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Towards a net-zero carbon economy: A sustainability performance assessment of innovative prefabricated construction methods for affordable housing in Southern Africa

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ABSTRACT

Recently, efforts to mainstream sustainability principles into affordable housing projects through the adoption of modern methods of construction, like innovative prefabricated construction methods (IPCMs), have been observed. However, limited studies have evaluated the sustainability performance of IPCMs deployed to affordable housing projects in Southern Africa, where the delivery of sustainable affordable housing remains a regional imperative. This study bridges this gap by assessing the sustainability performance and index scores of six IPCM variants implemented on affordable housing projects. The study adopted a two-phased quasi-experimental research design. In the first phase, the technical specification, lifecycle energy and cost and actual performance of these variants under varying conditions pertaining to sustainability were assessed and compared. The Sustainable, Innovative, Affordable Housing (SIAH) framework was adjusted to enhance its utility for computing sustainability index scores using expert opinions. Afterwards, the experts computed the sustainability index score for each case using the adjusted SIAH framework. Subsequently, the Edge App and SimaPro were used to simulate the sustainability performance of these variants under varying conditions. The study's results indicate higher overall sustainability performance of IPCMs compared to conventional methods. Moreover, the research results proved that the monolithic IPCMs were more suitable for net-zero carbon buildings. The study highlights the SIAH framework's usefulness as an assessment tool for determining the sustainability performance of affordable housing projects and for successfully selecting optimum IPCMs to implement towards eliciting such performance. It is expected that this study's results will contribute towards advancing the SIAH agenda in Southern Africa.

1. Introduction

Rapid urbanisation has further exacerbated housing deficits across the globe (Blasi et al., 2022). As such, many urban dwellers have remained without shelter. However, equitable access to decent, affordable, shelter remains a fundamental human right as enshrined in various United Nations declarations and national legislations (Omer & Noguchi, 2020). Therefore, successive governments are mandated to provide shelter either directly or indirectly to most of their populace; a task that they have struggled to achieve, despite the development and implementation of multiple initiatives and legislations in collaboration with other relevant stakeholders (Bardhan et al., 2018; Malik et al., 2021; van Bortel & Gruis, 2019). Affordable housing schemes remain most prevalent among these initiatives, particularly in Southern Africa. The inability of governments in the Southern African context to successfully implement affordable housing initiatives has resulted in a housing backlog (Moghayedi et al., 2021).

The implementation of affordable housing initiatives has continued to receive significant attention in the academia where scholars have sought to study its performance (van Bortel & Gruis, 2019). Also, an increasing shift of focus from affordability to other societal aspirations like sustainability and innovative practices within the affordable housing space has been noticed in these studies (Adabre & Chan, 2020; Adabre et al., 2020; Chan & Adabre, 2019). This shift was predicated on the need to ensure that efforts expended at bridging the housing deficit are executed in ways that are in sync with society's sustainability

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aspirations (Chan & Adabre, 2019). This has contributed to the need for a drastic reduction in the degree of anthropogenic activities evident in contemporary society, most of which are associated with the construction industry (Awuzie & Monyane, 2020). Examples of these anthropogenic activities include the exploitation of natural resources for building materials and environmental displacement as a result of the construction process (Sithole et al., 2022).

From the foregoing, the construction industry's pivotal role in affordable housing and infrastructure stock delivery can be easily discerned. Also, the need to carry out this role in a way that engenders improved sustainability performance has been elucidated by scholars (Awuzie & Monyane, 2020). Suffice to state that the prioritisation of sustainability principles and innovative technologies, materials and practices remains critical to delivering sustainable affordable housing in an accelerated manner thereby reducing the housing deficit (Joglekar et al., 2018; Moghayedi et al., 2021; Omer & Noguchi, 2020; Windapo et al., 2021). This understanding has given rise to the increased adoption of modern methods of construction like prefabricated construction in the delivery of affordable housing (Luo et al., 2021).

Scholars have elucidated the potential utility of prefabricated construction methods as deployed in affordable housing contexts, to mitigate ecological footprint (Li et al., 2021), enable resource efficiency (Aghasizadeh et al. 2022), expedite housing delivery processes (Moghayedi et al., 2021) and facilitate sustainable supply (Jain & Bhandari, 2022). Prefabricated construction methods offer greater accuracy, and better value, whilst promoting recycling and waste reduction (Aghasizadeh et al., 2022). Also, this method has been described as being capable of resolving shortcomings associated with conventional on-site construction practice (Pittau, 2017). This is particularly the case when it is complimented with innovative technologies, materials, and practices to improve sustainability performance (Aghasizadeh et al., 2022; Masood et al., 2021). However, the effect of this integration on the sustainability performance in affordable housing projects remains underexplored by extant literature. This is particularly the case with the affordable housing schemes in the Southern Africa context. This study contributes towards filling this knowledge gap by conducting a sustainability performance assessment of different variants of innovative prefabricated construction methods (IPCMs) which have been implemented on affordable housing projects in Southern Africa. Access to sustainable affordable housing remains a challenge for most of the Southern African population, hence the topical and timeous nature of this study.

Therefore, it is expected that the outcomes of this study would provide insights on how to leverage innovative technologies and materials in improving the expedited supply of sustainable affordable housing using prefabricated construction methods. To achieve its objective, the study shall be guided by the following research questions, namely:

1. What are the suitable IPCMs applicable for sustainable affordable housing projects in developing countries?
2. What index is available for assessing the economic, environmental, and social sustainability performance of these IPCMs?
3. What is the economic, environmental, and social sustainability performance of these IPCMs?

The rest of this paper shall be structured as follows: Section 2 consists of a synthesis of relevant literature on sustainable, innovative, affordable housing, modern methods of construction and prefabricated construction methods. An articulation of the research methods used for data collection and analysis are presented in Section 3. In Section 4, the results accruing from the data is presented and subsequently, discussed in Section 5. The conclusions of the study are presented in Section 6.

2. Literature review

2.1. Shifting from affordable housing towards sustainable, innovative, affordable housing

The rapidly urbanizing nature of urban areas and cities has further exacerbated the affordable housing crisis globally. Evidence of ongoing efforts to curb this imbroglio can be found in the plethora of scholarly work and grey literature focusing on the expedited supply of affordable housing.

Affordability is often referred to as a subjective term due to the absence of a universal definition of affordable housing. However, affordability essentially reflects a market-based concept that is used to gauge an individual's capacity to pay for adequate housing (Moghayedi et al., 2021).Buttressing the context-dependent of nature of its definition, Collins et al. (2022) posit that the determination of affordability was dependent on a household's income, savings, disposable income, etc. Adabre et al. (2020) described it as housing of any tenure that is adjudged to be affordable to a particular household or income group by analysis of housing costs, income levels, and other factors.

Initially, the emphasis in affordable housing schemes was placed on the cost of production of housing units. Developers were expected to deliver houses at the lowest cost to enable the intended beneficiaries to acquire them. This emphasis was modified with due consideration to the rising cost of living. The housing affordability concept was expanded to cater to all other costs associated with house-ownership or rental (housing-linked costs). For housing to be deemed affordable under this new regime, housing-linked costs were not expected to surpass 30% of the household net income of the occupants (Moghayedi et al., 2021). This renewed focus on minimizing housing-linked costs alongside society's sustainable futures aspiration and quest to tackle climate change, gave impetus to the incorporation of sustainability as a salient deliverable within affordable housing ecosystems, hence the emergence of. the sustainable affordable housing (SAH) sobriquet (Chan & Adabre, 2019; Gan et al., 2017). The SAH concept connotes the integration of sustainability principles across the lifecycle of an However, scholars have argued that the sustainability component of the affordable housing envelope has largely being ignored, due to the lack of appropriate motivation and incentivization of developers to commit them towards supplying this housing type as well as restrictive regulatory and policy challenges (Collins et al., 2022), and the resort to unsustainable substandard quality housing which then becomes expensive to maintain in the long-term (Moghayedi et al., 2021).

The faultless delivery of SAH has been impeded by a variety of factors. Moghayedi et al. (2022) listed some of these barriers as consisting of a lack of understanding of sustainability, a lack of technological innovation knowledge and innovative practices, inadequate design and the adoption of inappropriate construction methods and materials. Similarly, Moghayedi and Windapo (2018) corroborated this viewpoint, stating that the selection of poor designs, construction methods, materials, and technologies played a significant role in undermining the development of SAH. Further, Adabre and Chan (2020) identified 26 potential barriers negating SAH development from the relevant literature. These barriers range from inadequate affordable housing policies or guidelines, high cost of sustainable building materials and technologies, to the shortage of skilled labour, among others. Although it is evident that these issues are common to other housing types, it can easily be discerned that these barriers have the potential to undermine the attainment of SAH, especially as it pertains to the product (house) success criteria and project management (process) success criteria respectively.

In their study, Moghayedi et al. (2021) identified available critical success factors (CSFs) for optimal incorporation of these innovative technologies and practices across lifecycle phases of SAH. The fusion of innovative technologies and practices in SAH culminated in the emergence of the sustainable, innovative, affordable housing (SIAH) concept.

SIAH as espoused by these authors, refers to the integration of innovative methods, materials, technologies and practices in the construction of sustainable and affordable housing with the main aim of improving and advancing the capacities of these houses to contribute to the economic, social and environmental needs of low- and medium-income classes, while still satisfying the technical aspects, and reducing the ecological impact on the environment without compromising affordability across their lifecycle (Moghayedi et al., 2021).

