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INTEGRATION OF SUSTAINABLE DEVELOPMENT PRINCIPLES AND AFFORDABILITY IN HOUSING CONSTRUCTION

***Summary.** The incorporation of sustainable development concepts into residential projects presents one of the most difficult and significant problems in modern-day construction. The notion that there is an inherent trade-off between sustainability investments and minimizing costs obscures the fact that sustainable development and affordability have complementary relationships during the entire life cycle of buildings. In this article we discuss four areas of the relationship between sustainability and affordability: 1) reconciling sustainability and affordability as two competing objectives; 2) the application of energy efficiency and lifecycle cost methods to produce long term affordability; 3) the production of large-scale housing using sustainable materials and locally sourced raw materials; and 4) how sustainable affordable housing can contribute to achieving the UN's Sustainable Development Goals (SDGs). Through the results of a systematic review of relevant academic literature, the authors position the integrated engineering and management methodology of Chirkin as the operational model for reconciling sustainability and affordability at the project level. Each of the four pillars of the Chirkin methodology - engineering-management integration, turnkey standardization, lean operational logic, and scalable modularity - addresses each of the tensions related to sustainability-affordability discussed within the literature*

to provide a structural method to produce houses that are both cost effective, energy efficient and aligned with SDGs. Directions for policy implications and potential avenues for future research based on the findings from the study will be presented.

Key words: *sustainable housing, affordable housing, energy efficiency, building lifecycle, ecological materials, SDGs, Chirkin methodology, lean construction.*

Introduction. There has traditionally existed a perceived conflict between achieving sustainability in new home development and addressing the issue of housing affordability. Sustainability measures such as using energy efficient systems, utilizing materials and products that meet certain environmental standards, implementing passive design standards, etc., all require substantial initial investments of funds. These expenses are often considered to be counterintuitive to the goal of providing affordable housing due to their expense.

This perceived conflict has resulted in a continued division in both academic research and professional practice, where affordable housing developments rarely include significant investments in sustainable practices and sustainable developments rarely offer price levels that are available to low income families. The end result of these two paths is a built environment where many of the lowest-income households, who will incur higher long-term costs associated with inefficient use of energy, poorly performing thermal elements, and frequent costly maintenance repairs are unable to affordably pay for their housing needs.

Increasingly, researchers have challenged this perceived division based on empirical evidence. In addition to documenting relationships between the amount of household expenditures devoted toward housing costs, including utilities and maintenance, and reduced quality-of-life [1], recent studies have demonstrated that there exists a strong link between the level of household expenditures devoted

toward meeting basic living needs and the likelihood that those households will experience economic stress or "material hardship" as a result of increased utility bills. Shamsuddin and Campbell (2022) further extended the previous body of research by demonstrating that households residing in less-than-energy-efficient affordable homes, face additional financial stresses beyond simply being unable to afford the monthly mortgage/rent payments, due to escalating utility bills that were previously not accounted for in their budget [19]. Finally, Colburn et al. (2025) added another important layer of analysis by examining how households move into and out of cost-burdened situations over time as energy and maintenance costs vary; they noted that the previous research on the impact of energy and maintenance costs on households was limited because it typically examined these impacts in static terms, i.e. as fixed values over time [9]. They also underscored the need for new methods of evaluating the affordability of housing that account for the changing nature of these costs over time.

Finally, Liu et al. (2020) provided the technical-economic rationale for an alternative perspective on sustainability and affordability in housing production by presenting results of techno-economic optimizations of renewable energy systems in high-rise residential structures that showed integrated sustainability investment produces cost savings across the entire lifespan of a structure when compared to traditional non-sustainable construction strategies [15]. Bae et al. (2023) expanded upon this line of reasoning by demonstrating that when applied within a structured project management approach, comprehensive structural and mechanical optimization of buildings can produce sustainability benefits while reducing overall project costs [5]. Together, these bodies of research form the basis for this paper's central assertion: the apparent tradeoff between sustainability and affordability is a function of insufficient methodologies - not a fundamental requirement.

The integrated engineering and management methodology presented in

Chirkin, forms the operational platform for resolving what is now recognized as a false trade-off between sustainability and affordability in housing production. Through its ability to embed multiple sustainability-related objective functions (energy consumption targets, eco-materials specification requirements, lifecycle cost criteria, and SDG alignment protocol compliance requirements) within a single engineering and management framework, Chirkin provides an opportunity for affordable housing developers to develop sustainable solutions simultaneously with cost-effective ones. As such, this paper presents an overview of existing literature related to integrating sustainability with affordable housing followed by an overview of Chirkin's methodology. The remainder of the paper follows a typical format with the findings from each area being evaluated using Chirkin's framework as the evaluation tool.

