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A SYSTEM DYNAMICS SIMULATION-BASED SUSTAINABILITY BENCHMARKING

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ABSTRACT

Sustainability assessment is a multi-faceted, dynamic, and complex paradigm in the context of buildings with several social, economic and environmental interactions. Hence, the building sector lacks a robust sustainability evaluation and benchmarking mechanism. Consequently, a system thinking approach can solve these challenges due to its ability to evaluate complex systems. Therefore, this paper presents a methodological framework for sustainability benchmarking of buildings using the system dynamics modeling and simulation technique. The proposed methodology captures the dynamic trade-offs between the sustainability dimensions associated with a building while evaluating various policy scenarios for improvement. Further, through a series of system simulations, a benchmarking scale is developed to indicate the sustainability of the building as high, medium, and low levels based on the defined criteria. Results indicate the sustainability behavior of different buildings in comparison to achievable industry benchmarks for the building type evaluated while recommending measures for improvement to achieve better sustainability.

1 INTRODUCTION

The world is now witnessing several environmental issues such as climate change, global warming, and diminishing natural resources. Hence, globally there is a strong focus on achieving sustainable development and realizing a net-zero-based economy. The building and infrastructure sectors represent an excellent opportunity to achieve large-scale energy use reductions through efficiency and conservation, particularly for developing economies (Srinivasu et al. 2013). Therefore, sustainability assessment/benchmarking schemes and frameworks gain relevance in the building sector to set the right policies and strategies. The existing sustainability assessment methods range from indicator-based scoring methods, rating systems, composite indices and life cycle assessment methods (Bragança et al. 2010; Ness et al. 2007; Ugwu et al. 2006). However, it is observed that most of them lack a holistic approach to measuring sustainability by simultaneously considering the economic, environmental, and social pillars.

In addition to the sustainability assessment schemes, benchmarking sustainability has recently gained priority among various organizations and businesses, mainly in the manufacturing sector (Wiedmann et al. 2009). Benchmarking strategies facilitate setting benchmarks/levels for the desired parameter, which would eventually help the stakeholders select the right policies. (Deng 2015). However, sustainability benchmarking using the existing assessment tools/frameworks in the building industry is quite challenging, primarily due to the lack of internationally comparable data or data inventory (Hossain and Ng 2020; Khasreen et al. 2009). Furthermore, buildings, owing to their long life span, exhibit a dynamic behavior in the form of physical changes to the external and interior envelope with age and changes to the surrounding environment and energy consumption of the building (Sohn et al. 2017; Su et al. 2019). Since sustainability performance encompasses several elements, its benchmarking requires a data-driven approach and a systemic consideration for evaluating the trade-offs between social, economic, and environmental pillars (Maltz et al. 2018).

Therefore, apart from the standard sustainability assessment methods in the building industry, a comprehensive benchmarking scheme that helps define the sustainability levels and parameters of a proposed building project is found lacking. Given the multi-dimensional and dynamic nature of sustainability assessment for the building sector, a simulation-based benchmarking scheme is proposed in this study using a systems dynamics simulation approach that is capable of handling non-linear, uncertain, multi-feedback, complex, and dynamic systems. Using system dynamics, a range of scenarios can be generated and evaluated for buildings that are then used to develop benchmarks for the sustainability performance of buildings. Overall, the methodological framework proposed through this study introduces lifecycle-based sustainability benchmarking that can be set as standards to ensure wide acceptability and adaptation to promote sustainable development in the building industry.

2 RESEARCH BACKGROUND

Measuring the sustainability of buildings is essential as it promotes adopting practices that could improve their contribution to sustainable development. Therefore, several methods such as rating systems (Mahmoud et al. 2019), indicator-based assessment (Yu et al. 2018), scoring methods (Liu et al. 2013), Life Cycle Assessment (LCA), and its extended methods (Kloepffer 2008; Sohn et al. 2017) and energy assessments (Yucer and Hepbasli 2011) are developed for sustainability assessment. Most of these tools either focus only on the environmental pillar of sustainability or consider the three pillars of sustainability in a discrete and individualistic manner. However, sustainability is not a paradigm with one perspective alone; it is multi-dimensional and interconnected in nature (Francis and Thomas 2022b). Therefore, it is ideal if treated as a complex network of interacting elements.

