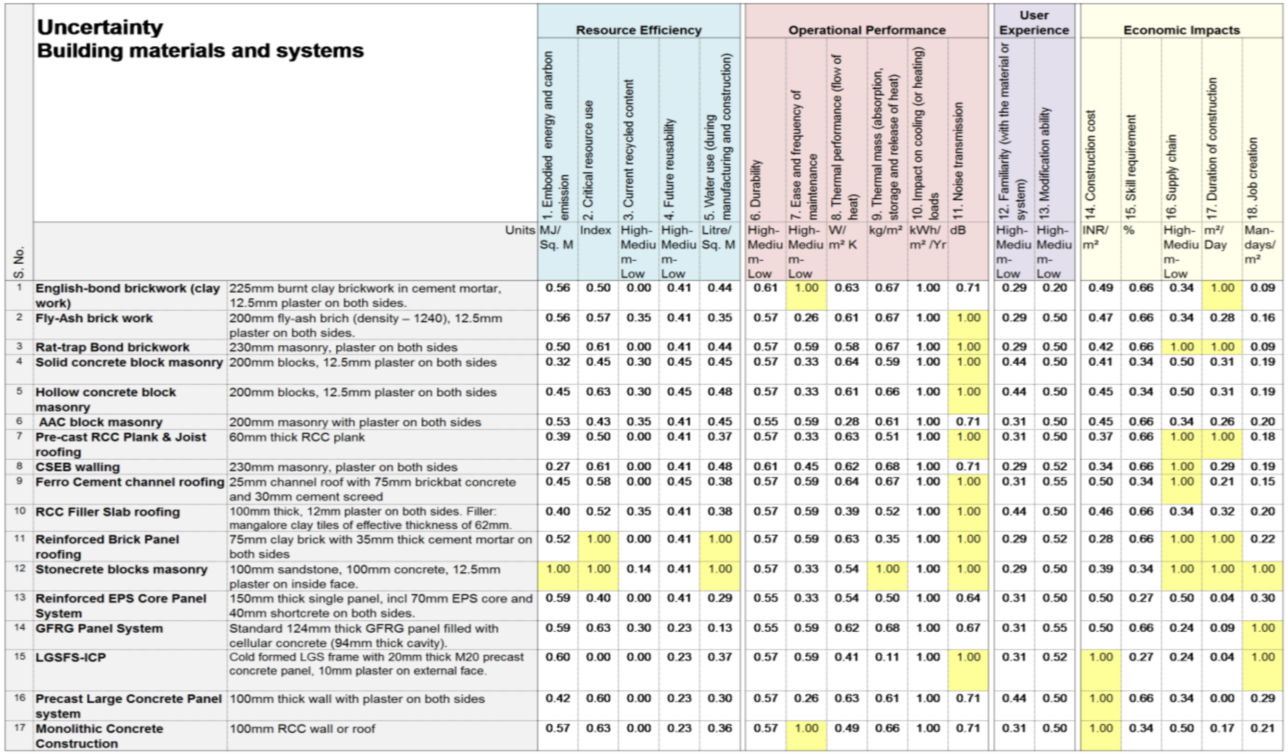
Qualitative data

Quantative data

## Calculation of Belief, Plausibility and Uncertainty

Three matrices for calculating belief, plausibility and uncertainty were formulated from the Base Matrix. The mathematical calculations fundamental for their formulation have been explained in simpler terms below.

- Belief: It is the minimum probability of any particular building system being better than another (amongst the selected 17 building systems) for the same attribute. As there is no evidence of belief regarding the missing values, the belief for the same will be zero. For ‘NA’ values or missing data Belief = 0.
- Plausibility: It is the maximum probability of any particular building system being better than another (amongst the selected 17 building systems) for the same attribute. For ‘NA’ values or missing data Plausibility = 1.
- Uncertainty: It is the difference between its plausibility and belief values. The value of the best performing building system (amongst the selected 17 building systems) under any attribute will have a ‘zero’ uncertainty.