2. Literature Review

2.1. Reconciling Affordability and Sustainability as Co-Objectives.

Conceptual Reconciliation of Affordability and Sustainability *in Housing Construction Begins* with a Definition of What an Affordable House Means Over its Building Lifecycle. According to Galster & Lee (2021), an affordable house is defined by many factors, including acquisition/rental cost, all other housing expenditures such as utility bills, maintenance costs, and opportunity costs due to poor quality of location; the overall housing-related expenditure burden [13]. An expanded definition of affordability allows for investment in sustainability, i.e., measures that will raise the initial construction cost of a house but reduce long term costs associated with utility bills and maintenance. These investments can be seen as increasing the affordability of a house on a lifecycle basis when viewed solely based on the increased construction costs.

Ezennia and Hoskara (2022) support this statement by providing evidence from a systematic review of literature examining various methods used to measure

affordability [10]. The authors demonstrated that the residual income method was far more responsive to the total lifecycle cost of a dwelling than the common ratio method. Therefore, it was far better suited to capture the benefit of energy efficiency investments. Akinsulire et al. (2024) provided the strategic planning component to this methodology-based argument. They demonstrated that development projects for affordable housing created using explicit lifecycle costing models had superior long-term viability than projects developed without these types of models [3]. As a result, projects utilizing lifecycle costing models were able to attract capital sources that would have been deterred by the low profit margins typically found in the affordable segment.

The additional social returns factor added another level of justification to the integrated framework. Favilukis et al. (2023) quantified these social returns using welfare analysis and demonstrated that there existed positive externalities related to affordable housing production; specifically, reductions in commuting time, increases in labor market efficiency, and higher levels of neighborhood stability [11]. Furthermore, the authors demonstrated that energy efficiency and optimal location were additive to these benefits; resulting in an amplified positive externality effect. In conclusion, the authors' results suggest that the social return on investment for sustainable affordable housing is larger than that of non-sustainable affordable housing. Therefore, it is reasonable to justify government subsidies for the extra cost of incorporating sustainable design elements into affordable housing projects.

2.2. Energy Efficiency and Building Lifecycle as Determinants of Long-Term Affordability. The connection between energy efficiency and housing affordability over time has been studied for decades in the area of sustainable construction. For example, Liu et al. (2020) present a detailed techno-economic assessment of hybrid renewable energy systems used in tall residential buildings [15]. They demonstrate that the optimized operation of solar, wind, and storage can

lead to positive financial returns from an economic standpoint using different assumptions for energy prices and discount rates. One important aspect of their research is its relevance to affordable housing since they show that the economic benefits of investing in energy efficient products or services do not depend on higher up-front costs; instead, the greater the extent to which these systems are considered part of the engineering system of the building versus being treated as additional products or systems, the lower will be their overall cost.

In another study Bae et al. (2023), expanded upon the prior research to include the structural and mechanical systems of residential buildings [5]. Using a coordinated approach to designing the thermal performance of the building envelope, heating ventilation and air conditioning (HVAC) systems, and interior lighting systems (all as one cohesive process), the researchers demonstrated that it is possible to meet energy performance goals while maintaining construction costs similar to those found with traditional methods of building. As such, their method of optimizing building designs is also applicable to the engineering management integration component of the Chirkin framework; the researchers showed that the efficiencies gained through integrating all aspects of engineering into a single process occur through coordinating multiple areas of engineering rather than through selecting specific technologies.

Finally, Bedon et al. (2023) discussed how the results obtained by the other two studies fit into the larger trend of innovation in structural design practices [6]. The authors argued that incorporating performance based on energy use into structural design (as opposed to simply including energy performance considerations as a secondary consideration related to mechanical systems) is currently the leading edge of sustainability-based building design. Since the first pillar of the Chirkin framework seeks to integrate energy engineering decisions into a unified project-based decision making process rather than treating them as separate specialist fields,

it provides the means to coordinate engineering disciplines necessary for designing energy efficient buildings.