However, in recent times, benchmarking sustainability is gaining precedence over sustainability assessment because it helps achieve better performance standards (Deng 2015). Benchmarking is the process by which the best standards in providing products/services are achieved through suitable policy interventions (Bhutta and Huq 1999). However, sustainability benchmarking is less standardized and not widely applied due to the unavailability of genuine targets, sufficient data, and differences in methodological approaches (Trigaux et al. 2021). Nevertheless, benchmarking the sustainability of buildings involves assessing their performance across a range of possible scenarios and comparing their overall performance across the three pillars of sustainability. Generating scenarios helps investigate the impact of various interventions taken today on future development plans (Boyko et al. 2012). Hence, using simulation to generate a wide range of scenarios could help policymakers and project stakeholders visualize and plan building projects better.

In this context, evaluating building sustainability using system dynamics simulation gains relevance. System dynamics is a branch of systems thinking developed primarily to consider non-linear interactions between components in a complex system with the aid of a computational platform (Forrester 1970; Sterman 2012). System dynamics modeling technique has been particularly used in the building and construction segment to assess sustainability-related aspects such as reducing carbon dioxide emissions (Sim and Sim 2016), optimizing energy consumption (Feng et al. 2013; Thomas et al. 2016), and waste reduction (Li Hao et al. 2008). Similarly, it has been a popular approach in evaluating urban growth and sustainability (Huang and Chen 1970; Tan et al. 2018). However, most of these studies present sustainability from a macro-scale perspective than from the standpoint of an individual building. A recent study by Francis and Thomas (2022a and 2022b) demonstrates a novel framework for evaluating and comparing the sustainability of individual buildings by considering social, economic, and environmental aspects of sustainability. Nevertheless, most of these tools only reinforce the strengths of the system dynamics approach as a policy analysis tool. However, evaluating sustainability by quantifying various sustainability indicators and their mutual interactions would only result in knowing the performance level of the assessed buildings. It does not indicate the level of improvement that the building can achieve in terms of overall performance. Therefore, the application of system dynamics simulation can be further extended to benchmarking sustainability, enhancing its potential as a tool for standardizing performance targets. It will primarily benefit building projects in the early stages of planning to increase their contribution to sustainable development. The following section describes the research methodology proposed for sustainability benchmarking of buildings.

3 METHODOLOGY

Figure 1 represents the methodology adopted for developing the proposed framework. The first step in the methodology is to establish a database of similar projects and collect primary building data such as materials used, the number of households, building area, location of the building, and period of construction and operation planned. Once this database is created, it serves as a building training set which is the basis for benchmarking for the specific type of buildings chosen. The next step involves using system dynamics modeling and simulation to capture various sustainability indicators and their interactions as described in the framework proposed by Francis and Thomas (2022a; b)

Figure 1: Research methodology.

The framework includes sub-models to account for the materials used in the building (material sub-model), water (water sub-model) and energy (energy sub-model) used during the entire lifespan (material manufacturing, construction operation, and demolition), and wastes generated during construction, operation, and demolition (waste sub-model). Then, the sustainability performance of the projects is computed in the form of sustainability indicators in the sustainability indicator sub-model. The various sustainability indicators chosen for the study are briefly described in Table 1. These indicators are chosen because of their quantitative nature and their global acceptance. Furthermore, these indicators exhibit significant interdependencies that can be quantified using system dynamics models to evaluate sustainability in a holistic manner (Francis and Thomas 2022a). The equations governing the system dynamics models for this framework are fundamentally based on the stock-flow equation by Sterman (2012). The sustainability indicators are computed as the stocks regulated by the different input parameters of the buildings and governed by equations and control variables defined by multiple codes and standards such as ISO standards, building codes, energy codes, and design codes of different reference locations.