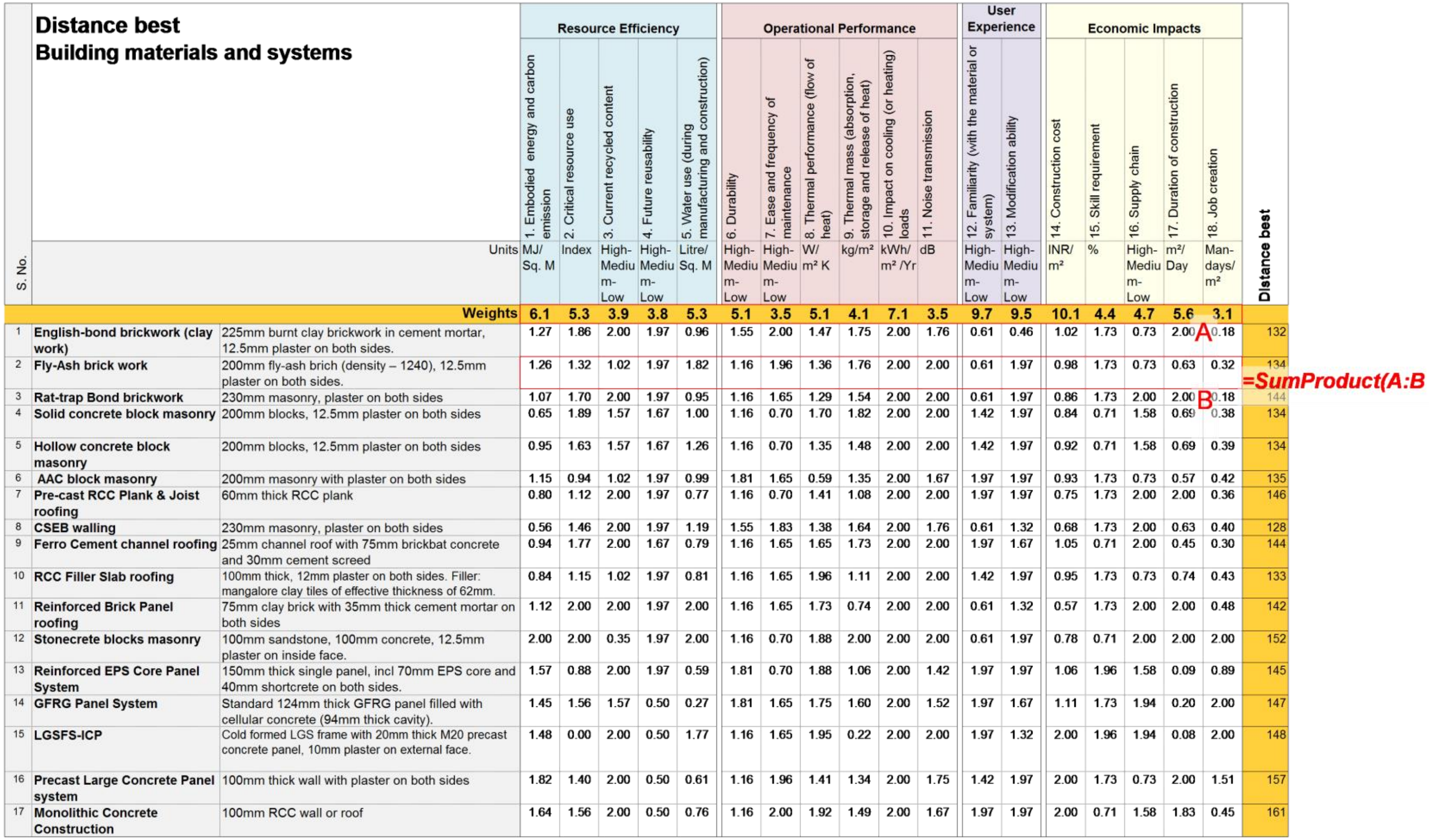


| S. No. | **Uncertainty**<br>**Building materials and systems** | | Resource Efficiency | | | | | Operational Performance | | | | | | User Experience | | Economic Impacts | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1. Embodied energy and carbon emission | 2. Critical resource use | 3. Current recycled content | 4. Future reusability | 5. Water use (during manufacturing and construction) | 6. Durability | 7. Ease and frequency of maintenance | 8. Thermal performance (flow of heat) | 9. Thermal mass (absorption, storage and release of heat) | 10. Impact on cooling (or heating) loads | 11. Noise transmission | 12. Familiarity (with the material or system) | 13. Modification ability | 14. Construction cost | 15. Skill requirement | 16. Supply chain | 17. Duration of construction | 18. Job creation |
| | | Units | MJ/ Sq. M | Index | High-Medium-Low | High-Medium-Low | Litre/ Sq. M | High-Medium-Low | High-Medium-Low | W/ m² K | kg/m² | kWh/ m² /Yr | dB | High-Medium-Low | High-Medium-Low | INR/ m² | % | High-Medium-Low | m²/ Day | Man-days/ m² |
| 1 | **English-bond brickwork (clay work)** | 225mm burnt clay brickwork in cement mortar, 12.5mm plaster on both sides. | 0.56 | 0.50 | 0.00 | 0.41 | 0.44 | 0.61 | 1.00 | 0.63 | 0.67 | 1.00 | 0.71 | 0.29 | 0.20 | 0.49 | 0.66 | 0.34 | 1.00 | 0.09 |
| 2 | **Fly-Ash brick work** | 200mm fly-ash brich (density – 1240), 12.5mm plaster on both sides. | 0.56 | 0.57 | 0.35 | 0.41 | 0.35 | 0.57 | 0.26 | 0.61 | 0.67 | 1.00 | 1.00 | 0.29 | 0.50 | 0.47 | 0.66 | 0.34 | 0.28 | 0.16 |