2.3. Ecological Materials and Local Resources in Mass Housing Construction. The potential for using ecological materials and local resources for constructing large-scale developments creates an interesting economic-environmental trade-off. From an environmental standpoint, ecological materials (such as wood products, recycled aggregate, low carbon cement alternatives and bio-based insulation systems) have significantly lower carbon footprints compared to traditional building materials and therefore contribute to the overall environmental sustainability of a project. However, from an economic standpoint, there is no guaranteed price advantage to ecological materials over traditional materials. Depending upon the level of development of the local supply chain, the amount of regulatory support or incentives available, and the volume of product being purchased; ecological materials may be economically competitive with traditional materials.

Both Bertram et al. (2019), and Razkenari et al. (2019) note that modular construction techniques provide opportunities to create a consistent method for the incorporation of ecological materials into mass housing projects through the creation of pre-fabricated units in factories [7; 18]. Factory-based construction provides the opportunity to select materials, process materials and install materials under tightly controlled conditions thereby reducing the amount of waste created during construction and optimizing the use of ecological substitutes.

Fei (2023) expanded on these ideas by examining how the factory based nature of prefabricated construction allows for the use of tight tolerance materials such as bio-based and recycled materials which require tighter dimensional tolerances than most traditionally constructed materials [12].

Avelar et al. (2020) examined the impact of lean construction principles in

small- to medium-sized enterprises (SMEs) by documenting how lean supply chain management practices (e.g., developing long-term relationships with suppliers and minimizing waste in purchasing processes) can improve both the environmental performance and the cost effectiveness of construction materials used in buildings [4]. Adekunle et al. (2023) identified sustainable material technologies as a major obstacle for SMEs in adopting new methods of construction due to high initial capital expenditures required to develop knowledge and implement the new technologies [2]. Both issues associated with implementing sustainable construction practices are minimized with the Chirkin methodology’s two primary pillars – lean operations and turnkey standardization. The Chirkin methodology’s lean operational pillar includes embedding sustainable material selection criteria into standardized purchase orders and contracts that are used across multiple projects and thus minimize the per-project cost associated with selecting ecological construction materials.

Sustainable Affordable Housing and the UN Sustainable Development Goals. The authors argue that an important part of the process of achieving the Sustainable Development Goals (SDGs) is to map out how sustainable affordable housing may contribute to those goals. Those authors identify five SDGs that relate most closely to sustainable affordable housing: SDG 1 (no poverty); SDG 3 (good health and well-being); SDG 7 (affordable clean energy); SDG 11 (sustainable cities and communities); and SDG 13 (climate action). Each of these goals includes elements of providing housing that is not only affordable, but also provides an environmentally friendly approach to energy consumption.

Three studies support several aspects of the relationship between the availability of affordable housing and the achievement of at least two of these SDGs. Acolin and Reina (2022) along with Shamsuddin and Campbell (2022) report on one aspect of SDG 1 (no poverty) and another aspect of SDG 3 (good health and well-

being): they find that housing costs represent a significant source of income limitation; housing costs limit families' ability to purchase food or medical care; and housing costs limit families from participating in activities that improve their overall sense of well being [1; 19]. These same three studies found that affordable energy efficient housing reduces all of these problems because it results in reduced expenditures for housing and improved indoor air quality. Colburn et al. (2025) added a new dimension to the analysis and demonstrated that the protective effects of affordable housing against poverty and hardship were sustained only if there was no increase in housing costs (including energy costs) during subsequent years [9]. This study supports the idea that energy efficiency in affordable housing should be considered an effective method for eliminating poverty.

In addition to providing evidence regarding the contributions of affordable housing to two of the four dimensions of SDG 11 (social inclusion and spatial equity), Van Doorn et al. (2019) and Favilukis et al. (2023) also provided evidence about the economic impact of such affordable housing in terms of increased metropolitan-wide productivity [11; 21]. The two studies suggest that the creation of sustainable affordable housing in high opportunity locations will have positive impacts on the individuals who reside in such homes and on the entire metropolitan area. Such positive impacts include improvements in urban welfare as measured by increases in the productivity of residents, businesses, and government entities across the metropolitan region. In regard to the fourth dimension of SDG 13 (reducing greenhouse gas emissions), Zohourian et al. (2025) and Cao et al. (2025) demonstrated that use of factory-based prefabricated modules resulted in lower levels of embodied carbon than did traditional site built residential construction [8; 23]. Additionally, Liu et al. (2020) showed that integrated energy systems could reduce operational carbon emissions from buildings [15].