The sub-models and their interactions are represented in Figure 2, and a small part of the system dynamics framework is shown to describe the basic structure of the framework. It can be observed that the material sub-model interacts with the transportation, water, energy, and waste sub-models as well as the sustainability indicator sub-model by influencing carbon footprint (CFP), water footprint (WFP), Life Cycle Energy (LCE), Ecosystem quality (EQ), Human Health (HH), and Resource depletion (RES). Similarly. The water sub-model influences the energy sub-model and vice versa and hence, feeds into the sustainability indicator sub-model accounting for WFP, influencing Ecological Footprint (EFP) and Life Cycle Costs (LCC) as well. Accessibility impacts the jobs as well as CFP due to the travel distances. Similarly, the Social Cost of Carbon (SCC) is influenced by CFP, which influences EFP. Further equations and interdependencies governing these sub-models are developed based on the framework by Francis and Thomas (2022a and 2022b). Some of these mathematical relationships are shown in Table 1.

Table 1: Sustainability Indicators.

Pillars	Indicator	Brief Description
Environmental	Carbon Footprint (CFP)	The total amount of carbon emissions generated in the creation, use, and demolition of the buildings is represented as kilograms of carbon dioxide equivalent ($kgCO_{2e}$). The same is computed as the stock-flow equations integrated across the procurement, construction, and operation periods as conceptually shown below. $CFP = \int (Material\ Emissions + Material\ Transport\ Emissions) + \int Equipment\ Emissions + \int Operating\ Emissions$
	Water Footprint (WFP)	The total water consumed in kiloliters (KL) during the entire life span of the project. The same is computed as the stock-flow equations integrated across the procurement, construction, and operation periods as conceptually shown below. $WFP = \int Material\ manufacturing\ water\ use + \int Construction\ water + \int Building\ occupant\ water\ consumption$
	Ecological Footprint (EFP)	The pressure on land resources due to the impact of water use, carbon dioxide emissions, change in land use, waste generation that is represented in global hectares (gha). $EFP = EFP_{built-land} + EFP_{water} + EFP_{CO2} + EFP_{waste}$
	Life Cycle Energy (LCE)	It is computed as the total energy consumed for raw material manufacturing, building construction, transportation, building operation, maintenance and demolition represented as Giga Joules (GJ). $LCE = \int Initial\ Embodied\ Energy + \int Construction\ Energy + \int Operation\ Energy + \int Recurring\ Embodied\ Energy + \int Demolition\ Energy$
	Ecosystem Quality (EQ)	It represents the fraction of species that would be lost due to environmental damage every year denoted in species. year. It is a ReCipe end-point indicator computed using LCA databases
Economic	Life Cycle Cost (LCC)	The total cost incurred in the creation and use of the buildings throughout its whole life cycle, including all material, equipment, energy, and water costs, is denoted in monetary terms (Rupees, Dollars or Euros).
	Social Cost of Carbon (SCC)	The monetary impact on nations due to climate change impacts such as floods, fires, winds, heat waves, etc., resulting from carbon dioxide emissions from the building processes. It is measured in US Dollars per kilogram of CO_2 emissions emitted. It is computed based on the carbon footprint and the unit the monetary value per unit of CO_2 emissions. $SCC = CFP\ X\ USD\ per\ tonne\ damage$
	Resources Scarcity (RES)	The damage to resources that occurs due to various processes and the resulting money required to be spent to extract these resources. It is measured in US Dollars. It is a ReCipe end-point indicator computed using LCA databases
Social	Human Health (HH)	The years lost or disabled due to the environmental impacts on human health are represented as Disability Adjusted Life Years (DALY). It is a ReCipe end-point indicator computed using LCA databases
	Accessibility to facilities (ACC)	The accessibility of the building to various basic facilities such as schools, hospitals, bus stops, supermarkets and parks is defined as a unified index based on the number of these available facilities within a pre-defined threshold distance. $\text{Accessibility} = \sum Opportunities\ within\ a\ distance\ defined$
	Job Generation Potential (JOB)	The number of jobs generated per square meters (sqm) of the project area is based on local employment reports available in government databases and is denoted as jobs generated per sqm of new construction. $\text{Jobs} = Project\ area\ X\ Jobs\ per\ sqm$

Developing such a system dynamics-based framework helps to quantify such interactions as well as account for uncertainties such as changing electricity consumption with time and varying material, water, and energy usage conditions. The system dynamics framework is developed using the AnyLogic software, Version 8.5.2. AnyLogic is a multi-method simulation software with capabilities to perform system dynamics, discrete event and agent-based simulation. It also has a GIS interface, which helps incorporate location-related aspects into the models. In the part model shown in Figure 2, the carbon footprint of the entire project is represented as the stock whose inflow is regulated by the carbon emissions during manufacturing, construction and building operation. On similar lines, the entire framework is developed to evaluate the sustainability of buildings across various indicators.

