Built Environment Ecosystem Framework towards Sustainable Urban Housing

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Abstract. With rapid urbanization the need for affordable and sustainable housing is a global issue with social, economic and ecological implications. The housing sector directly impacts eight of the seventeen United Nations (UN) Sustainable Development Goals (SGDs). However, striving to achieve these goals in a compartmentalized or siloed manner is not enough; rather they need to be considered as an interdependent system of goals for sustainable development. This paper introduces the Built Environment Ecosystem (BEE) framework which address these eight SDGs taking a systems thinking approach that promotes greater integration of environmental system behaviours into built environment design. We explain the BEE framework through a demonstration project named Ecological Living Module (ELM) and characterize the house in terms of the SDG framework. We demonstrate how interlinking multi-faceted, interdependent building interventions – solar, air, water, food, and materials – covers a broad spectrum of sustainable development dimensions. We outline how the BEE framework enabled the association of SDGs as an integrated package, with ELM performing as as a sustainable inter-reliant intervention or as an *ecosystem of systems*. We conclude by projecting the potential of the BEE framework for transformational and systemic change, including the need for more research towards a scale up of such housing systems across multiple climatic and cultural contexts towards ubiquitous sustainable urban housing.

1. Introduction

In the face of rapid urbanization and continued climate change, the provision of housing for urban inhabitants, where 68% of the world's population is projected to live by 2050 [1], is a global problem. The provision of decent housing is a social justice issue and with the housing sector contributing to the depletion of earth's resources, the need for sustainable housing within our urban environments is of immediate importance. The housing sector consumes 40% of the earth's natural resources and contributes to a third of global greenhouse gas emissions [2]. More frequented climate-related disasters threaten our urban infrastructures for water, energy, food, waste management, and air quality [3].

Given that the built environment directly impacts eight of the seventeen United Nations (UN) Sustainable Development Goals (SDGs) [4], a demonstration project of a microhouse which addressed these eight SDGs is outlined in this paper. The microhouse named Ecological Living Module (ELM) was a collaboration between UN Environment, UN Habitat, Yale University School of Architecture, Yale Center for Ecosystems in Architecture (CEA) and Gray Organschi Architecture [5]. ELM aimed to heighten awareness of the urban housing crisis and lead to a dialogue on how to redesign and rethink building systems and urban infrastructure. The demonstration project addressed how secure onsite clean energy, safe sustainable water, fresh indoor air quality, urban micro-farming, bio-based renewable materials, and waste management could be managed and integrated into the unit itself.

The ELM demonstration project brings several prior demonstration projects together under the umbrella of the Built Environment Ecosystem (BEE) Framework [6], [7], [8]. Some of the preceding demonstration projects include prototypes which have been in ongoing development for several years, in the areas of indoor air quality remediation [9], [10], solar energy [11], water capture and purification [12], and food production and renewable material systems [13] as well as data monitoring, acquisition, and visualization [14], [15], [16]. These accumulate in the ELM demonstration project showing how several sustainable technologies can be successfully applied, with an aim to accelerating the technical and learning processes that can spur adoption of such technologies towards transformative and systemic change. Through this paper we explain the principles of the BEE Framework, how it was demonstrated via ELM and propose future research into how it can facilitate scale-up and adaptation to multiple climatic and cultural contexts.

2. Methods

This section outlines the methodological approach taken to investigate the potential of the Built Environment Ecosystem (BEE) framework. It starts be describing the design and development of the demonstration project (i.e. ELM). It continues by characterizing the BEE Framework in terms of the SDGs and relating the building interventions in ELM with previous research and demonstration projects.

2.1. Description of the the demonstration project - ELM Design and Development

The design of the demonstration project involved the integration of material systems and environmental systems. The demonstration project was an interdisciplinary effort including architects, engineers, data scientists and policy experts. The module, with a floor area of $22m^2$, was designed to house four people and to be modular in its construction. The structure was fabricated off-site in a controlled fabrication environment. Stored as a compact container, it was transported to site by truck. It was erected on site in three days without the need for industrial equipment. The environmental systems, which are also modular in their design, where predesigned to fit in the structure and these were also assembled on site over the three-day period. A sensor network coupled with a data visualization and analytics platform was installed to monitor the overall performance of the ELM and the environmental conditions both inside and outside the home.