Two other researchers noted that the SDG framework allows for evaluating

policies related to housing based on multiple criteria (e.g., sustainability, affordability, etc.), which is consistent with a lifecycle cost perspective and co-objective decision-making. Hilber and Schoni (2022) and Galster and Lee (2021) point out that the introduction of a multi-criteria evaluation logic into housing policy via the SDGs has many structural similarities with a lifecycle cost perspective and co-objective decision making [13; 14]. As a result, this approach may help make decisions about housing investments more transparent and accountable. Finally, developers and investors may benefit from using this type of policy framework as described by Moorhead et al. (2023) who show that feasibility evaluations conducted according to sustainability criteria in conjunction with cost-related criteria are likely to result in more accurate feasibility assessments and attract a wider variety of financial instruments (e.g., green bonds, ESG aligned funds, etc.) [17].

Methodology. In order to adopt an appropriate evaluative structure for the research conducted here, the authors employed an analytical review methodology; utilizing the integrated engineering and management framework developed by Chirkin (1996) as the primary lens for evaluating how researchers have addressed the issue of integrating sustainability into the development process while minimizing construction costs.

As indicated above, the Chirkin framework is utilized here as the tool through which it will be shown that, although there appears to be a trade-off between investing in sustainability-related features and minimizing construction costs, the framework can provide a means of resolving this trade-off through methodologically-integrated decision-making at the project level. Each of the four pillars of the Chirkin framework was used to evaluate the various literatures reviewed regarding the sustainability-affordability tensions.

For example, the first pillar of the Chirkin framework - engineering-management integration - was evaluated using data from the energy efficiency and

building lifecycle literature. Specifically, the literature indicates that when energy engineering decisions were integrated into the structural, mechanical and project management decision making process (i.e., "design optimization") for low-cost buildings, lower costs were associated with achieving desired energy performance levels compared to sequential or isolated design methods. Therefore, this pillar represents the evaluation criterion used to determine whether the findings of the literature related to energy efficiency depend upon methodological integration.

Similarly, the second pillar - turn-key standardization - was evaluated based on data from the ecological materials and SDG compliance literature. For example, when standardized procurement protocols were established that included ecological material specification requirements and SDG compliance criteria, the literature indicated that such standardized protocols would decrease the cost of adopting sustainable construction practices on a per-project basis, thus providing for similar levels of sustainable performance across all projects in an affordable housing developer's portfolio. In addition, this pillar provides the basis for evaluating whether the literature has provided sufficient support to demonstrate that standardized procurement can enhance sustainability.

Thirdly, the third pillar - lean operational logic - was evaluated based on data from the supply chain and waste reduction literature. Based on these studies, the application of lean procurement and scheduling systems that minimized waste generation during construction and maximized utilization of suppliers located locally would result in reduced construction costs and decreased environmental impacts. Thus, it may be concluded that part of what creates a trade-off between affordability and sustainability is an inefficient use of resources during production and delivery - a problem that may be addressed via implementation of lean principles.

Finally, the fourth pillar - scalable modularity - was evaluated based on data

from the SDG scaling literature. A framework that includes protocols that can be consistently replicated across multiple project types and contexts enables affordable housing developers to implement SDG criteria systematically rather than on a case-by-case basis. Therefore, this pillar provides a basis for evaluating whether existing frameworks enable systematic pursuit of SDG alignment.

A common evaluative approach was used throughout both the Findings and Discussion sections to evaluate each body of literature on their ability to utilize or reference a variety of forms of engineering-management coordination described in the Chirkin framework. When bodies of literature referenced a form of engineering-management coordination that was also contained within one or more of the operational logic components of the Chirkin framework, then such references were viewed as confirming evidence of the relevance of that component(s) of the framework to the sustainability-affordability integration agenda.

Results. The body of research reviewed regarding the relationship between sustainability and affordability provides empirical support for the contention that sustainability and affordability are not mutually exclusive, but rather can be compatible in terms of housing cost; specifically, it has been shown through an examination of energy-efficient design/building systems, building design optimization, and the overall lifecycle costing methodologies utilized by researchers in these areas that "green" construction/energy-efficiency investments can provide savings over time (i.e., at the expense of increased upfront construction costs) if such features are incorporated into the project's design and/or management frameworks as opposed to being specified as separate requirements (See Figure 1).