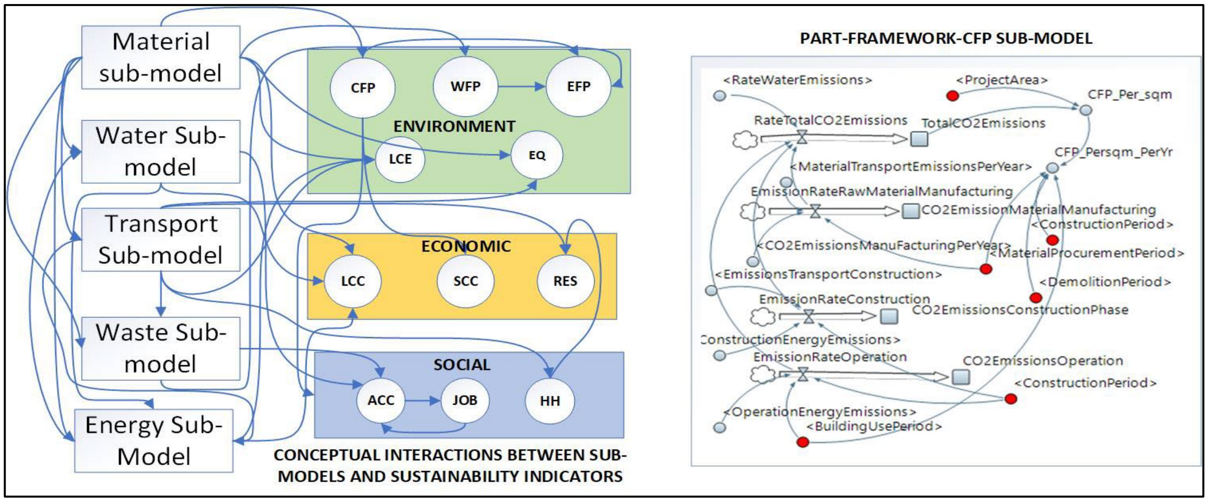

Figure 2: System dynamics modelling framework.

Once the system dynamics framework is developed to evaluate the sustainability of the buildings assessed, it is essential to validate it using suitable methods to ensure that the computational model represents the real-life scenario closely. As recommended by Qudrat-Ullah and Seong (2010), a few basic tests are performed. Accordingly, dimensional consistency is verified, and structural verification tests are conducted to ensure that the model results are close to actual available data. The results obtained for each of the sustainability indicators are compared with the results in the various literature, reports, and other documents available.

Post validation, the next step is to create a database of policy interventions that can improve the sustainability performance of the buildings by impacting the various indicator measures. These interventions could be material reduction policies, policies to reduce water consumption and transportation of materials, or approaches to reduce the energy consumption of buildings. These policies are integrated into the framework through a range of percentage variations, which can help generate different scenarios for each building in the training set. Therefore, several thousand scenarios for all the buildings in the training dataset are generated, thereby creating a large dataset of indicator values for each scenario. Once this scenario analysis is done and the results are generated in the form of the indicators mentioned in Table 1, the next step involves computing a composite index representing building sustainability against each scenario. For this, a methodology similar to that proposed for calculating the composite sustainability development goals (SDG) index by the united nations (UN) as adapted from Lafortune et al. (2018) is used. The steps involved in computing the index are described below.

Step 1: Normalization:- Eleven indicator values are obtained from the system dynamics simulation results for each of the several scenarios generated for buildings. Since the units and nature (for some indicators, higher the value is bad, while for others, higher the value is good) of these indicators is different, it is essential to normalize them into uniform units to evaluate them collectively. Therefore, the following method is used for normalization.