Notwithstanding the emergence of the SIAH concept and its importance in facilitating improved levels of housing affordability and sustainability, its implementation remains constrained by construction industry-related challenges. The construction industry is known to be a slow adopter of innovation (Windapo et al., 2021). However, in response to an increasing advocacy for industry-wide transformation, the construction industry is gradually making strides to adopt relevant innovations for the purposes of improving its sustainability performance. These strides have focused on the housebuilding sector, with emphasis on the sustainability performance of the building process and the house as a product (Joglekar et al., 2018; Lehman, 2013; Windapo et al., 2021). This is informed by an understanding that buildings reflect a strong potential for cost-effective greenhouse gas (GHG) emissions reduction via the implementation of contemporary strategies like prefabricated construction methods and innovative technologies like net-zero energy buildings, as the transition to zero-emission buildings is gradually advancing too (van Oorschot, Halman & Hofman, 2021).

2.2. Implementing SIAH using modern methods of construction (prefabricated construction methods)

Based on the foregoing, the criticality of modern methods of construction (MMC) in developing SIAH cannot be overemphasised. The contribution of these methods towards improving the performance of the construction industry and projects respectively has been established in various studies (Jain & Bhandari, 2022; Khan et al., 2022; Moghayedi et al., 2023; Saad, Zulu, & Dulaimi, 2023). The 'modernise or die' report (Farmer, 2016) alluded to the imperative contribution of these methods towards redeeming the image of the construction industry through improvement of productivity levels, waste minimisation, appropriate material selection and usage as well as safe working environments.

In the United Kingdom, a framework for defining MMCs to enable the evolution of a commonly used terminology for identifying different categories has been proposed (MMC Working Group, 2019). This framework outlines seven MMC categories, namely; Pre-manufacturing (3D primary structural systems), Pre-manufacturing (2D primary structural systems), Pre-manufacturing components (non-systemised primary structure), Additive manufacturing (structural and non-structural), Pre-manufacturing (non-structural assemblies and sub-assemblies), Traditional building product-led site labour reduction and productivity improvements, and, Site process led site labour reduction/productivity/assurance improvements (MMC Working Group, 2019).

Conventional prefabricated construction methods belong to category 2, pre-manufacturing (2D primary structural systems). This category depicts a systemic process wherein flat panel units comprising of different materials are manufactured in a factory and subsequently used for flooring, walling and roof structures thereby resulting in a 3-D building skeletal structure comprising of frames and open panels on site. A prefabricated construction method can be described as a method of construction wherein an entire building or its components are manufactured at an off-site facility (factory-setting) and assembled onsite from self-sustained volumetric modules or separate panels (Dou et al., 2019; Gunawardena & Mendis, 2022). With the prefabricated construction method, many aspects of building activities can be moved away from traditional construction sites to factories using off-site, manufacturing-type production (Noorzai et al., 2022). Consequently, because the prefabricated construction method involves the production of individual sections (called modules), its production line is ideally a much faster and more convenient process than those associated with conventional construction methods. Prefabricated building units have been widely used for residential, commercial, and public infrastructure, post-disaster structures and many other applications around the world.

According to Gunawardena and Mendis (2022) and Noorzai et al. (2022), prefabricated construction methods emanated from three main construction types, namely; Modular (volumetric) construction, Panelised construction and Hybrid prefabricated construction (semi-volumetric).

Recently, a transformation from these three types into the monolithic system has been witnessed.

The monolithic system is a type of building technology type that allows accelerated housing construction whilst maintaining optimal levels of quality and durability. This type of construction allows structure (columns, loud baring walls), walls and slabs to be constructed together with usually same or similar materials. This means the concrete pouring in slabs and walls can be done simultaneously. This is a very fast construction technique that has helped reduce project costs in instances where it has been deployed for the development of flats and other built asset types. It looks like a box type construction which demonstrates resilience against horizontal forces (Earthquake, Cyclone, etc.), thereby placing it in good stead to serve in natural disaster-prone areas (Jain & Bhandari, 2022).

There is a growing demand for modern methods of construction, particularly prefabrication in the housing sector (Mandala & Nayaka, 2023). Scholars have admitted to the innovation potential of prefabricated construction methods which can be leveraged to improve the sector's performance (Khan et al., 2022; Li et al., 2021; Saad, Zulu, & Dulaimi, 2023; van Oorschot et al., 2021). Moving the housing sector towards utilising prefabrication methods not only addresses the perpetual housing issues and tackles the huge backlog but also advances the affordability and sustainability performance of housing.

This much has been confirmed by various scholars. For instance, Mandala and Nayaka (2023) highlight the following as benefits associated with the use of prefabricated construction methods in affordable housing delivery; time and cost effectiveness, reduced environmental impact, reduction of construction waste, and reduced energy consumption. Corroborating the potential benefits associated with the deployment of prefabricated construction methods in affordable housing delivery, Jain and Bhandari (2022) proposed a synergistic framework illustrating the relationship between the prefabricated construction characteristics and sustainable affordable housing requirements. The elements in this framework were positioned along a social, environmental, economic and technological sustainability trajectory. This implied that this construction method was well-positioned to deliver the requirements of S(I)AH.

Despite the benefits associated with the adoption of prefabricated construction methods for sustainable affordable housing solutions which are well-documented in the literature (Masood et al., 2021), there are certain challenges which have continued to pose a threat to its adoption. Some of these challenges include the lack of on-site skilled labour and on-site automation protocols, which are very important for the installation of prefabricated components on site (Jain & Bhandari, 2022; Moghayedi et al., 2022). Possession of the right skill sets is imperative as the prefabricated components are likely to get damaged during transportation and installation. Therefore, the arrangement of these units must be done with precision, avoiding congested places to prevent sloppiness. Other barriers identified in the literature include lack of comprehensive understanding, perceived impact on local jobs, high capital investment requirement, limited flexibility, unfavourable climatic conditions, emissions from transportation of components, etc. (Jain & Bhandari, 2022).

2.3. Prefabricated construction methods and sustainability performance

Various studies have observed that the use of prefabricated construction methods facilitated the attainment of substantial environmental, economic, and social sustainability-related benefits when compared to conventional construction methods (Khan et al., 2022; Pittau et al., 2017; Zhou et al., 2022). Similarly, Aris et al. (2019) affirmed the aptness of industrialized building system (IBS) and prefabricated construction methods in engendering sustainable affordable housing construction in Indonesia and Malaysia, respectively. Also, Colistra (2019) examined the suitability of prefabricated construction methods to enable the development of a ready-to-use technology infrastructure in senior citizens' sustainable affordable housing to support the seamless implementation of aging-in-place strategies and telehealth technology use among occupants. Lehmann (2013) demonstrated the utility of 'design for disassembly', low carbon prefabricated components in facilitating building sustainability performance through reduction in GHG emission and waste prevention.

Furthermore, the integration of innovative technologies and practices into prefabricated construction methods has been viewed as capable of engendering energy efficiency within affordable mass housing schemes (Chippagiri et al., 2021). Other scholars have also demonstrated the salient nature of prefabrication as a strategy for executing housing energy retrofit projects (Pittau et al., 2017). Aye et al. (2012) conducted an energy analysis of prefabricated reusable building modules. Results from this study indicated the potential for material reuse from prefabricated steel structures, culminating in 81% saving in embodied energy. This result differs from the result presented by Abey and Anand (2019) wherein, prefabricated construction methods exhibited a higher percentage of embodied energy than conventional onsite construction methods. However, this was attributed mostly to the energy associated with transport-related activities between factory and site in the case of prefabricated construction.

Obviously, whereas prefabricated construction methods can benefit from fusion with innovative technologies and practices to bring about improved sustainability performance (Khan et al., 2022), limited studies have tried to investigate this benefit and provide empirical evidence thereof. Therefore, the sustainability performance of prefabricated building sections/components remain a matter of conjecture (van Oorschot et al., 2021). This was further confirmed by Aye et al. (2012) who lamented the absence of studies detailing empirical evidence as it concerns the environmental benefits of the prefabricated construction methods. This knowledge gap is even more glaring within the context of SIAH where the emphasis lies on the utilization of innovation to facilitate improved sustainability performance of affordable housing projects. Rather, available studies have tried to gauge the sustainability performance of materials- brickwork (Joglekar et al., 2018) and sustainable building technologies (Windapo et al., 2021) within low-cost and affordable housing contexts. This study stems from the need to fill this knowledge gap and to contribute to the growing discourse on SIAH delivery in developing country contexts, albeit using a Southern Africa exemplar. To achieve its objective, it utilizes the SIAH index (a holistic sustainability performance measurement toolkit) (Moghayedi et al., 2021) in assessing the sustainability performance of variants of different IPCMs, across the social, economic, and environmental sustainability dimensions.

The comprehensive nature of the SIAH index which was derived from the SIAH CSF framework for sustainability performance assessment made it a natural choice for this study due to the shortcoming of existing assessment tools like Green Star, BREEAM, LEED, etc. which tend to prioritize the environmental and physical components of houses while neglecting or giving little consideration to their economic and social sustainability (Sharifi et al., 2021) (See sustainability and green assessment list in appendix). This limitation made the use of the prevailing assessment and rating systems untenable for this study which focused on critical economic and social sustainability-related issues confronting low-income households, major beneficiaries of the sustainable affordable housing initiative in Southern Africa.

For instance, the Building Research Establishment's Environmental Assessment Method (BREEAM) served as the UK's first green building rating system, addressing factors for improved environmental performance of buildings. In 2000, the U.S. Green Building Council (USGBC) developed another rating system known as Leadership in Energy and Environmental Design (LEED). In response to the growing interest in green design, additional rating systems emerged, with many influenced by these early programs but tailored to their specific contexts with particular priorities in environmental sustainability. Some other rating systems aimed to address broader sustainability issues or novel concepts like net-zero energy, living buildings, and restorative design. Furthermore, the SIAH Index enabled the accurate comparison of the cost of different systems, through an estimation and utilization of the cradle-to-grave lifecycle cost (construction cost, maintenance cost, and operational cost) for variables relating to the economic sustainability dimension.