| 3 | **Rat-trap Bond brickwork** | 230mm masonry, plaster on both sides | 0.50 | 0.61 | 0.00 | 0.41 | 0.44 | 0.57 | 0.59 | 0.58 | 0.67 | 1.00 | 1.00 | 0.29 | 0.50 | 0.42 | 0.66 | 1.00 | 1.00 | 0.09 |
| 4 | **Solid concrete block masonry** | 200mm blocks, 12.5mm plaster on both sides | 0.32 | 0.45 | 0.30 | 0.45 | 0.45 | 0.57 | 0.33 | 0.64 | 0.59 | 1.00 | 1.00 | 0.44 | 0.50 | 0.41 | 0.34 | 0.50 | 0.31 | 0.19 |
| 5 | **Hollow concrete block masonry** | 200mm blocks, 12.5mm plaster on both sides | 0.45 | 0.63 | 0.30 | 0.45 | 0.48 | 0.57 | 0.33 | 0.61 | 0.66 | 1.00 | 1.00 | 0.44 | 0.50 | 0.45 | 0.34 | 0.50 | 0.31 | 0.19 |
| 6 | **AAC block masonry** | 200mm masonry with plaster on both sides | 0.53 | 0.43 | 0.35 | 0.41 | 0.45 | 0.55 | 0.59 | 0.28 | 0.61 | 1.00 | 0.71 | 0.31 | 0.50 | 0.45 | 0.66 | 0.34 | 0.26 | 0.20 |
| 7 | **Pre-cast RCC Plank & Joist roofing** | 60mm thick RCC plank | 0.39 | 0.50 | 0.00 | 0.41 | 0.37 | 0.57 | 0.33 | 0.63 | 0.51 | 1.00 | 1.00 | 0.31 | 0.50 | 0.37 | 0.66 | 1.00 | 1.00 | 0.18 |
| 8 | **CSEB walling** | 230mm masonry, plaster on both sides | 0.27 | 0.61 | 0.00 | 0.41 | 0.48 | 0.61 | 0.45 | 0.62 | 0.68 | 1.00 | 0.71 | 0.29 | 0.52 | 0.34 | 0.66 | 1.00 | 0.29 | 0.19 |
| 9 | **Ferro Cement channel roofing** | 25mm channel roof with 75mm brickbat concrete and 30mm cement screed | 0.45 | 0.58 | 0.00 | 0.45 | 0.38 | 0.57 | 0.59 | 0.64 | 0.67 | 1.00 | 1.00 | 0.31 | 0.55 | 0.50 | 0.34 | 1.00 | 0.21 | 0.15 |
| 10 | **RCC Filler Slab roofing** | 100mm thick, 12mm plaster on both sides. Filler: mangalore clay tiles of effective thickness of 62mm. | 0.40 | 0.52 | 0.35 | 0.41 | 0.38 | 0.57 | 0.59 | 0.39 | 0.52 | 1.00 | 1.00 | 0.44 | 0.50 | 0.46 | 0.66 | 0.34 | 0.32 | 0.20 |