For indicators where a higher value means bad performance, Equation (1). is used for normalization, and for indicators where higher value means good performance, Equation (2). is used.

$$N = 1 - \frac{x - Max(x)}{Max(x) - Min(x)} \quad , \tag{1}$$

$$N = \frac{x - Min(x)}{Max(x) - Min(x)} \quad , \tag{2}$$

In the above equations, 'N' implies the normalized value for each indicator, 'x' is the actual value of the indicator, max(x) implies the maximum value among a particular indicator value, and min(x) is the minimum value among a particular indicator value

Step 2: Computation of composite building sustainability index (BSI):- It is computed as the arithmetic mean of the normalized values after the weights are incorporated into the normalized values, as shown in Equation (3). Allocation of weights is important for the indicators so that user preferences on social, economic, and environmental dimensions of sustainability are accounted for in computing the index. Further, weights assigned significantly influence the sustainability value derived and the decision-making process in planning building projects (Francis and Thomas 2022b). Hence, the BSI for each scenario is computed as shown in Equation (3).

$$BSI = \sum_{k=1}^{Nij} \frac{1}{N(w_{ij} X\, N_{ij})} \quad , \tag{3}$$

In Equation 3. 'N' is the total number of indicators considered, 'wij' is the weights assigned for each indicator 'i' under scenario 'j', and 'Nij' is the normalized value of each indicator 'i' under scenario 'j'

Step 3: Defining thresholds:- Once the composite index is defined for each scenario simulated, the next step is to use threshold criteria to define the benchmarking scale as high, medium, and low levels of sustainability. For this study, the mean (μ) and standard deviation (σ) are calculated from the BSI computed for these several thousands of scenarios. Based on the principles used in Ayyoob et al. (2013) the thresholds of high, low, and medium sustainability of projects were defined as shown in Equations (4),(5), and (6).

$$\text{High sustainability if } BSI_j \geq \mu + 0.5\sigma , \tag{4}$$
$$\text{Medium sustainability if } \mu + 0.5\sigma \geq BSI_j \geq \mu - 0.5\sigma , \tag{5}$$
$$\text{Low sustainability if } BSI_j \leq \mu - 0.5\sigma , \tag{6}$$

Step 4: Testing Projects:- The last step in the methodology involves evaluating test projects and determining their BSI levels based on the benchmark scale developed. If the project falls in the low or medium sustainability levels, the system dynamics simulation results will indicate the measures for improvement based on suitable policy interventions. The following section describes the case study application of this simulation-based benchmarking framework for a particular group of buildings.

3.1 Case study demonstration

To demonstrate the application of this framework, a series of similar projects were chosen from Mumbai in Maharashtra, India, that fall under the category of the Pradhan Mantri Awas Yojana projects (PMAY) (Gohil and Gandhi 2019). PMAY category of projects is a scheme launched by the government of India to provide housing for all. The scheme is involved in developing residential projects mainly targeting to meet the housing demand in urban and rural areas, particularly for the low-income groups. A set of 18 such building projects is chosen as the building training set based on the details available on the environmental clearance website (EIA) of Maharashtra. Figure 3 shows the geographical location of these projects. The typical data gathered as input parameters for the system dynamics modeling framework include; the project location, size, and area; materials consumed, namely cement, sand, steel, brick/blocks, and aggregates; number of construction workers, number of people, and households who are beneficiaries of these projects. The choice of these five primary materials is based on the understanding that their contribution is maximum in terms of energy and emissions in the Indian context as per existing literature (Praseeda et al. 2016).