2.2. Characterizing the BEE Framework in terms of the SDGs

The methodological approach involved developing a demonstration project to investigate the potential of Built Environment Ecosystem (BEE) framework. The ecosystemic approach of the BEE Framework aims to address multi-faceted, interdependent building interventions – solar, air, water, food, and materials – that cover a broad spectrum of the economic, social, and environmental dimensions of sustainable development. We used the SDG framework to characterize each design intervention of the demonstration project, as outlined in **Table 1**. We also indicated in **Table 1,** previous literature and demonstration projects that each intervention builds upon. We then used the SDG targets and indicators as a monitoring mechanism and highlighted those aspects, which cut across environmental, social and economic spectrums [17]. Finally, by considering the associated SDG indicators as an integrated package that worked in harmony with one another, we analysed the overall building as an *ecosystem of systems* and studied how it functioned as a sustainable interdependent intervention. This allowed us to project the potential of the BEE framework for transformational change. In this regard, we evaluated the demonstration project against demonstration projects in the literature that have proposed that such projects accelerate the technical and social learning processes leading to rapid dissemination and adoption of sustainable technologies [18].

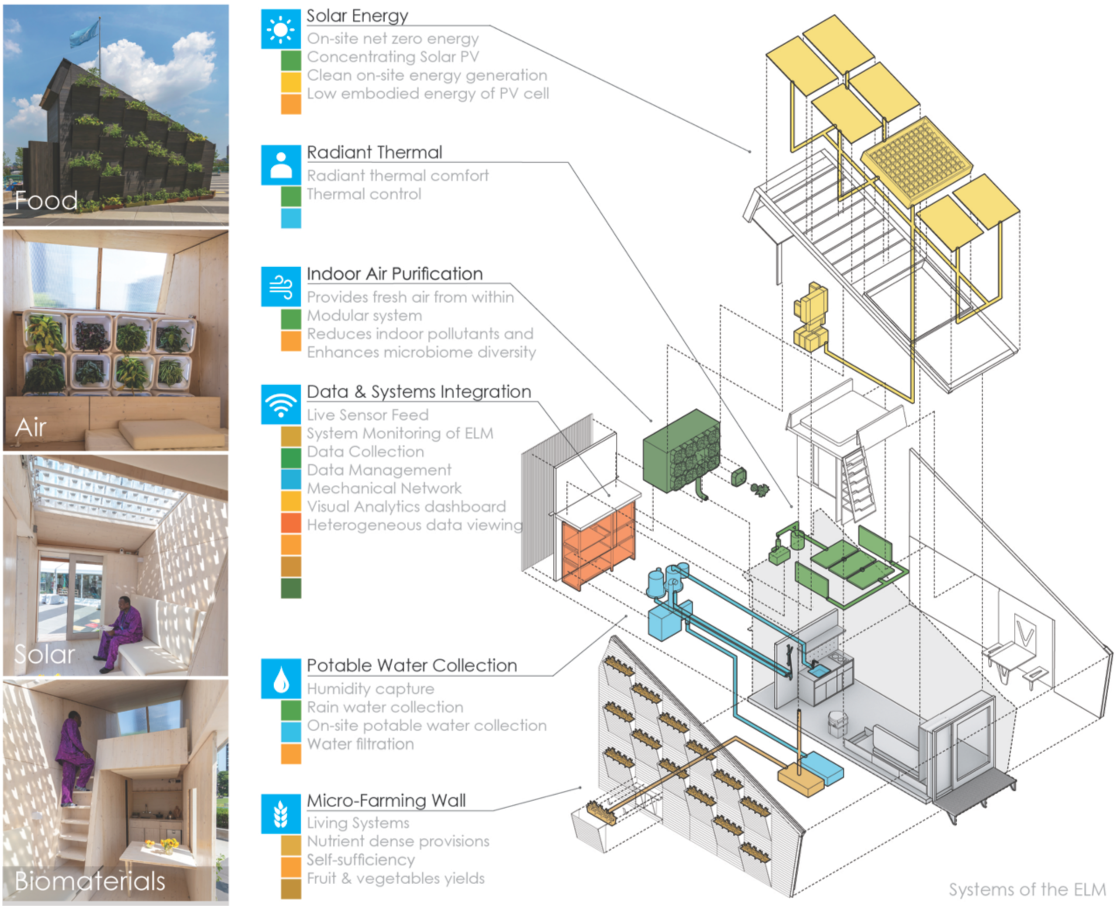

Figure 1. Axonometric view of ELM with associated SDGs towards an integrated systems thinking approach to sustainable development within the Built Environment. Photos © David Sundberg/Esto