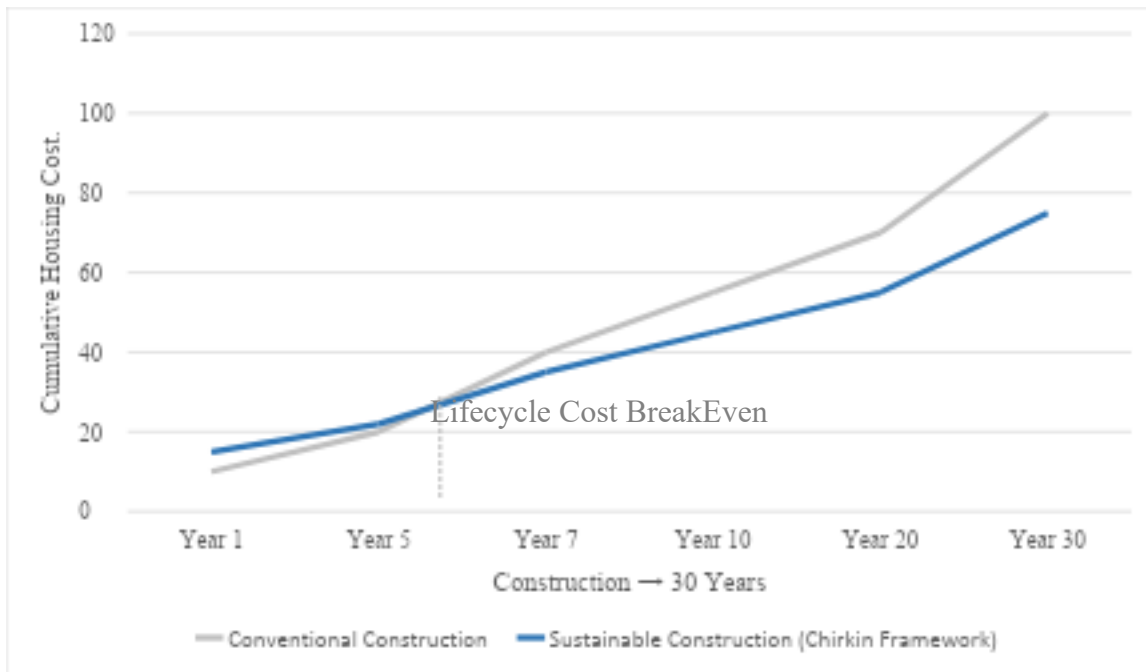


Fig. 1. The sustainability-affordability relationship: short-term cost premium versus long-term lifecycle cost advantage of sustainable affordable housing

Table 1

Sustainability-Affordability Tensions and Chirkin Framework Pillar Responses

Sustainability Dimension	Affordability Tension	Chirkin Response	Pillar	Outcome
Energy efficiency	Higher upfront capital cost	Turnkey Standardization		Lifecycle cost reduction offsets initial premium
Ecological materials	Local supply chain variability	Lean Logic	Operational	Waste reduction compensates material cost
Building lifecycle optimization	Design complexity and cost	Engineering-Management Integration		Integrated design reduces lifecycle expenditure
SDG-aligned construction	Multi-criteria compliance burden	Scalable Modularity		Replicable protocols embed SDG criteria across projects

Source: assessment based on synthesis of reviewed literature

Table 1 shows how each of the four major dimensions of sustainability (the paper’s) have been mapped to the affordability tensions created for each dimension; the Chirkin Pillar(s) addressing the affordability tensions; and what outcomes result from the operational logic of each pillar. This mapping clearly illustrates the relationship between the literature documenting the various sustainability - affordability tensions and the operational structure of the Chirkin Framework. Thus, this research has demonstrated that the Chirkin Framework provides a solution to the core problems identified as part of the sustainability - affordability integration agenda.

The results of this research are also important from a policy standpoint. From an evidence based perspective, there are substantial links between Sustainable Affordable Housing (SAH) and at least five of the 17 Sustainable Development Goals (SDGs). Specifically, SAH has the greatest linkages to SDG 1 (Reducing poverty through alleviating housing cost burdens); SDG 7 (Providing Affordable Clean Energy through Energy Efficient Design); and SDG 11 (Creating Sustainable Cities through Providing Inclusive Well-Located Housing). While these relationships exist independently of one another, they arise from the same underlying structural premise as does the concept of affordability itself. Therefore, SAH which is truly affordable throughout a resident's life cycle (through energy efficiency, use of long lasting materials, etc.) will be contributing to both the social and environmental goals outlined in the SDG framework.