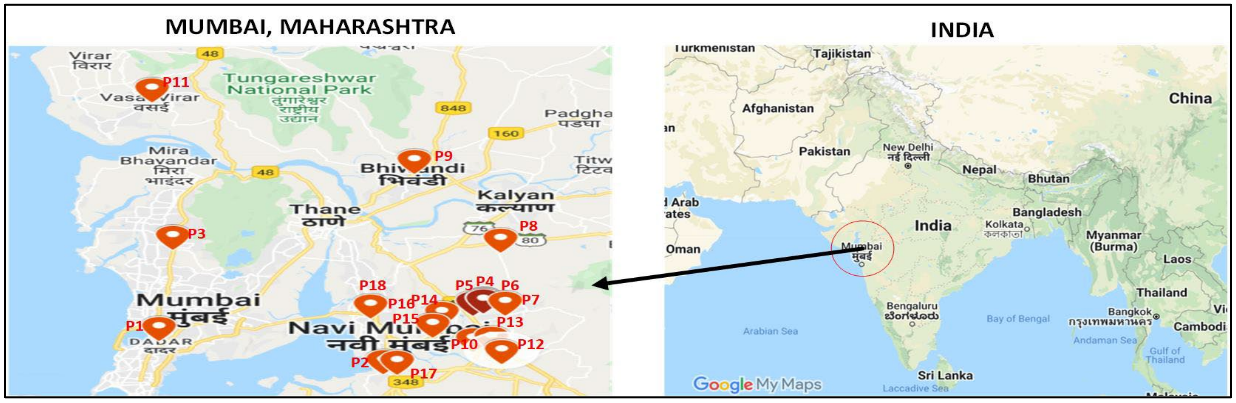

Figure 3: Geographical location of projects chosen.

Based on this basic information and the details of sustainability impacts obtained from various sources such as the International Finance Corporation (IFC) emission database (IFC database 2017), Energy Conservation Building code (ECBC) (Kumar et al. 2009), and National Building Code (NBC) (BIS 2016) the system dynamics framework is modified and refined for predicting the sustainability of these projects. Once the sustainability indicator values are obtained for the base case, a series of 420 policy interventions are incorporated into each of these building projects. The list of policy interventions implemented and the variation applied with permissible limits are provided in Table 2. These interventions are chosen from the perspective of a decision-maker/policy maker influencing the planning and design of similar projects at a national or local level. Hence few national policies are also incorporated into the framework for decision-making.

The advantage of system dynamics simulation in sustainability assessment is that it provides a good amount of flexibility in evaluating numerous scenarios and incorporating various strategies, as demonstrated by several studies (Francis and Thomas 2020; Leon et al. 2018;). Hence, for each of the 18 projects chosen, the 420 policy interventions are incorporated, thereby generating 7560 (420 X 18) scenarios, and the corresponding sustainability indicators are obtained. Therefore, the next step is to compute the BSI for each of these scenario instances. Hence, a benchmarking scale is developed for similar projects based on the scenario analysis results, as explained earlier in the methodology. For this, a python program is designed and integrated with AnyLogic using the py-communicator plugin to make it an integrated system dynamics benchmarking framework. Further, two test projects are chosen to evaluate sustainability on the benchmarking scale developed. The test projects again are selected from within the same geographical region. Depending on their performance, suitable policy interventions are recommended for sustainability improvement.

4 RESULTS AND DISCUSSIONS

The policy interventions on the chosen 18 projects and the scenario analysis enable the development of a sustainability performance benchmark scale for evaluating similar projects, as shown in Figure 4. It shows four benchmarking cases depending on the weights allotted to the different indicators. In the base case, when all the indicators are given equal weightage, if the BSI is greater than 0.63 (on a scale of 0-1), it represents high sustainability. However, when the BSI is below 0.51, it is considered in the red zone or of low sustainability performance and needs to improve. The yellow zone between these two values indicates a medium level of sustainability. However, if higher weights/preferences are given to environmental parameters, the scale gets modified marginally, as shown in Figure 4. This is true in the case of higher weights for social and economic parameters as well. For instance, it can be observed that the scale changes notably when social indicators such as accessibility and jobs generated are given higher importance. Here the projects with higher accessibility and size tend to be more sustainable due to their social contribution. Nevertheless, the size of the zones is relatively similar for all the cases, ensuring that the robustness of the data generated is maintained irrespective of the variation in weighing criteria.

Table 2: Policy intervention from which 420 scenarios were generated for each project.