The SIAH CSF framework comprises of 127 CSFs clustered into housing design, elements, production methods, and technology. Each cluster was subsequently further sub-categorized into the three components of sustainability (economic, environment, and social), with the technical aspect added as a fourth sub-category. See Moghayedi et al. (2021) for more on the SIAH framework.

Accordingly, it is expected that the use of the SIAH index for this study will enable the determination of the IPCM variant with the highest sustainability performance score within the sustainable affordable housing context.

3. Research methodology

The study draws significantly from a postpositivist philosophical stance in the articulation of an appropriate research methodology. Accordingly, data was collected and analysed using quantitative methods. In furtherance to this, the study adopted a quasi-experiment research design to accurately analyse the performance of various innovative prefabricated methods through modelling energy and validating the results through experiment a case study with the individual innovative prefabrication construction method variants serving as cases to provide a high level of evidence without randomisation. Furthermore, it developed logical analyses to build formal explanatory concepts for quantifying the sustainability index of these innovative prefabricated construction method variants and compare them with a brick house as a baseline conventional construction method for affordable housing projects in Southern Africa using South Africa as an exemplar.

The most commonly used Agrément accredited prefabricated construction methods for housing projects and their technical characteristics were used as case studies in this study. Agrément is an internationally trusted certification body which is responsible for regulating the use of innovative building materials and modern methods of construction across 72 countries globally. Agrément's mandate is to support and promote the creation of a truly sustainable world-class built environment by introducing and applying technological innovations which embed sustainability principles. The Agrément certificate is an internationally accredited product and system certificate scheme which enables manufacturers of products used in the construction industry to demonstrate a product's fitness for purpose. The Agrément certificate is a mark of excellence based on rigorous international standards that validate an innovative building and construction product specialist formulation, capability, and uniqueness (Agrément BBA, 2023).

Also, the cradle to grave lifecycle energy and cost of the selected commonly used prefabricated methods were modelled using EDGE App, SimaPro. Excellence in Design for Greater Efficiencies (EDGE) is developed by International Finance Corporation (IFC), a member of the World Bank Group to respond to the need for a measurable and credible solution to prove the business case for building green. EDGE is a green building standard and an international green building certification system. EDGE considers aspects such as the climatic conditions of the location of the building, the type of building and its occupants, and the design and specifications. In addition, EDGE incorporates embodied energy data attained internationally; the predominant source is a report conducted by "Think step" for EDGE. The study also collected the actual data such as temperatures inside and outside the buildings in summer and winter, the level of humidity and infrared thermograms from the houses built with the selected systems. The research protocol adopted for this study is presented in Fig. 1 below.

3.1. Design and details of typical affordable housing

For the purposes of the current study, one of the most common affordable housing designs in the Southern Africa included 2 bedrooms, a toilet and bathroom was used as input for evaluating the sustainability performance of selected prefabricated construction methods (case studies) in EDGE. Fig. 2 illustrates the selected typical single-storey two bedrooms detached house as one of the most common affordable housing designs in the Southern Africa particularly in Africa. It was observed that this basic design best represented the collection of a common layout and size available on the affordable housing market in the Southern Africa.

The study does not focus specifically on the case study design but

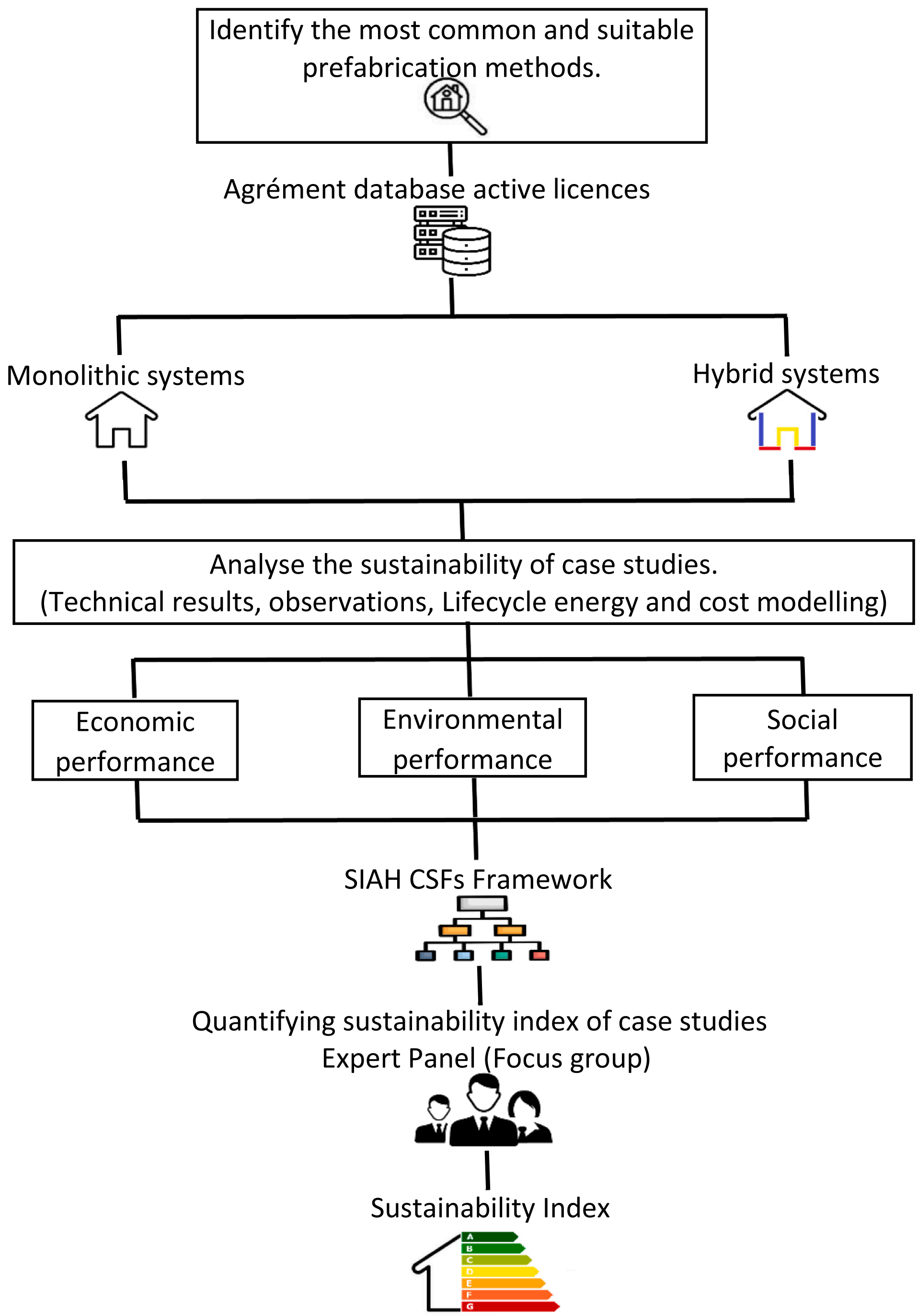

Fig. 1. Research protocol for the study.

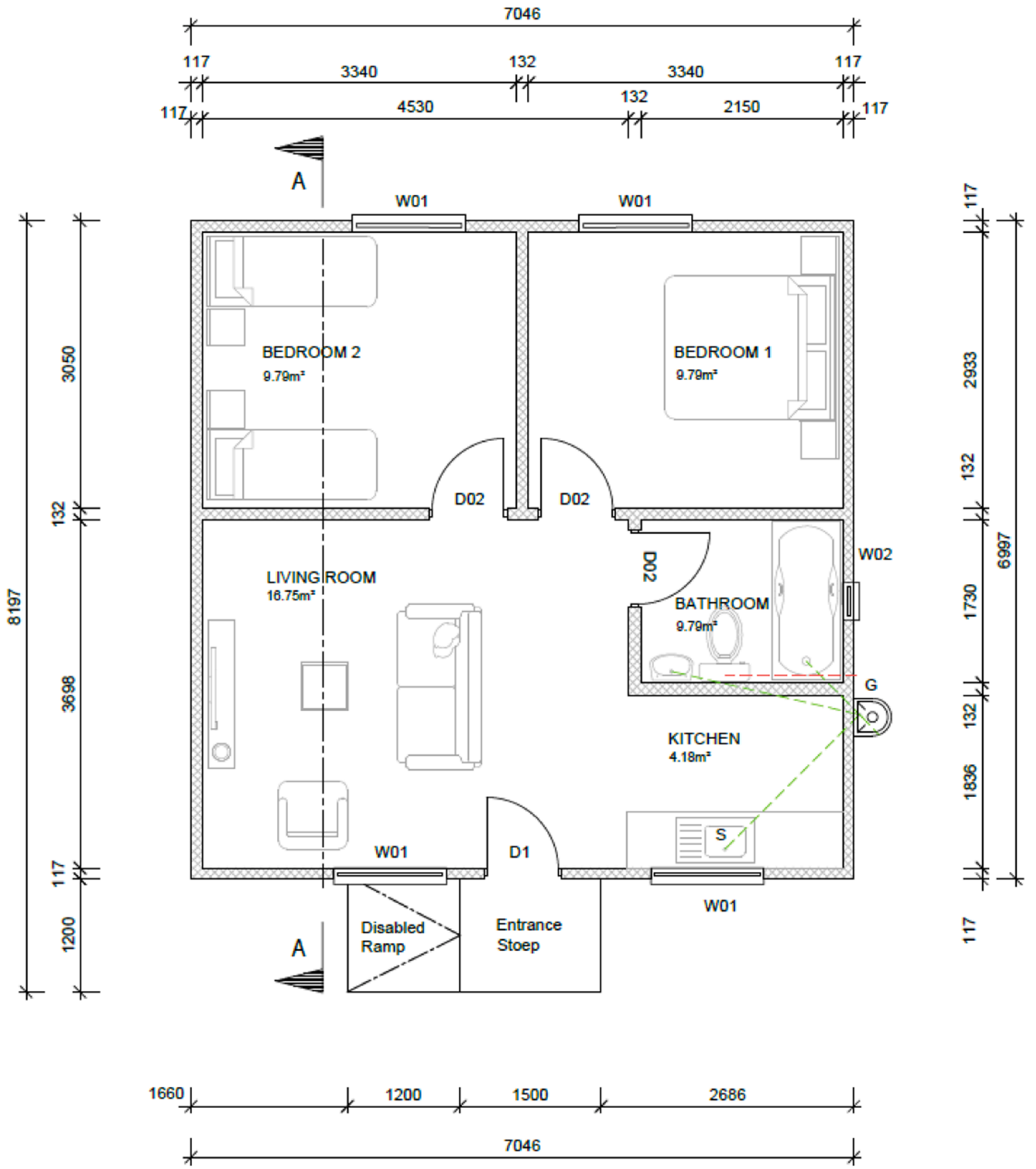

Fig. 2. Layout of a typical affordable house in Southern Africa *(all dimensions are in mm)*.
Note: Gross floor area: 50 m^2, Gross internal area: 48.7 m^2, Foundation: Raft, Roof: Gable with 12.6° pitched angle.