Step 1 was to characterize the interventions within the demonstration project in terms of SDGs. These are described in **Table 1.** We analysed the ELM demonstration project referencing prior research on the individual demonstration projects, how each one addressed its associated SDG.

Table 1. Demonstration projects and

SDG No.	Research Areas	Demonstration Projects	Type	Literature source
2	Urban farming	Micro-farming facade	prototype	
3	Indoor air purification	Active Modular Phytoremediation System	prototype	[9], [10]
6	Water capture and purification	De-Humidification systems and rainwater capture	prototypes	[12]
7	Renewable energy	BAPV and ICSF	Renewable technologies	[11]

9	Circular Material Life Cycle	CLT building	building	[13]
11	Socio-ecological design	Ecosystem of systems	building	[14], [15], [16]
12	circular material life cycle, onsite clean renewable energy and water	CLT building, BAPV and ICSF, De-humidification systems and rain water capture	Building, prototypes	[13], [19]
13	BEE framework	Ecological Pavilion Exhibit, Accra exhibit, Haiti pavilion etc.	exhibit	[6], [7], [8], [20]

3. **Results – Demonstration of SDGs**

Our results outline the potential of the BEE framework for built environment design. Below aspects and interventions within the ELM demonstration project are outlined in terms of eight SDGs and their associated targets and indicators. Finally, we outline how these interventions are not incremental silos, but rather interventions that work together to foster systemic change.

3.1. SDG 2 End hunger, achieve food security and improved nutrition, and promote sustainable agriculture – Micro-farming façade to produce fruit and vegetables on site

The micro-farming wall was located on the west façade of the ELM. The façade tapers out at many locations to allow for food growing in each pocket of the façade. These were designed to allow for optimum sunlight for fruit and vegetable growth and is irrigated via harvested rainwater from the roof which is distributed by channels in the walls to a water reservoir in each planter. In terms of the BEE framework criteria for plant growth and water is designed to fit the specific context including the selection of native fruit and vegetables. For the New York context, the ELM micro-farming wall provides 65% of the nutrient dense fruit and vegetable servings recommended for a family of four per year based on [21]. In particular, this addresses Target 2.1 and 2.2 which aims to end hunger and end all forms of nutrition by 2030.

3.2. SDG 3 Ensure healthy lives and promote well-being for all at all ages – A combination of environmental and material systems to encourage enhanced human health and well-being

As stated above the BEE framework considers human health in terms of providing nutritious food to its inhabitants via micro-farming, but it also considers human health in terms of indoor air quality and a healthy microbiome. The Active Modular Phytoremediation System (AMPS) [9] [10] within ELM has proven to provide fresh air from within by cleaning airborne pollutants associated with global environmental health risks. Therefore, in very polluted environments where the outdoor air quality is compromised, this system aims to clean the indoor air enhancing the occupants' human health and well-being. This is in response to SDG Indicator 3.28. "Mortality from indoor air pollution". Further experiments will test the human health and well-being of occupants living in the ELM.

3.3. SDG 6 Ensure availability and sustainable management of water and sanitation for all – Rain Water Capture and Dehumidification Systems and Ecological Waste Management.

In terms of water, the BEE framework proposes multiple strategies to deal with water including water capture by means of desiccation in hot humid climates. However, in this demonstration project with the humid subtropical Koppen climate classification type of New York, water was collected via rain water capture and potable water was produced using a dehumidification system which captured and condensed water vapour from the ambient air. This intervention aimed to address Target 6.1 in achieving safe and affordable drinking water for all by 2030. A dry composite toilet was installed for waste management and sanitation, responding to Target 6.2 to achieve adequate sanitation for all by 2030.

3.4. SDG 7 Ensure access to affordable, reliable, sustainable, and modern energy for all –Building Integrated Renewable Energy Systems – Stand Alone Renewable Energy System compatible with smart grid technology.