Table 2

Sustainable Affordable Housing Contributions to the UN Sustainable Development Goals

SDG	Affordable Housing Contribution	Sustainability Mechanism
SDG 1: No Poverty	Reduced housing cost burden	Affordable rent-to-income

	freed household income	ratios
SDG 3: Good Health & Well-Being	Improved habitability reduces stress and illness	Energy-efficient thermal comfort
SDG 7: Affordable Clean Energy	Energy-efficient housing reduces household energy expenditure	Renewable energy integration, passive design
SDG 11: Sustainable Cities	Inclusive communities reduce spatial inequality	Mixed-income, transit-accessible affordable housing
SDG 13: Climate Action	Low-carbon construction reduces embodied and operational emissions	Ecological materials, energy optimization

Source: SDG contributions synthesized from Acolin & Reina (2022), Shamsuddin & Campbell (2022), Liu et al. (2020), Favilukis et al. (2023), and Zohourian et al. (2025)

Table 2 illustrates how sustainable affordable housing contributes to five SDGs through the application of one or more affordable housing mechanisms and/or sustainability instruments. The map demonstrates that achieving SDG alignment with respect to affordable housing is not a separate compliance goal; it is an outcome of affordable housing that is well-designed, energy efficient and durably affordable. All of which can be achieved through the combined use of the four pillars of the Chirkin Framework.

Discussion. The main analytical contribution of this study is demonstrating that the trade off between affordability and sustainability in housing construction does not have to be a structural one; it can be eliminated by a better methodological approach - namely integrating engineering and management into an overarching project framework with both sustainability and cost effectiveness treated as joint goals. The Chirkin Methodology achieves this integration, and the evidence collected in this paper demonstrates the applicability of the methodology to all four dimensions of sustainability identified above.

Where the methodology has the greatest direct quantification potential is in

terms of energy efficiency. Liu et al. (2020) demonstrated that the lifecycle cost benefit of optimizing an integrated energy system in residential construction is sufficiently large to cover the additional construction stage premium required to achieve such systems, over periods ranging from five to ten years, depending on the assumed future prices of energy [15]. Bae et al. (2023) extended these findings to include the building design optimization literature, providing empirical confirmation that systematic multi-system optimization will produce energy performance benefits associated with minimal marginal cost premiums that can easily justify lifecycle cost reductions [5]. What is key in both studies is that the energy performance benefits were produced only when the sustainability investments were treated as integral parts of the overall engineering and project management architecture, and not simply as add-ons or separate specification layers. This represents exactly the operational logic that the Chirkin methodology's engineering-management integration pillar formalized and made uniformly replicable across all projects.

The ecological materials dimension appears less conclusive. Collectively, evidence presented by Bertram et al. (2019) [7], Razkenari et al. (2019) [18], and Fei (2023) [12] establish that factory-based modular and prefabricated construction provide the most suitable manufacturing environments for using ecological and recycled materials, because they allow manufacturers to control environmental conditions, maintain precise dimensions and minimize waste. However, Adekunle et al. (2023) reported that small medium enterprises (SMEs) may experience obstacles to implementing sustainable material technology - although economic feasibility exists - including initial knowledge costs and lack of organization structure to enable systematic procurement [2]. The Chirkin methodology resolves this obstacle through its turn-key standardization pillar: by incorporating ecological material requirements into standardized procurement processes, the methodology converts the per-project acquisition costs of sustainable materials into a

documentation/sourcing process - which SMEs can accomplish without having to incur organizational overhead for achieving sustainability through ad-hoc approaches (See Figure 2).

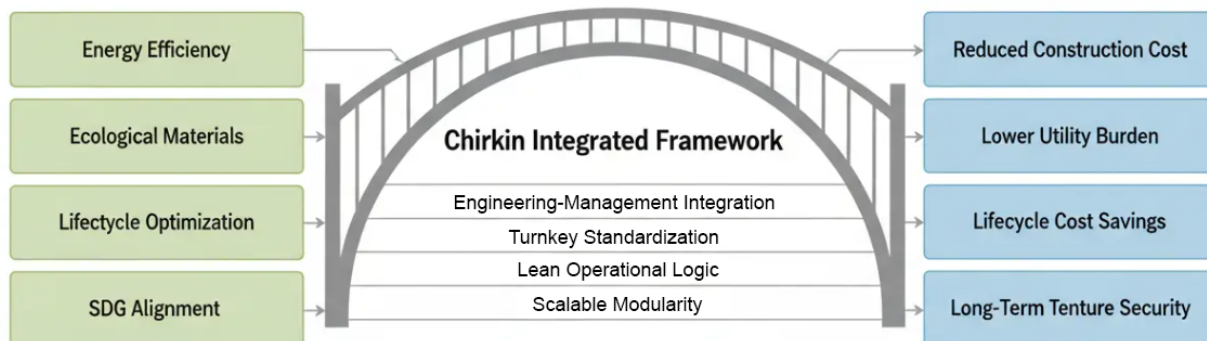


Fig. 2. The Chirkin methodology as the operational bridge between sustainable construction principles and affordable housing delivery