used it as input to evaluate the impact of different prefabricated construction methods on a house's sustainability performance during its lifespan (considered as 50 years in this instance).

3.2. *Description/specification of cases*

3.2.1. *Baseline study: conventional brick and mortar*

The most conventional materials used to construct affordable housing across the Southern Africa are clay kiln-fired bricks and cement mortar for load-bearing wall systems and corrugated steel sheeting on wood trusses for the roof system.

3.2.2. Case study 1: monolithic system, prefabricated expanded polystyrene structural insulated panel (EPS-SIP)

This system can be used for the entire house. These prefabricated panels consist of a 50 mm Expanded Polystyrene core of density 16 kg/m^3, encapsulated by 0.50 mm Zinc-Aluminium sheets with 50 mm glass wool cavity batt insulation of density 14 kg/m^3, 15 mm firestop board on either side and 2 coats of water-based acrylic paint. The overall thickness of the panel is 117 mm, as shown in Fig. 3.

3.2.3. Case study 2: monolithic system, prefabricated cross-laminated timber (CLT)

The prefabricated cross-laminated timber (CLT) consists of three, five, or seven layers of dimensional timber oriented at right angles to one another and then glued to form structural panels with exceptional strength, dimensional stability, and rigidity as shown in Fig. 4. In housing projects, usually 7 layers are used as exterior walls while five layers are used as roof or slab and another three layers used for internal partitioning. CLT panels can be used as a finished surface or covered with other materials.

3.2.4. Case study 3: hybrid system, prefabricated light steel frame (LSF)

This hybrid MMC provides walling and light steel trusses for roofing manufactured from cold rolled galvanised sheet metal 'C' sections. Wall panels are lined internally with a 15 mm thick gypsum firestop board, a lad with 15 mm of oriented strand board and a 9 mm fibre cement board. Cores of wall panels are filled using insulation foam as shown in Fig. 5. The light roof trusses steel covered with insulation and lightweight roofing coverings.

3.2.5. Case study 4: hybrid system, prefabricated autoclaved aerated concrete panel (AACP)

This system provides prefabricated load-bearing panels that can be used for two-storey buildings. Panels consist of two 4.5 mm thick fibre cement boards fixed 66 mm apart that filled with polystyrene beaded concrete mix with a density of 650 kg/m^3 as illustrated in Fig. 6. Panels are joined together using a tongued mould slotted into the panels. A light gauge structural steel roof trusses with lightweight roof cladding is used for roofing.

3.2.6. Case study 5: hybrid system, prefabricated structurally insulated panel (SIP)

The panels in this system are manufactured from 0.5 mm thick Z expanded metal sheets, reinforced with 10 mm bars horizontally at 200 mm spacing. The metal sheets are encapsulated with reinforcing mesh on both sides. 5 mm fibre cement boards are covered both sides if the metal sheets. The cavity is filled with cement mortar as shown in Fig. 7.

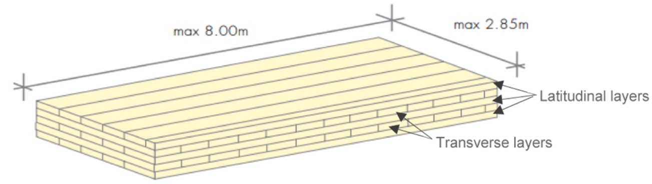

Fig. 4. CLT details.
Source: Local manufacturer.

3.2.7. Case study 6: hybrid system, prefabricated insulated recycled wood panel (IRWP)

This MMC provides lightweight structural panel comprised mineralised wood chips combined chemically by pozzolanic reaction with lime cement that is structurally reinforced with two expanded metal lighting meshes. Panels are capsulated with 5 mm thick fibre cement board as shown in Fig. 8. The panels are connected to each other using Z-shape steel dry joints. The wooden trusses and lightweight steel sheet are used for roofing.

Since a common design was used for developing these case studies, only the critical success factors associated with the elements and production methods cluster identified in Moghayedi et al. (2021) were used. The SIAH CSFs framework assesses entire affordable housing, the rating framework was adjusted for relevance to cater to the current research on evaluating the sustainability performance of selected prefabricated construction methods only. The assessment did not consider other aspects and building elements across the case studies, such as design or foundation. The adjusted SIAH CSFs framework with appropriate sustainability indicators under method and element was conceptualised as an index for assessing the sustainability performance of these innovative prefabricated construction method variants serving as case studies (Table 1).

The reliability and accuracy of results was dependent on the expertise and experience of the panel. According to Stewart and Shamdasani (2014), the focus experts' groups typically consist of between six and ten experts as the optimum size for focus group discussion. To ensure the reliability of data, the upper bound limit is recommended considered. Therefore, a total of ten highly experts in housing were recruited for this research.

Due to the interdisciplinary nature of this research, these experts were selected carefully from different disciplines as well as cultural and geographical locations. These parameters were therefore followed when assembling the expert panel. The detailed specifications and

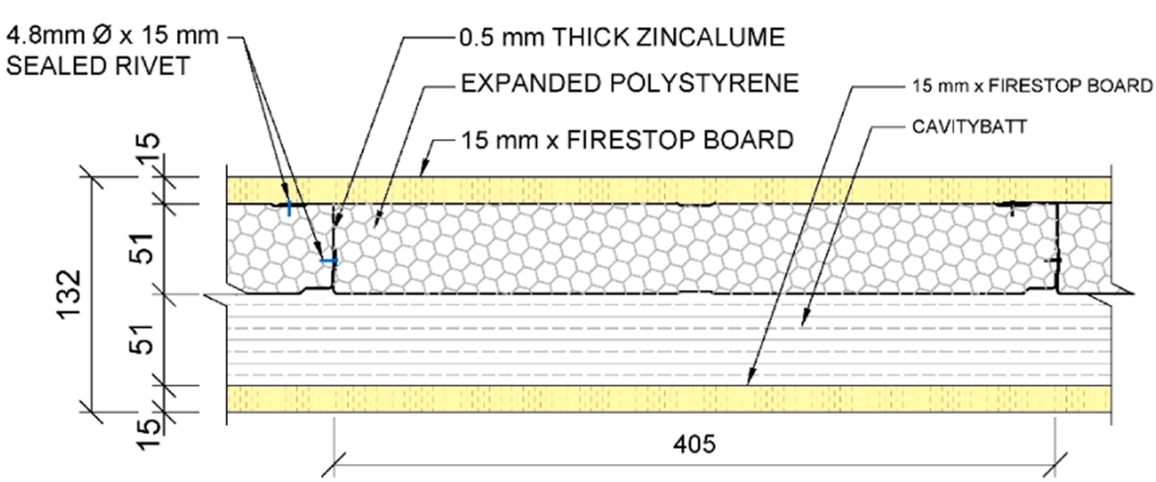

Fig. 3. EPS-SIP details (all dimensions are in mm).
Source: Agrément.