Two solar systems operate in the ELM to allow on-site renewable electricity production to meet the energy demands of the building. The building was off-grid and energy self-sufficient, producing enough energy to meet the needs of four people. A previous study [22] quantified the gross yearly electricity demand of ELM as 2,600 kWh/yr compared to a typical New York home with a yearly electricity demand of 6,860 kWh/yr for New York [23] . We assume the difference to be due to the smaller footprint and overall morphological form of the building. The concentrating solar Façade (ICSF) [11] is located within the roof light of ELM. It captures solar energy, transforms that energy to electricity and distributes it through the building. Since it captures the direct solar radiation beam, it only allows diffuse light into the space, thereby providing natural daylighting without glare and the reducing the use of artificial lighting. By relying solely on renewable energy to meet the electricity demand of ELM using modern energy services, Targets 7.1 and 7.2 are being met and demonstrated.

3.5. SDG 9 Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation – modular design and circular material life cycle.

By producing water and energy on-site and developing construction and environmental systems which are modular and therefore, easily disassembled and reassembled, the ELM is designed to exhibit a resilient response to urban infrastructure and construction ecologies. The building energy systems are compatible for smart grids and distribution networks. The material systems are based on biomaterials, namely Cross-Laminated Timber (CLT), which is locally sourced and promotes sustainable industrialization in terms of new means of building with biomaterials and in the fabrication of buildings off site in a controlled environment for more sustainable, accurate and cost efficient construction and manufacturing processes. These aspects of ELM are example of the BEE framework principles, which aims to promote a circular economy and systems-thinking approach in terms of energy and material flows within the built environment. Through demonstrating new sustainable infrastructure mechanisms for water, energy and material life cycle, the ELM demonstrates aspects of Target 9.1 and 9.5, such as developing reliable, sustainable and resilient infrastructure enhanced by scientific research.

3.6. SDG 11 Make cities and human settlements inclusive, safe, resilient and sustainable – ecosystems of systems.

The goal of the BEE Framework, as demonstrated in the ELM, is to provide a sustainable toolkit for on-site self-sufficiency that addresses the multi-faceted requirements of buildings from shelter, liveability, cultural significance to air, water, heating, cooling, lighting, waste management and sanitation. Providing these must not have adverse environmental effects. This complex web of requirements needs an ecosystemic logic to track these needs and map their performance and potential consequences. The BEE framework provides this mapping mechanism for the built environment through a framework that links these requirements with the SDGs in order to lens it through a global context and framework what is internationally recognized. By doing this we can analyse and evaluate if our built environments are meeting Targets 11.1 - 11.3 of inclusive, safe, resilient, sustainable and affordable housing and urban fabric.

3.7. *SDG 12 Ensure sustainable consumption and production patterns – circular material life cycle, onsite clean energy.*

The BEE framework promotes a circular economy approach influenced by a socio-ecological mind-set. This means waste cycles in material and energy flows are virtually eliminated, unless categorically not viable. In ELM this is showcased through the on-site renewable energy and water production as outlined in sections 2.2.3 and 2.2.4, but also through the use of a renewable bio-material in CLT as is outlined in section 2.2.5. From a life cycle perspective, biomaterials promote sustainable consumption and production patterns by moving away from the linear material economy of conventional non-renewable construction materials. These materials, such as concrete and steel, depend on the extraction of natural resources and intensive energy usage and for their manufacture, transportation and construction, ultimately increasing carbon emissions and exasperating climate change effects. In the case of bio-based renewable materials such as the CLT used in ELM, these locally sourced materials, sequester carbon within the building during their operational life time which would otherwise have been released into the atmosphere [24]. In terms of urbanization, this potential to reduce the carbon footprint of buildings has great potential for resilient and regenerative cities, aligning with Targets 12.1, 12.2, 12.4 and 12.5.

3.8. SDG 13 Take urgent action to combat climate change and its impacts – ELM aims to address the challenges of the Built Environment in reducing adverse environmental impacts – including the scalability of such an approach.