Policy intervention	**Variation implemented within permissible/possible limits**
Replacement of cement, sand, and aggregate by suitable materials	15-35% (15 scenarios) (by incrementing by 5%)
Use of Blended Cement	15-35% (5 scenarios) (by incrementing by 5%)
Use of Recycled steel	2-10% (5 scenarios) (by incrementing by 2%)
Use of Recycled aggregates	10-20% (3 scenarios) (by incrementing by 5%)
Replacement of fire clay bricks with fly ash bricks	40-100% (13 scenarios) (by incrementing by 5%)
Replacement of fire clay bricks with AAC blocks	40-100% (13 scenarios) (by incrementing by 5%)
Use of improved kilns for brick production	As a fixed policy (1 scenario)
Use of improved decarbonizing technology in steel	As a fixed policy (1 scenario)
Recycling construction and demolition wastes	10-20% (3 scenarios) (by incrementing by 5%)
Enabling water recycling	10-50% (5 scenarios) (by incrementing by 10%)
Enabling rainwater harvesting	10-50% (5 scenarios) (by incrementing by 10%)
Using energy-saving water Fixtures	10-20% (3 scenarios) (by incrementing by 5%)
Increase use of local available materials	10-20% (3 scenarios) (by incrementing by 5%)
Incorporating renewable energy	10-50% (5 scenarios) (by incrementing by 10%)
Implementing practices in ECBC	As a fixed policy (1 scenario)
Implement moderate energy-saving scenarios	As a fixed policy (1 scenario)
Implement aggressive energy-saving scenarios	As a fixed policy (1 scenario)
Implement very aggressive energy-saving scenarios	As a fixed policy (1 scenario)
Combination of the above policies	336 scenarios formed from the combination of the above set of individual policies.

For validating the results generated from the framework, the range of indicator values generated across the 7560 are compared with the available data in the literature. The life cycle energy values vary between 2.98 GJ per sqm to 24.475 GJ per sqm, with the initial embodied energy changing between 1.33-3.63 GJ per sqm for such residential projects in India. This is comparable to the results reported for life cycle energy in the literature associated with Indian buildings (Bansal et al. 2021; Kumar et al. 2021; Praseeda et al. 2016; Ramesh et al. 2010). Similarly, the ecological footprint in global hectares per sqm in this study varies from 0.28-3.04 gha per sqm, which agrees with the results of Kumar et al.(2021). The accessibility index is obtained from the geographical information system (GIS) maps feature in AnyLogic, which captures actual location data. Further, the carbon footprint results range from 0.847-8.958 tonnes kgCO2e per sqm for the buildings analyzed, comparable to the results reported in the literature for residential buildings (Atmaca and Atmaca 2015; Sengupta 2008). Therefore, computing the indices from these values will provide the composite performance of buildings across various sustainability indicators.

Further, testing of this framework is done using two test projects. The benchmark results of the test projects are also shown in Figure 4 at the bottom. Test project-1 has a BSI of 0.49, which shows that it has a low sustainability level according to the equal weightage scale. However, since its accessibility is relatively high, it is in the medium sustainability region if social sustainability is given higher weightage. On the other hand, project-2 has a medium level of sustainability because its BSI value is 0.535 and indicates the same in all the benchmark scales. This shows that the weighting criteria on indicators must be given due consideration in sustainability evaluation. It also shows the vital role of system dynamics technique in sustainability assessment and in demarcating a building's sustainability performance against a range of performance scenarios.