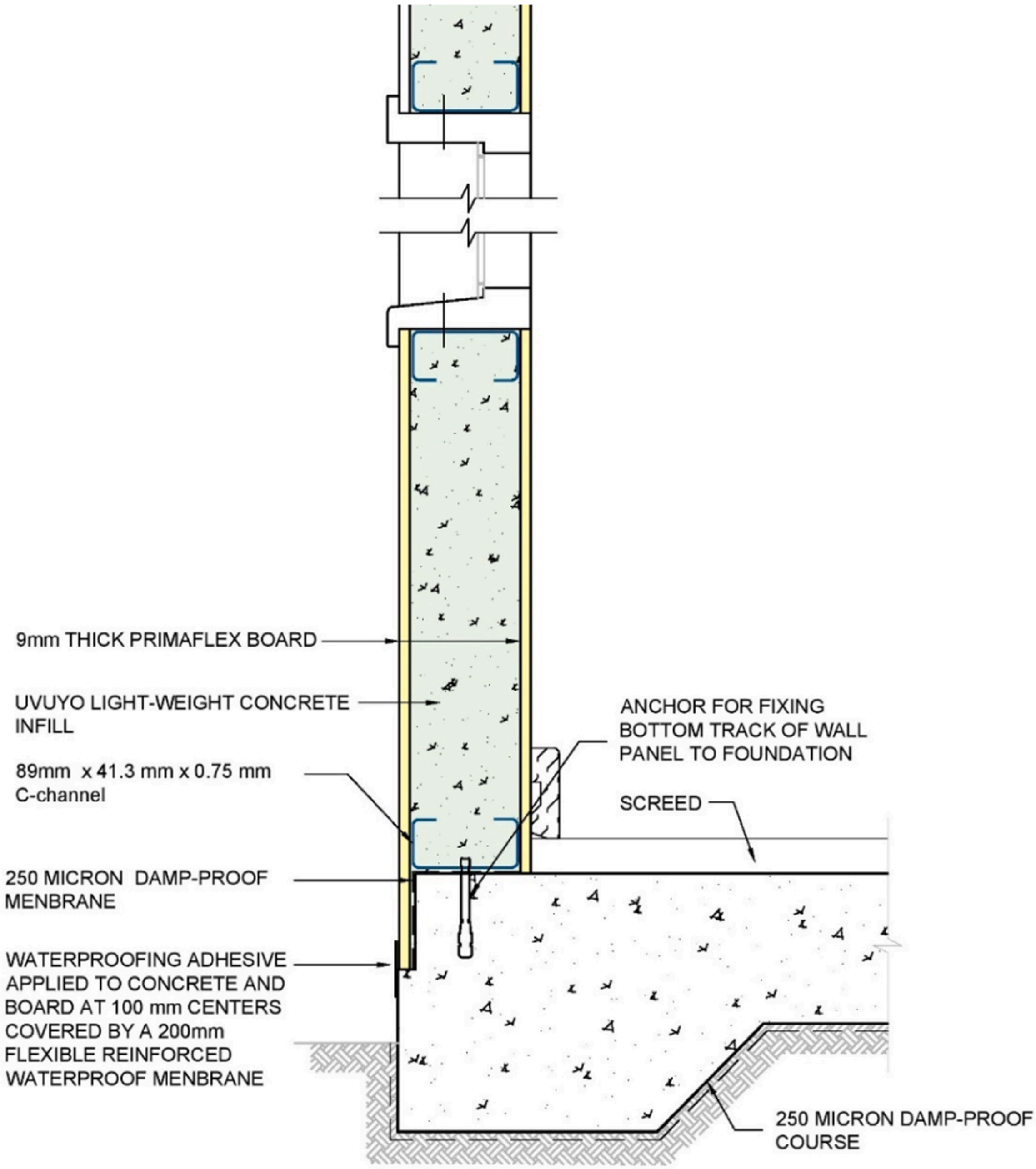

Fig. 5. LSF details *(all dimensions are in mm)*.
Source: Agrément.

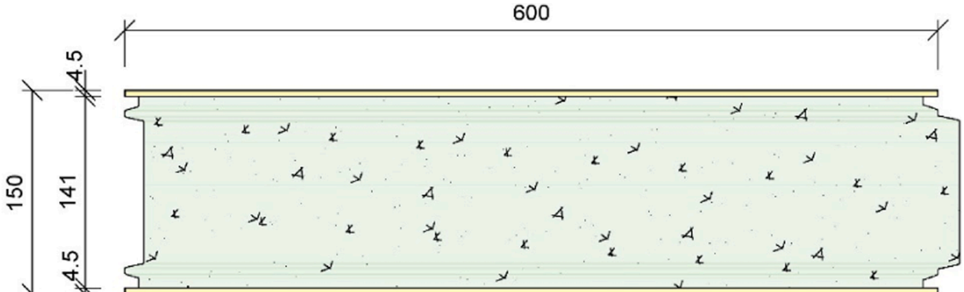

Fig. 6. AACP details *(all dimensions are in mm)*.
Source: Agrément.

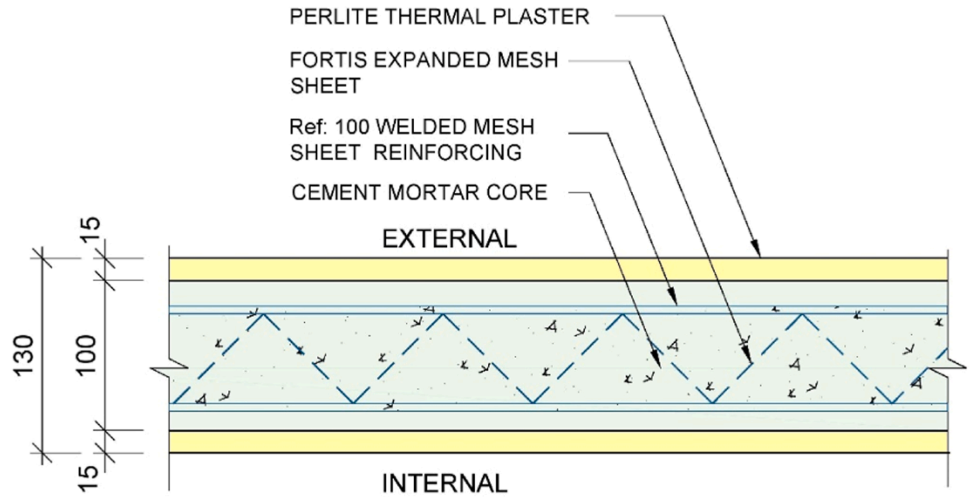

Fig. 7. SIP details *(all dimensions are in mm)*.
Source: Agrément.

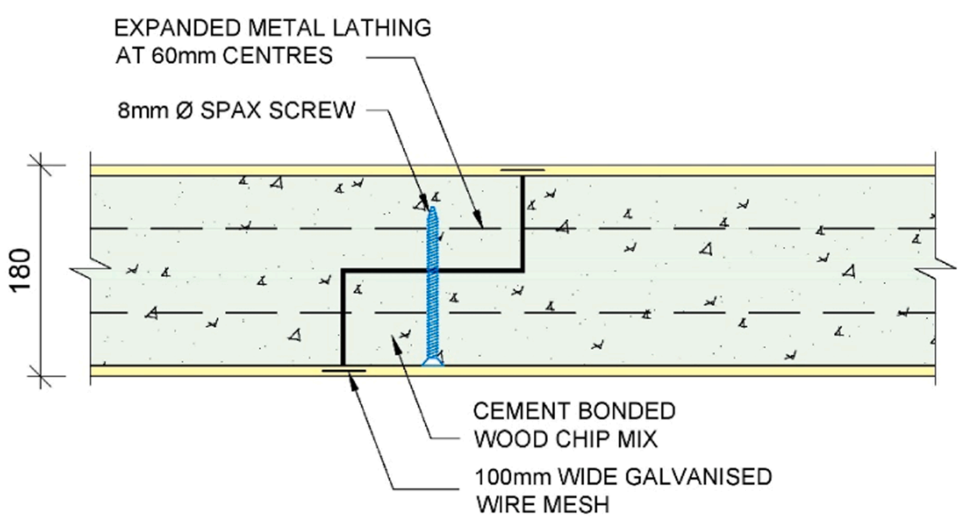

Fig. 8. IRWP details *(all dimensions are in mm)*.
Source: Agrément.

performance of the baseline case as well as the six case studies were presented to this cohort of 10 housing experts who had experience working in affordable housing schemes situated within the Southern Africa. These experts quantified the sustainability performance of the cases based on the actual data on a scale of 1–5 in a virtual focus group discussion session. Subsequently, the authors converted the collected scales from ten experts into a weighting-based using the Interquartile range formula. The weight of CSFs for each case study were then reviewed and agreed upon by all ten experts participating in this study.

The details of the selected panel are summarized in Table 2.

Finally, the consensus weights of the CSFs were used to calculate the total sustainability index of the case studies using Eq. (1).

$$Sustainability\ Index = \frac{\sum_1^n EC_n + \sum_1^n EN_n + \sum_1^n SO_n}{N \times 5} \quad (1)$$

Where EC: Economic CSF, EN: Environment CSF, SO: Social CSF, N: total number of CSFs

4. Results

4.1. Technical details, modelling, and observation results

The technical specifications of six most commonly used pre-fabricated methods in affordable housing projects in Southern Africa, serving as case studies were extracted from the Agrément certificate and cross checked with conventional brick-and-mortar system as shown in Table 3.

Consequently, each case study was modelled on the EDGE app and SimaPro based on the local climatic condition of Pretoria, South Africa and their embodied, operational and lifecycle energy of baseline and case studies were evaluated and listed in Table 4.

As listed in Table 4, all IPCMs contained lower embodied energy compared to conventional method due to the use of less materials with almost no wastages highlighted. The highest reduction of embodied energy belonged to CLT (73.7%) and EPS-SIP (50.2%). IPCMs save a significant amount of operational energy and provide better thermal performance due to the well-insulated materials (>*R*-value) used in these systems. The EPS-SIP and IRWP possessed the potential of reducing operational energy of house to 39.1% and 36.8% respectively.

Table 1
Adjusted SIAH CSFs framework.

Economic	Environment	Social
➢ Local value creation (EC1) ➢ The economy of scale mass production (EC2) ➢ Lifecycle cost (EC3) ➢ Material cost (EC4) ➢ Transport cost (EC5) ➢ Construction/ assembly cost (EC6) ➢ Operational/ maintenance cost (EC7) ➢ Demolition/ recycling cost (EC8) ➢ Construction duration (EC9) ➢ Compatibility with other methods (EC10) ➢ Durability (EC11) ➢ Airtightness (EC12) ➢ Water tightness (EC13) ➢ Thermal conductivity (EC14) ➢ Prefabrication degree (EC15) ➢ Required equipment/ tools (EC16)	➢ Water efficient (EN1) ➢ Energy efficient/ thermal (EN2) ➢ Using natural and local materials (EN3) ➢ Using recycled materials (EN4) ➢ Recycling and deconstruction ability (circular economy) (EN5) ➢ Waste efficient (lean construction) (EN6) ➢ Nontoxic (EN7) ➢ Lifecycle energy (EN8) ➢ Lifecycle GHG (EN9) ➢ Fire resistance (EN10)	➢ Social acceptance (SO1) ➢ Aesthetics (SO2) ➢ Local job creation (SO3) ➢ Compatible with local culture (SO4) ➢ Security (SO5) ➢ Skill requirement (SO6) ➢ Ease of construction (SO7) ➢ Acoustics (SO8) ➢ Expandability (SO9) ➢ Designability (SO10)

Table 2
Expert panel demographics.