A number of studies have demonstrated that Lean Operational Logic can help with integrating sustainability and affordability for construction. For example, Avelar et al. (2020), showed how using Lean Supply Chain Management practices could improve procurement logistics and eliminate waste associated with the procurement process [4]. These improvements to logistics and procurement processes reduced construction costs while reducing greenhouse gas emissions related to transporting materials. As a result, the same efficiencies that contribute to lower costs also contribute to achieving lower levels of environmental impact.

Lean Construction's Waste Elimination principle is an ideal fit for sustainability. Therefore, it follows that when a project is managed according to Lean principles there will be a reduction in environmental footprint due to the focus on eliminating waste and improving efficiency.

According to the Chirkin Methodology, the relationship between waste elimination and resource efficiency is formalized so that the application of Lean Operational Logic becomes a governing principle for managing all aspects of a

project including procurement, scheduling, and on-site work. As a result, the economic benefits of waste elimination occur concurrently with the environmental benefits.

The Sustainable Development Goals (SDG) Dimension of Sustainability Affordability Integration represents another important way that sustainability and affordability relate. Specifically, the SDG Alignment Dimension relates the sustainable affordable housing initiatives to broader global commitments embodied in the United Nations' Sustainable Development Goals. In other words, the SDG Alignment Dimension connects the initiatives described in this research report to global normative standards regarding sustainability. The five SDGs listed in Table 2 illustrate some of these global commitments and suggest that they provide both the funding and political will required for sustainable affordable housing initiatives. Recent developments in Green Finance Instruments include Environmental Social Governance (ESG) aligned loan products and Green Bonds. According to Favilukis et al. (2023), Akinsulire et al. (2024), etc., recent developments in Green Financial Instruments have provided many more sources of funding for affordable housing initiatives that can clearly articulate their commitment to meeting specific SDGs [3; 11].

In addition to facilitating access to funding through Green Financial Instruments, the scalability and modularity of the Chirkin Methodology facilitate compliance with global normative standards. By structuring project protocol to specifically reference SDG criteria, the Chirkin Methodology facilitates the generation of consistent measurable performance information necessary for demonstrating compliance with ESG investor requirements or the terms of a Green Bond. Therefore, the ability to articulate a clear connection between a project and specific SDGs transforms what was previously an obligation to report on sustainability efforts into a tangible source of funding.

The implications for Small Medium Enterprises (SMEs) in this regard are significant. Makabate et al. (2022) [16], Vidalakis et al. (2020) [22], etc., documented various organizational impediments to implementing Digital Tools that are now becoming increasingly common among those involved in sustainable construction (e.g., Building Information Models (BIM) systems capable of performing energy performance modeling; life cycle costing models). Rather than requiring SMEs to individually develop digital sustainability capabilities, the Chirkin Methodology provides an organized operational structure in which existing digital tools (e.g., BIM Systems, Energy Modeling Software, Lean Scheduling Systems) can be used productively and in coordination. Stehn and Jimenez (2024) illustrated that SMEs who operate in stable organizational structures develop digital sustainability capabilities based upon organizational learning and experience rather than relying solely upon initial capital investments [20]. Consequently, the use of the Chirkin Framework may serve as a basis for developing digital sustainability capabilities by SMEs over time (See Figure 3).