| 11 | **Reinforced Brick Panel roofing** | 75mm clay brick with 35mm thick cement mortar on both sides | 0.52 | 1.00 | 0.00 | 0.41 | 1.00 | 0.57 | 0.59 | 0.63 | 0.35 | 1.00 | 1.00 | 0.29 | 0.52 | 0.28 | 0.66 | 1.00 | 1.00 | 0.22 |
| 12 | **Stonecrete blocks masonry** | 100mm sandstone, 100mm concrete, 12.5mm plaster on inside face. | 1.00 | 1.00 | 0.14 | 0.41 | 1.00 | 0.57 | 0.33 | 0.54 | 1.00 | 1.00 | 1.00 | 0.29 | 0.50 | 0.39 | 0.34 | 1.00 | 1.00 | 1.00 |
| 13 | **Reinforced EPS Core Panel System** | 150mm thick single panel, incl 70mm EPS core and 40mm shortcrete on both sides. | 0.59 | 0.40 | 0.00 | 0.41 | 0.29 | 0.55 | 0.33 | 0.54 | 0.50 | 1.00 | 0.64 | 0.31 | 0.50 | 0.50 | 0.27 | 0.50 | 0.04 | 0.30 |
| 14 | **GFRG Panel System** | Standard 124mm thick GFRG panel filled with cellular concrete (94mm thick cavity). | 0.59 | 0.63 | 0.30 | 0.23 | 0.13 | 0.55 | 0.59 | 0.62 | 0.68 | 1.00 | 0.67 | 0.31 | 0.55 | 0.50 | 0.66 | 0.24 | 0.09 | 1.00 |
| 15 | **LGSFS-ICP** | Cold formed LGS frame with 20mm thick M20 precast concrete panel, 10mm plaster on external face. | 0.60 | 0.00 | 0.00 | 0.23 | 0.37 | 0.57 | 0.59 | 0.41 | 0.11 | 1.00 | 1.00 | 0.31 | 0.52 | 1.00 | 0.27 | 0.24 | 0.04 | 1.00 |
| 16 | **Precast Large Concrete Panel system** | 100mm thick wall with plaster on both sides | 0.42 | 0.60 | 0.00 | 0.23 | 0.30 | 0.57 | 0.26 | 0.63 | 0.61 | 1.00 | 0.71 | 0.44 | 0.50 | 1.00 | 0.66 | 0.34 | 0.00 | 0.29 |
| 17 | **Monolithic Concrete Construction** | 100mm RCC wall or roof | 0.57 | 0.63 | 0.00 | 0.23 | 0.36 | 0.57 | 1.00 | 0.49 | 0.66 | 1.00 | 0.71 | 0.31 | 0.50 | 1.00 | 0.34 | 0.50 | 0.17 | 0.21 |