Expert	Experience Year	Geographical location	Professional background
Expert 1	15	Europe	Construction project management
Expert 2	17	Middle East & Northern Africa	Sustainable design architecture
Expert 3	16	North America	Bio-architecture
Expert 4	20	South America	Public health in the built environment
Expert 5	19	Australia	Civil Engineering
Expert 6	15	Sub-Sahara Africa	Housing Policymaker
Expert 7	21	Central Asia	Urban/town planning
Expert 8	17	East Asia	Environmental science
Expert 9	20	Europe	Socio-technical innovations
Expert 10	22	Southeast Asia	Quantity Surveyor

Source: Authors' compilation (2023).

Overall, the prefabricated systems reduced the lifecycle energy of a house from 18.7% to 45.4%. The monolithic CLT and EPS-SIP reduced lifecycle energy of houses 45.5% and 44% respectively as shown in Table 4. Furthermore, the lifecycle cost (cradle-to-grave) of the baseline and six case studies was estimated using SimaPro software, and the results are presented in Table 5. For developing the lifecycle costs, the AECOM building materials database (2023) and local MMCs manufacturing price lists were utilized.

Since the prefabricated construction methods are still nascent within the affordable housing sector in Southern Africa, the construction and maintenance cost of these systems are expected to be slightly higher than the conventional construction system as shown in Table 5. However, due to massive energy saving during the projected 50-year life span of the house, the lifecycle cost of prefabricated houses ends up being lower than the conventional brick and mortar house except in the case of LSF.

Furthermore, the actual performance of the baseline and each prefabricated case study including differences in temperature during winter nights and summer days and level of humidity in winter in houses were observed, and the results of observations are summarised in Table 6.

As listed in Table 5, monolithic prefabricated systems had the highest difference in temperature on both winter nights (5 °C outside) and summer days (35 °C outside). Similarly, these systems had lower level of humidity in winter compared to other prefabricated systems and particularly, when compared to conventional system (42%).

Finally, the thermal performance of different systems was assessed using FLIR TG267 (accuracy of ±1.5 °C) infra-red camera on a summer day while the outside temperature was 32 °C. The infrared images of different systems are shown in Fig. 9.

As shown in the infrared images above (Fig. 9.a), the conventional system has the lowest thermal performance due to the low R-Value, lack of insulation and many thermal bridges, between walls and roof and openings. This perfectly justifies the lowest difference in temperature of inside and outside of the house in both winter and summer as listed in Table 4.

As shown in Fig. 9.b and c, both monolithic systems provide for better thermal performance, and there is no thermal bridge between the wall and roof since it uses the same prefabricated panel and materials for both wall and roof. The EPS-SIP panel was able to keep the same temperature inside the house regardless of the outside temperature in winter or summer (maximum temperature difference between inside and outside in both summer and winter), because of its better R-value, double insulation, and ideal airtightness. However due to not adopting double glazed windows still the house losing temperature through the windows as the infrared thermograms show the windows temperature with red, compared to panel with blue. On the other hand, the infrared images of hybrid systems illustrated a significant thermal bridge (different colour between wall and roof illustrates different temperature) between wall and roofing (See Fig. 9d–g). Regardless of the R-value

Table 3
Technical specifications and details.

Specification	Baseline Bricks and mortar	Case 1 EPS-SIP	Case 2 CLT	Case 3 LSF	Case 4 AACP	Case 5 SIP	Case 6 IRWP
Size of panel $L \times W \times H$ (m)	N/A	1.6 × 0.12 × 2.4	4 × 0.15 × 2.85	1.5 × 0.2 × 2.5	0.6 × 0.15 × 2.7	1.1 × 0.1 × 2.5	1.2 × 0.2 × 2.2
Density (kg/m^3)	1400	95	480	450	400	270	200
Compressive strength (MPa)	5	10	7	11	6	8	6
Thermal R-value (m^2 k/W)	0.75	2.30	1.25	0.95	1.11	1.42	2.2
Fire resistance (Mins)	180	60	60	30	120	60	60
Acoustic performance (dB)	40	48	49	52	44	43	49
Construction duration (day)	45	10	10	16	10	10	14
Ease of construction	Hard	Easy	Easy	Hard	Intermediate	Intermediate	Intermediate

Source: Agrément.

Table 4
Lifecycle energy assessment.

Energy specification	Baseline Bricks and mortar	Case 1 EPS-SIP	Case 2 CLT	Case 3 LSF	Case 4 AACP	Case 5 SIP	Case 6 IRWP
Embodied energy (GJ)	327.6	163	86.1	230.6	265.7	273.5	240.1
Embodied energy reduction	0%	50.2%	73.7%	2.1%	18.9%	16.5%	26.7%
Operational energy (kWh/year)	2356.8	1435.4	1800.8	2095.6	1918.9	1688.5	1490.6
Operational energy reduction	0%	39.1%	23.6%	11.1%	18.6%	28.4%	36.8%
Lifecycle energy (GJ/50 years)	751.8	421.4	410.2	607.8	611.1	577.4	508.4
Lifecycle energy reduction	0%	44.0%	45.4%	19.2%	18.7%	23.2%	32.4%

Source: Modelling in EDGE app and SimaPro.

Table 5
Lifecycle cost assessment.

Cost specification	Baseline Bricks and mortar	Case 1 EPS-SIP	Case 2 CLT	Case 3 LSF	Case 4 AACP	Case 5 SIP	Case 6 IRWP
Construction cost	£10,500	£11,434	£12,316	£12,778	£11,812	£11,466	£11,980
Incremental construction cost	0	8.9%	17.3%	21.7%	12.5%	9.2%	14.1%
Maintenance cost	£1155.00	£1715.10	£1970.56	£1661.14	£1771.80	£1490.58	£1557.40
Operational cost per year	£326.4	£198.8	£249.4	£290.2	£265.8	£233.9	£206.4
Lifecycle cost	£27,975.8	£23,089.3	£26,757.1	£28,951.2	£26,872.2	£24,649.4	£23,859.8
Lifecycle cost reduction	0%	17%	4%	−3%	4%	12%	15%

Source: AECOM and local manufacturers.

Table 6
Thermal and humidity of actual houses.

Description	Baseline Bricks and mortar	Case 1 EPS-SIP	Case 2 CLT	Case 3 LSF	Case 4 AACP	Case 5 SIP	Case 6 IRWP
Temperatures difference in winter	8 °C	13 °C	10 °C	9 °C	10 °C	11 °C	12 °C
Temperature difference in summer	7 °C	17 °C	9 °C	7 °C	11 °C	12 °C	15 °C
Level of humidity in winter	42%	20%	31%	39%	30%	27%	24%

Source: Authors' observations.

of panels because of poor airtightness of hybrid systems, houses are not able to maintain desirable temperature inside during cold or hot days.

4.2. Quantifying sustainability performance and index

The technical details, modelling, and observation results of baseline and six case studies were used by the group of experts to quantify the sustainability performance and overall sustainability index of each system. The results are presented in Figs. 10–13.

The overall sustainability performance of brick houses is low, particularly with regards to the environmental aspects as illustrated in Fig. 10.a. The sustainability index calculated for the brick house is 45.56.

The sustainability of EPS-SIP monolithic systems is considerably high, as shown in Fig. 10.b. Only 5 CSFs ranked 3 out of 5 while other CSFs were ranked 4 or 5 out of 5. Overall, the sustainability index of this system was 86.67, which is almost double the index achieved for the conventional

Due to the natural material used in this monolithic prefabricated system, the environmental sustainability and overall sustainability index of the system was very high averaging 81.67. However, due to high material cost and lack of social acceptance of CLT among local communities because of unfamiliarity with CLT and incompatible with local culture, this system does not consider the main alternative material and system to replace the conventional building methods in the Southern Africa (See Fig. 11a).

The LSF system received a 57.22 sustainability index, which is slightly above the conventional brick-and-mortar system. The high lifecycle cost and low thermal performance of systems are the main reason for low sustainability index of LSF as shown in Fig. 11a and b.

The sustainability index of this system is 68.89, which is noticeably higher than the standard brick house. However, due to the use of cementitious materials, the environmental sustainability score for this system was low, as shown in Fig. 12a.

Like cement panels, the use of cementitious and steel materials resulted in low environmental sustainability score for this system, hence impacting on the overall sustainability index of the system which amounted to 63.33. The system has a better sustainability index compared to the brick house, but compared to other similar panels that are manufactured by more carbon-neutral or recycled materials, the sustainability index was much lower. See Fig. 12b.

Since these systems contain recycled materials, the environmental sustainability performance and overall sustainability index of the system 74.44 was much higher than the brick house or similar hybrid prefabricated construction methods. See Fig. 13.