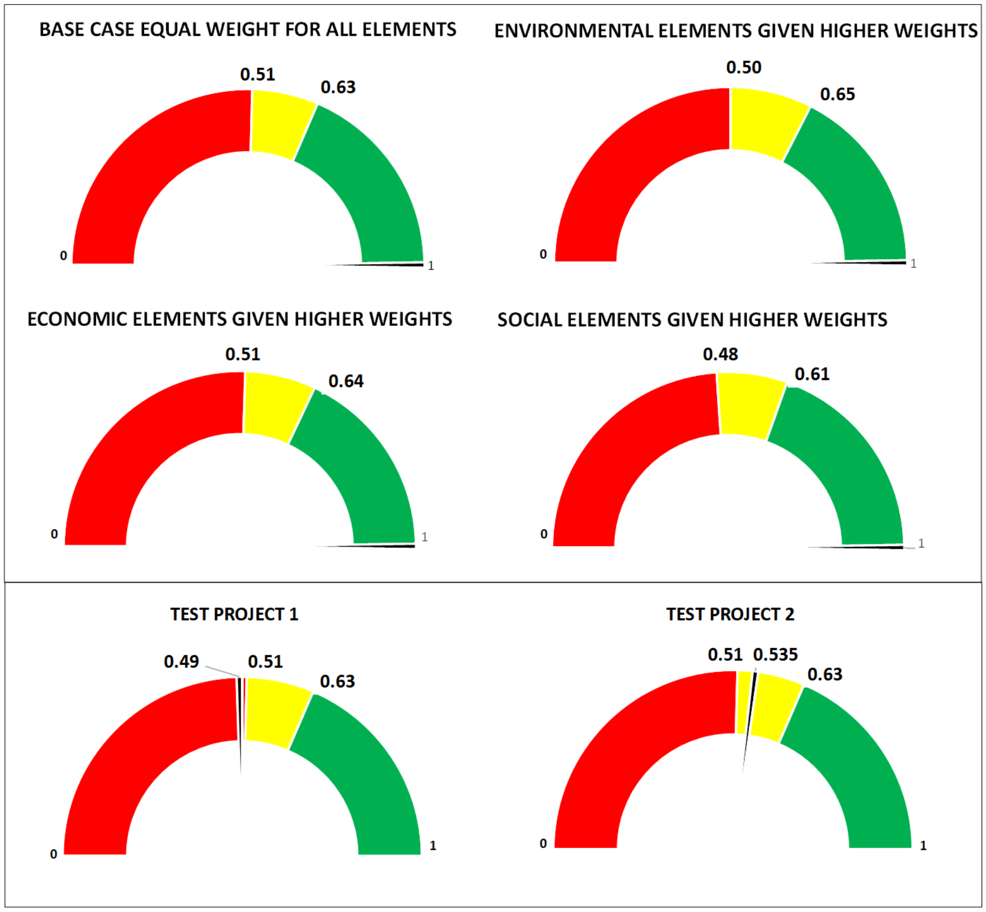

Figure 4: Benchmarking scale for different weighting criteria.

Further improvement measures can also be derived through simulation and scenario analysis. Therefore on simulating the improvement scenarios in test project 1, it can be derived that a renewable energy intervention by about 50% easily improves it to a high sustainability level, with the BSI value improving to 0.72. However, even combining material policies involving sand, cement, steel, and aggregate replacement above 15% along with 10% renewable energy can considerably improve sustainability. For test project 2, even a 30% integration of renewable energy can bring it into the green zone by bringing the BSI value to 0.632. However, material policies combined with water policies and about 10% renewable energy interventions can considerably improve the sustainability levels of this project. Furthermore, incorporating the locations helps capture its influence on accessibility and the effect of different electricity mixes and corresponding carbon footprint. Accessibility influences the carbon footprint due to passenger travel and job generation potential of the area due to the project location. However, the case studies considered in this study for demonstration are only from Maharashtra, India; hence the effect of location is not predominantly seen in the results. Therefore, the benchmarking framework helps ascertain the sustainability level of a particular building project at the project planning stage and take necessary interventions to enhance its performance.

5 CONCLUSIONS

Sustainability assessment and benchmarking of buildings is a complex, multi-dimensional, dynamic problem requiring systems thinking approach. System dynamics modeling has the potential to capture the non-linear interactions and dynamism between the social, economic, and environmental systems associated with building sustainability. Therefore, this study demonstrates a methodological framework for benchmarking the sustainability of buildings using the system dynamics simulation technique. This paper utilizes the potential of system dynamics to model and simulates a range of multiple policy scenarios that predicts varying instances of a building's sustainability performance. When this process is done for a large set of numerous projects of similar nature, an extensive database of building sustainability performance can be created. This range of index values generated is then used to develop a benchmarking scale that demarcates the sustainability levels of other similar projects. Therefore, this paper addresses the need for sustainability benchmarking by following a combination of top-down and bottom-up approaches that are ideal for achieving policy targets. Hence, as most existing literature indicate, the application of system dynamics modeling is not limited to policy analysis. It can be effectively used for standardizing and setting benchmarks for sustainability performance in the building sector. Although the methodological framework developed for this study is generic and widely applicable for different projects, it is demonstrated only for a small set of building data. Future studies could therefore be, directed at expanding the training dataset of buildings so that an improved benchmarking scale can be applied to a broader range of projects.

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