**Uncertainty = Plausibility – Belief**
**For ‘NA’ values Uncertainty = (1 – 0) = 1**

## Distance from the best and worst value

After step 2, belief, plausibility and uncertainty values for all building systems against the 18 attributes had been evaluated. Khatibi's distance measure was used to find the distance of values of each building system in an attribute, from the best and worst values for the same attribute.  These were then multiplied with the weights of the respective attributes' resultant from the AHP survey and summed across. This gave the weighted summation of best distances and the worst distances.



**Distance best**
**Building materials and systems**

| S. No. | | | Resource Efficiency | | | | | Operational Performance | | | | | | User Experience | | Economic Impacts | | | | | Distance best |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1. Embodied energy and carbon emission | 2. Critical resource use | 3. Current recycled content | 4. Future reusability | 5. Water use (during manufacturing and construction) | 6. Durability | 7. Ease and frequency of maintenance | 8. Thermal performance (flow of heat) | 9. Thermal mass (absorption, storage and release of heat) | 10. Impact on cooling (or heating) loads | 11. Noise transmission | 12. Familiarity (with the material or system) | 13. Modification ability | 14. Construction cost | 15. Skill requirement | 16. Supply chain | 17. Duration of construction | 18. Job creation | |
| | | Units | MJ/ Sq. M | Index | High-Medium-Low | High-Medium-Low | Litre/ Sq. M | High-Medium-Low | High-Medium-Low | W/ m² K | kg/m² | kWh/ m² /Yr | dB | High-Medium-Low | High-Medium-Low | INR/ m² | % | High-Medium-Low | m²/ Day | Man-days/ m² | |
| | | **Weights** | **6.1** | **5.3** | **3.9** | **3.8** | **5.3** | **5.1** | **3.5** | **5.1** | **4.1** | **7.1** | **3.5** | **9.7** | **9.5** | **10.1** | **4.4** | **4.7** | **5.6** | **3.1** | |
| 1 | **English-bond brickwork (clay work)** | 225mm burnt clay brickwork in cement mortar, 12.5mm plaster on both sides. | 1.27 | 1.86 | 2.00 | 1.97 | 0.96 | 1.55 | 2.00 | 1.47 | 1.75 | 2.00 | 1.76 | 0.61 | 0.46 | 1.02 | 1.73 | 0.73 | 2.00 | 0.18 | 132 |
| 2 | **Fly-Ash brick work** | 200mm fly-ash brich (density – 1240), 12.5mm plaster on both sides. | 1.26 | 1.32 | 1.02 | 1.97 | 1.82 | 1.16 | 1.96 | 1.36 | 1.76 | 2.00 | 2.00 | 0.61 | 1.97 | 0.98 | 1.73 | 0.73 | 0.63 | 0.32 | 134 |
| 3 | **Rat-trap Bond brickwork** | 230mm masonry, plaster on both sides | 1.07 | 1.70 | 2.00 | 1.97 | 0.95 | 1.16 | 1.65 | 1.29 | 1.54 | 2.00 | 2.00 | 0.61 | 1.97 | 0.86 | 1.73 | 2.00 | 2.00 | 0.18 | 144 |
| 4 | **Solid concrete block masonry** | 200mm blocks, 12.5mm plaster on both sides | 0.65 | 1.89 | 1.57 | 1.67 | 1.00 | 1.16 | 0.70 | 1.70 | 1.82 | 2.00 | 2.00 | 1.42 | 1.97 | 0.84 | 0.71 | 1.58 | 0.69 | 0.38 | 134 |
| 5 | **Hollow concrete block masonry** | 200mm blocks, 12.5mm plaster on both sides | 0.95 | 1.63 | 1.57 | 1.67 | 1.26 | 1.16 | 0.70 | 1.35 | 1.48 | 2.00 | 2.00 | 1.42 | 1.97 | 0.92 | 0.71 | 1.58 | 0.69 | 0.39 | 134 |