5. Discussion

The main objective of this study was to evaluate the sustainability performance of various prefabricated construction methods deployed to affordable housing projects. Also, the study sought to quantify the sustainability index scores of these prefabricated construction methods in Southern Africa and to compare these with the scores of the brick-and-mortar conventional building method which is mostly used in affordable housing projects. The results accruing from the analyses and observations proved that the overall sustainability performance of the conventional building method was way lesser than the prefabricated construction methods. Also, it was discovered that the popularity of conventional methods in the Southern Africa might be due to the relative ease of supply for brick and mortar as well as the high availability of

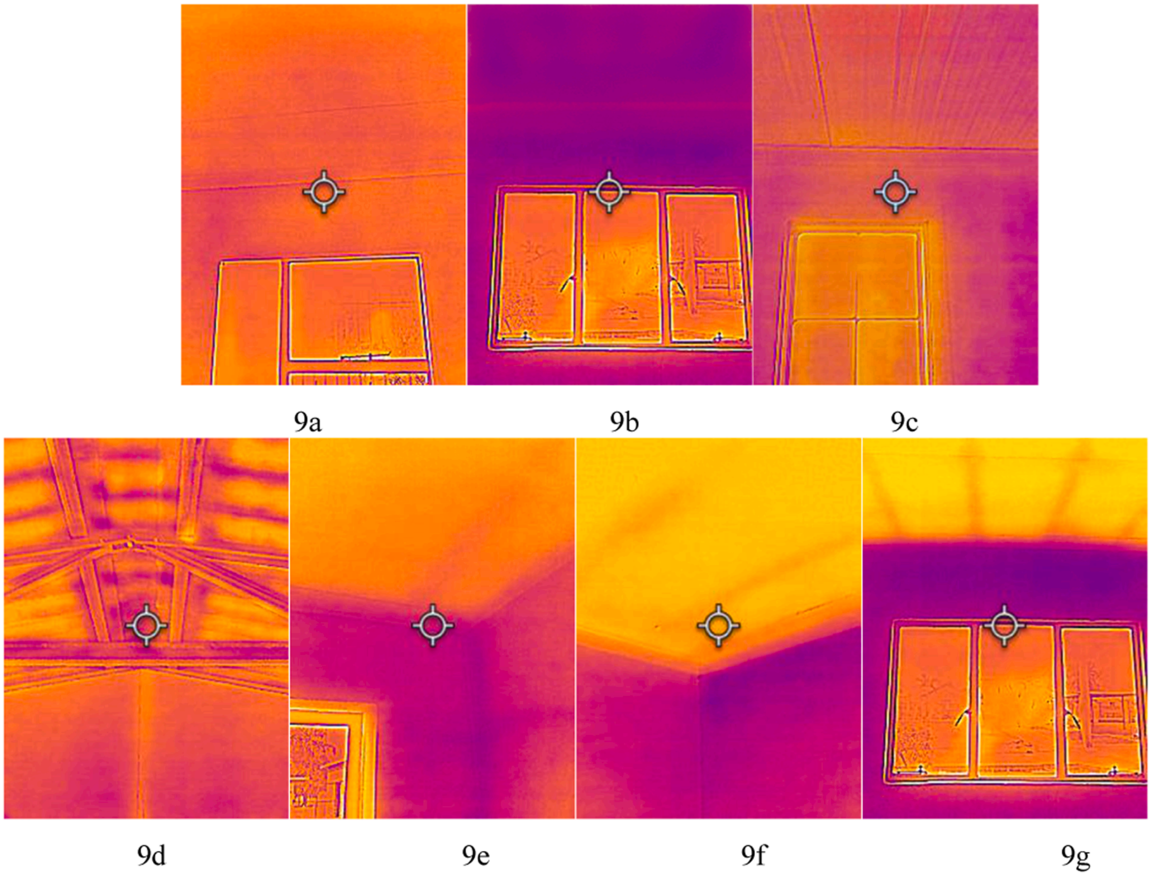

Fig. 9. Infra-red thermograms of a. Conventional brick & mortar, b. EPS-SIP, c. CLT, d. LSF e. AACP, f. SIP g. IRWP.

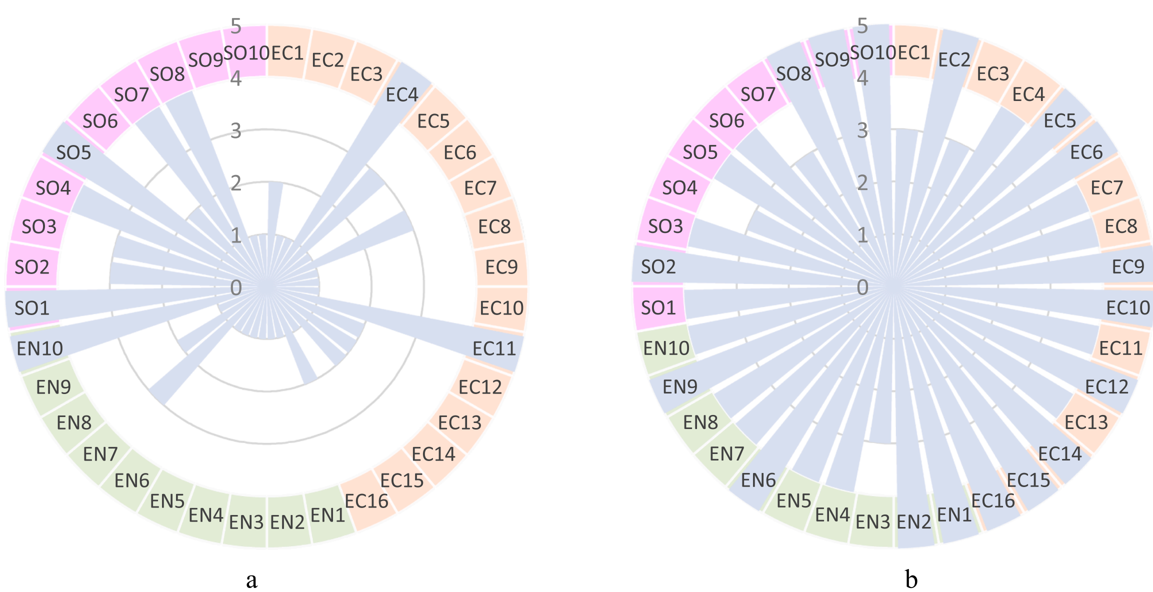

Fig. 10. Sustainability performance of a. Conventional brick & mortar; b. EPS-SIP.

labour as these conventional methods have been described as labour-intensive (Windapo et al., 2021).Various prefabricated construction method variants had been tested and certified with different regulatory bodies, such as Agrément, for use in Southern Africa. This study's results confirmed previously held belief that the sustainability index score of these variants was significantly higher than that of the conventional method of construction. While the index scores were higher than brick and mortar, the technical and sustainability aspect are varied. However, they are still not the dominant methods in affordable housing projects. This is mainly because of a lack of a proper framework and appropriate tool for evaluating the sustainability performance of construction methods and materials. So, a systematic framework such as SIAH CSFs is required to evaluate the suitability of innovative prefabricated construction methods for specific affordable housing projects and location

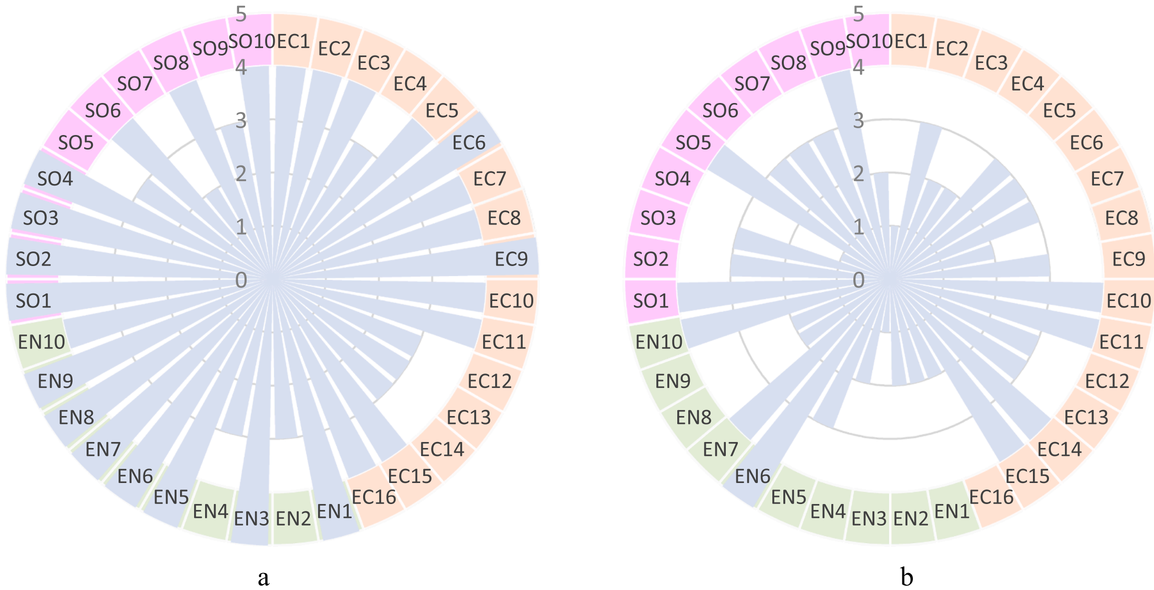

Fig. 11. Sustainability performance of a. CLT; b. LSF.