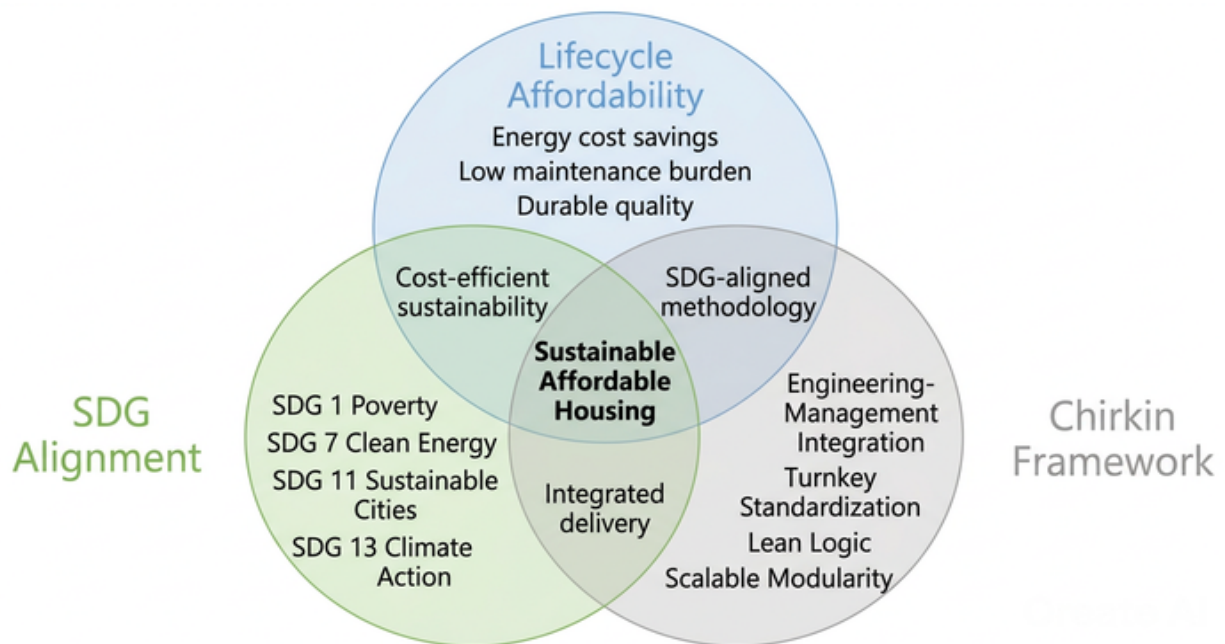


Fig. 3. Sustainable affordable housing as a convergence point for lifecycle affordability, SDG alignment, and the Chirkin integrated framework

The lifecycle cost-based affordability argument developed in this research study has significant implications regarding both the design of, and measurement of, housing affordability policy. Ezennia and Hoskara (2022), suggest that when comparing methods used to measure housing affordability that reflect the total housing cost profile (energy costs; maintenance costs; transportation costs); and those methods which simply reflect the cost of building, yield substantially different assessments of project viability [10]. Collectively, the above suggestions indicate that, in order to create an infrastructure for providing sustainable affordable housing -- i.e., measurement frameworks; subsidy architectures; developer incentives -- there must be alignment between such policy infrastructure and a lifecycle cost framework. In doing so, the generated affordable housing stock will be sustainably affordable (as opposed to being inexpensive to construct).

Conclusions. This study assessed the relationship of integrating principles of sustainable development and the goal of housing affordability along four dimensions; namely, reconciling the concepts of affordability and sustainability, economics of energy efficiency throughout the lifecycle of buildings, utilizing green materials and local resource inputs for construction, and how sustainable affordable housing can contribute to achieving some or all of the United Nations Sustainable Development Goals (SDGs). The results indicate that the long-asserted sustainability-affordability trade-off which has been considered an inherent aspect of housing economics is more accurately represented as a product of methodological inadequacy — i.e., not treating sustainability and cost-effectiveness as equally important and simultaneously achievable goals using a single unifying engineering and managerial structure.

Chirkin's integrated engineering and managerial approach presents a single structure in which to achieve the four pillars he identifies - engineering-management integration, standardized turn-key delivery systems, operational lean logic, and

scalable modular design - to achieve sustainability-affordability balance while allowing small-medium enterprises (SME) to provide both cost-effective, energy efficient, environmentally responsible and SDG compliant housing. As demonstrated in the review of lifecycle cost studies presented in this report, investments in sustainability made in conjunction with a holistic and consistent project management process create cost profiles favorably positioned at various stages of the building lifecycle - effectively converting what was perceived to be a trade-off between sustainability and affordability into two mutually beneficial co-objectives.

Future research will include longitudinal project level assessments of the lifecycle cost claims made herein, comparative evaluations of the sustainability performance of SMEs implementing an integrated methodology versus those that do not, and cross-nationally assessing how the contributions of sustainable affordable housing toward achieving SDGs may vary due to differences in policies and markets.

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