| 6 | **AAC block masonry** | 200mm masonry with plaster on both sides | 1.15 | 0.94 | 1.02 | 1.97 | 0.99 | 1.81 | 1.65 | 0.59 | 1.35 | 2.00 | 1.67 | 1.97 | 1.97 | 0.93 | 1.73 | 0.73 | 0.57 | 0.42 | 135 |
| 7 | **Pre-cast RCC Plank & Joist roofing** | 60mm thick RCC plank | 0.80 | 1.12 | 2.00 | 1.97 | 0.77 | 1.16 | 0.70 | 1.41 | 1.08 | 2.00 | 2.00 | 1.97 | 1.97 | 0.75 | 1.73 | 2.00 | 2.00 | 0.36 | 146 |
| 8 | **CSEB walling** | 230mm masonry, plaster on both sides | 0.56 | 1.46 | 2.00 | 1.97 | 1.19 | 1.55 | 1.83 | 1.38 | 1.64 | 2.00 | 1.76 | 0.61 | 1.32 | 0.68 | 1.73 | 2.00 | 0.63 | 0.40 | 128 |
| 9 | **Ferro Cement channel roofing** | 25mm channel roof with 75mm brickbat concrete and 30mm cement screed | 0.94 | 1.77 | 2.00 | 1.67 | 0.79 | 1.16 | 1.65 | 1.65 | 1.73 | 2.00 | 2.00 | 1.97 | 1.67 | 1.05 | 0.71 | 2.00 | 0.45 | 0.30 | 144 |
| 10 | **RCC Filler Slab roofing** | 100mm thick, 12mm plaster on both sides. Filler: mangalore clay tiles of effective thickness of 62mm. | 0.84 | 1.15 | 1.02 | 1.97 | 0.81 | 1.16 | 1.65 | 1.96 | 1.11 | 2.00 | 2.00 | 1.42 | 1.97 | 0.95 | 1.73 | 0.73 | 0.74 | 0.43 | 133 |
| 11 | **Reinforced Brick Panel roofing** | 75mm clay brick with 35mm thick cement mortar on both sides | 1.12 | 2.00 | 2.00 | 1.97 | 2.00 | 1.16 | 1.65 | 1.73 | 0.74 | 2.00 | 2.00 | 0.61 | 1.32 | 0.57 | 1.73 | 2.00 | 2.00 | 0.48 | 142 |
| 12 | **Stonecrete blocks masonry** | 100mm sandstone, 100mm concrete, 12.5mm plaster on inside face. | 2.00 | 2.00 | 0.35 | 1.97 | 2.00 | 1.16 | 0.70 | 1.88 | 2.00 | 2.00 | 2.00 | 0.61 | 1.97 | 0.78 | 0.71 | 2.00 | 2.00 | 2.00 | 152 |
| 13 | **Reinforced EPS Core Panel System** | 150mm thick single panel, incl 70mm EPS core and 40mm shortcrete on both sides. | 1.57 | 0.88 | 2.00 | 1.97 | 0.59 | 1.81 | 0.70 | 1.88 | 1.06 | 2.00 | 1.42 | 1.97 | 1.97 | 1.06 | 1.96 | 1.58 | 0.09 | 0.89 | 145 |
| 14 | **GFRG Panel System** | Standard 124mm thick GFRG panel filled with cellular concrete (94mm thick cavity). | 1.45 | 1.56 | 1.57 | 0.50 | 0.27 | 1.81 | 1.65 | 1.75 | 1.60 | 2.00 | 1.52 | 1.97 | 1.67 | 1.11 | 1.73 | 1.94 | 0.20 | 2.00 | 147 |
| 15 | **LGSFS-ICP** | Cold formed LGS frame with 20mm thick M20 precast concrete panel, 10mm plaster on external face. | 1.48 | 0.00 | 2.00 | 0.50 | 1.77 | 1.16 | 1.65 | 1.95 | 0.22 | 2.00 | 2.00 | 1.97 | 1.32 | 2.00 | 1.96 | 1.94 | 0.08 | 2.00 | 148 |
| 16 | **Precast Large Concrete Panel system** | 100mm thick wall with plaster on both sides | 1.82 | 1.40 | 2.00 | 0.50 | 0.61 | 1.16 | 1.96 | 1.41 | 1.34 | 2.00 | 1.75 | 1.42 | 1.97 | 2.00 | 1.73 | 0.73 | 2.00 | 1.51 | 157 |
| 17 | **Monolithic Concrete Construction** | 100mm RCC wall or roof | 1.64 | 1.56 | 2.00 | 0.50 | 0.76 | 1.16 | 2.00 | 1.92 | 1.49 | 2.00 | 1.67 | 1.97 | 1.97 | 2.00 | 0.71 | 1.58 | 1.83 | 0.45 | 161 |

Finally, the worst and the best distance values were combined using the measure of relative closeness in order to arrive at the final score. Higher score of a building material or system with respect to the others signifies its better performance.

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