The BEE framework encourages the consideration of our buildings as ecosystems of systems. The ELM shows how multiple environmental systems and material systems can merge in a single building to form an ecosystem, which produces its own renewable water, energy, food, and clean indoor air and sequesters carbon via its material life cycle. On a global scale, such a premise could have huge consequences for how our built environments meet the needs of urban interventions greatly reducing the housing sectors consumption of natural resources and production of global greenhouse gas emissions, aligning with Target 13.1.

The ELM had a data collection and monitoring system embedded including a sensor network both inside and outside the house. Environmental data, such as indoor compared to outdoor environmental factors, and system performance, such as on site energy generation and consumption, are collected. Further research will test the biometric factors of occupants living within the home to learn more about the health impacts of such a framework. The collection and visualization of this data facilitates the understanding and monitoring of the house in terms of the SDGs. It allows for design upgrades on future iterations of a building design that employs the BEE framework.

This leads to further questioning of how the BEE framework can be tested and deployed at a large scale in order to have global impact. The following discussion section outlines the challenges of scale-up and potential strategies to overcome them.

4. **Discussion**

One issue outlined in the literature regarding sustainable development, was the challenge in achieving systemic change. Research found that a ‘siloed’ or non-integrated approach to dealing with energy, water, material life cycle, food production and air quality when considering housing design ultimately struggled to achieve fundamental sustainable change. Broto and Bulkeley [25] point out that siloed or forms of experimentation that do not fundamentally challenge mainstream ideas and approaches regarding the production and consumption of energy and other fundamental supply interventions in our cities, hamper the capability to foster systemic change. Broto and Bulkeley’s [25] investigation into numerous interventions and conclude that most experimentation involves incremental interventions, yet further research is needed to shift from incremental interventions to interventions which foster systemic change. Some examples are discussed, where systems thinking experimentation in housing is occurring, particularly with demonstration projects occurring in Europe [26], [27], [28]. A commonality between these demonstration projects and the ELM is their climate specific design and integration of building systems. The BEE framework, exemplified by ELM, promotes an ecosystem of systems approach that is scalable and adaptable to different global regions. The framework adopts systems thinking, encouraging technologies which are modular and can leverage the existing climate conditions of various regions. In other words, buildings do not function like globally uniform 'products', rather they must adapt to the climate in which they are located. The BEE framework allows and encourages this adaptation and embraces the integration of building systems which enable the building to capture and transform energy, water and air.

Research involving integrated building systems for energy, water and air, demonstrate a lack of communication and cooperation among building stakeholders in the design of these systems. Li et al. [29] argue that building integrated systems are necessary for scale up of sustainable development in the built environment. They identify the shortcomings in achieving this integration involves a lack of communication and cooperation among building stakeholders, especially architects, structural engineers, electricians and equipment division. They identify that current specifications among these groups are not standardized and there is a lack of collaboration in the architectural design phase, which is required for adequately integrating building systems in architectural design. In response to this challenge and that of scalability, the BEE framework calls for an interdisciplinary approach to built environment design where architects, engineers and construction experts work alongside other disciplines (e.g. biologists, ecologists, urban planners, environmental economists, data scientists and /or material scientists etc.) as needed. Such a response aims to achieve integration across building and urban scales that is capable of fostering transformational and systemic change.

5. Conclusion

There is a gap in the literature regarding the overlap of building scale and urban scale interventions and collaborations across-scales with the potential for cultivating systemic change. Hence, next steps in the development of the BEE framework is to develop a demonstrate project at the urban scale which explores and addresses the question of scalability. Demonstration projects are an important mechanism to assist in transformation change by exhibiting how barriers are overcome in reaching the intended upscaling. Meadowcroft [30] reinforces the benefits of demonstration projects, which showcase novel practices and technologies in order to initiate change and learn the potential and limitations of different methods. He calls this "learning-by-doing". Demonstration projects show what is capable. The ELM demonstration aimed to reveal a tangible example of applying the SDGs in terms of built environment. The demonstration was a method to further explore the potential of the BEE Framework. It was to be shown for one week during the UN High Level political forum in New York City, July 2018, but due to its success in spurring public engagement and awareness of the SDGs, it remained on the plaza as a demonstration of SDGs for two months. This is a testimony to the ELM but also to the power of demonstration projects as a means forward in adopting new suitable technologies and practices in the built environment. The literature stresses [18], [30] the necessity to link technology and social innovation in order for society to embrace a path forward towards sustainable development.

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