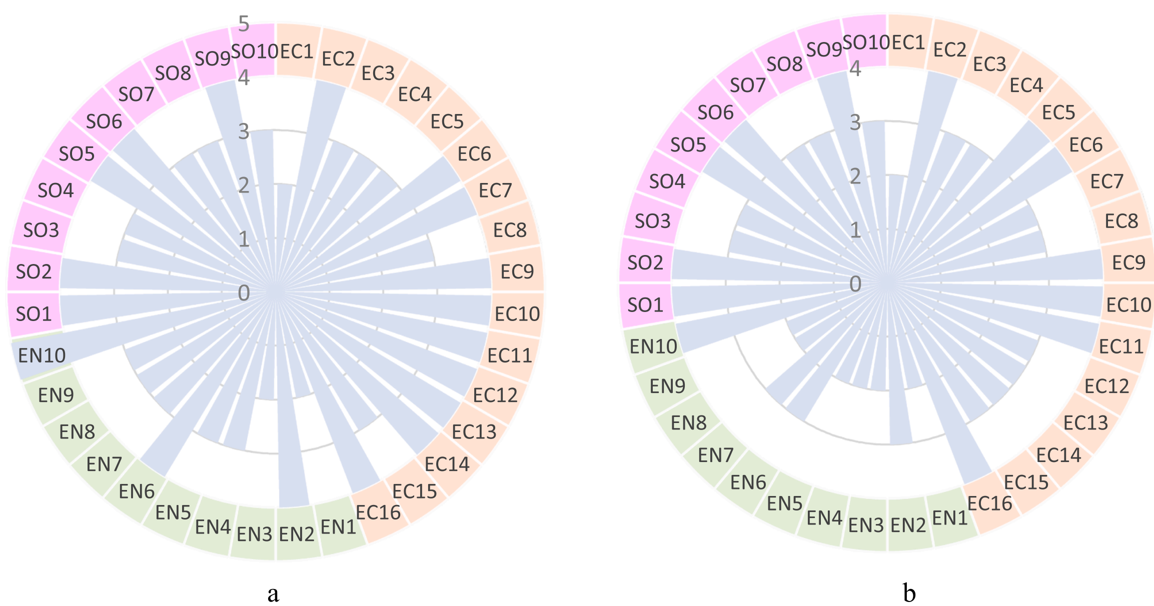

Fig. 12. Sustainability performance of a. AACP; b. SIP.

to achieve the project goals. Also, the tendency for affordable housing stakeholders to select methods based on construction cost and availability on the local market has contributed to the low usage of these variants despite their proclivity to delivering high levels of sustainability performance. This finding is in line with the conclusions reached by Moghayedi and Windapo (2018), wherein they observed that in the absence of a proper sustainability index, inappropriate construction methods and materials could be selected for projects, thereby posting a negative impact on the project, residents, and the environment.

5.1. *Economic sustainability*

While the construction cost of prefabricated methods remains slightly higher than conventional methods due to the inherent inability to manufacture them at scale. However, given that housing projects can be delivered over a much shorter time frame with lesser operational cost, the lifecycle costs of houses constructed using prefabricated construction methods remains significantly less than the conventionally constructed houses. Moreover, these innovative prefabricated construction methods were found to have a positive effect on residents and society posting better indoor air quality and thermal performance with lesser environmental impact. These findings align with the results from another study by van Oorschot et al., (2021).

A comparison of the economic sustainability performance of conventional and prefabricated construction methods revealed that the significant differences were observed in “economic opportunities” and “skills development training”. Although the conventional construction method required more workers on site, most of them were unskilled, holding jobs temporarily with low job security and safety, which is not a sustainable job definition. On the other hand, the prefabricated methods provided more sustainable jobs with opportunities for reskilling and upskilling construction workers. Therefore, this method of construction provided for more sustainable jobs in a safer and more secure off-site construction site. These findings are in sync with the findings posted

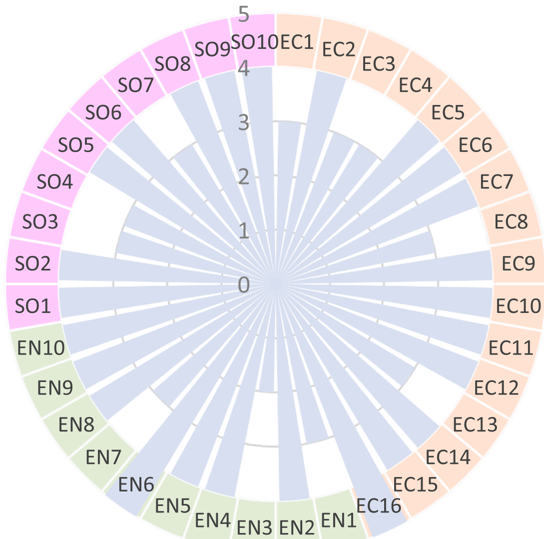

Fig. 13. Sustainability performance of IRWP.

by Windapo et al. (2021), wherein the scholars stated that measures should be taken to empower unskilled workers by providing them with training opportunities to enhance their employability.

5.2. Social sustainability

The analysis of social and economic sustainability performances of these construction methods also showed that the performance of conventional construction methods was extremely lower when compared to the prefabrication construction methods because of the dependency of conventional construction methods on unskilled labours for labour-intensive jobs. This has been adduced as the prime reason for the prevalence of most housing issues in the Global South ranging from poor quality and low productivity to high accident rates (Jain & Bhandari, 2022).

5.3. Environmental sustainability

The outcomes of the sustainability index calculation for prefabrication construction methods variants indicated that the monolithic prefabricated systems performed better than the hybrid prefabricated systems in all considered aspects. Furthermore, the results also proved the higher sustainability performance of prefabricated construction method variants that consisted of natural and local materials like CLT thereby making it apt for net zero emission buildings and improving circular economy performance therein.

Furthermore, the sustainability performance analysis revealed that the conventional building method and some prefabricated construction methods using cementitious materials had a much lower environmental sustainability performance level. This was due to their high degree of dependence on cementitious materials which has been flagged as a primary source of carbon dioxide (CO_2) emission whilst playing host to a large amount of embodied energy. This is in alignment with the finding of Lippiatt et al. (2020) who maintained that 8 and 37% of global and construction industry CO_2 emissions are related to cement and concrete. Therefore, these methods won't be considered as sufficient alternative methods for housing because they are not aligned with the 2030 net-zero emission targets. Alternatively, prefabrication methods have a higher environmental sustainability performance level due to the low level of embodied energy and carbon associated with the manufacturing process as well as faster and easier construction and operation processes.

Summarily, while the prefabricated systems, particularly the monolithic ones, are the predominant methods of constructing affordable housing in the Global North they remain relatively new in Housing projects within the Southern Africa and are not considered as the primary method for building housing projects. The study found that due to the limited affordable housing budget and subsidies available in the Southern Africa, the level of adaptation of innovative green building materials and elements, such as local-natural materials, biodegradable insulations, and double-glazed windows, facets which are considered supportive of cleaner production, remained minimal. This shortcoming significantly impacted on the efficiency and sustainability performance of affordable housing as the results of study show evidence of energy loss through conventional building elements and single glass windows due to poor thermal insulation.

6. Conclusions

This study contributes to the emerging discourse on fostering sustainability principles and practices in the delivery and operation of affordable housing projects in Southern Africa as a veritable means of improving their circularity performance and aligning with 2030 net zero emission targets. It achieved this objective by examining and quantifying the sustainability of various building methods using the SIAH framework as a comprehensive tool for quantifying the sustainability index. It determined the sustainability performance of conventional and various prefabricated construction methods utilised in affordable housing projects in Southern Africa. Its findings accentuate the relevance of continuous and consistent innovation adoption during sustainable affordable housing development to resolve the sustainability-related challenges associated with such activity.

The study's results proved that prefabricated construction methods recorded high levels of sustainability performance when compared to the brick-and-mortar conventional construction method which is mostly used on affordable housing projects. Furthermore, the results revealed that the performance of conventional construction methods in economic, social, and environmental aspects were significantly low and unsustainable. Therefore, it can be concluded that the continued use of conventional construction methods in affordable housing projects would not address sustainability-related issues bedevilling affordable housing in Southern Africa. Therefore, housing stakeholders should advisedly, utilise sustainable construction methods such as prefabrication, particularly the monolithic system and other prefabricated construction methods, which comprise of a significant proportion of local and natural materials, thereby allowing for better insulation levels when delivering affordable housing projects in the region.

Also, the study recommends that affordable housing stakeholders should utilise the developed sustainability performance and index to evaluate and determine the most optimum sustainable method. The developed sustainability tool based on the SIAH framework could be used as a systematic method that quantifies the sustainability performance of various methods across Southern Africa. This approach will promote utilising innovative sustainable construction methods such as prefabrication in affordable housing projects and, consequently, the emergence of more innovative methods and manufacturers of these methods on the local market, which will result in reducing the cost through mass production and competitive pricing. Also, it recommends that policymakers and financial organizations involved in affordable housing projects can use the sustainability index as a mechanism to allocate financial and other incentives to housing projects with a higher sustainability index to encourage affordable housing designers and developers to utilise more sustainable building methods such as prefabrication.

The study's results indicate that a multifaceted approach is crucial in promoting the deployment of prefabrication construction methods for affordable housing delivery in Southern Africa. Governments in the region should offer financial incentives and implement policies that encourage the adoption of these systems. Furthermore, investing in research and development tailored to local contexts and supporting capacity building and training for designers and developers will facilitate wider adoption. Collaboration between the public and private sectors, along with non-governmental organizations, can drive knowledge-sharing and funding opportunities. Encouraging the utilization of locally sourced materials, establishing industry standards, and promoting public-private partnerships will collectively enhance the feasibility and acceptance of prefabrication in affordable housing projects, leading to more sustainable and efficient construction solutions in Southern Africa.

This study is one of the pioneer studies in the built environment that used a quasi-experiment research design to accurately assess the social, environmental, economic, and technical aspects of IPCMs considering various modelling techniques, observations and experts' evaluation without randomisations. The current study provides a foundation for further studies seeking to evaluate the sustainability performance of a plethora of modern construction methods, such as 3D printing, modular, pod construction etc. and draw comparisons of their sustainability index scores. In addition, future studies should also consider measuring the sustainability performance of various affordable housing facets, including the design, materials, construction methods, building technologies and operations in the Southern Africa. Such studies should seek to articulate a more distinct comparison between the sustainability performance of different affordable housing typologies such as low-rise vs high-rise, etc. Also, further studies could be used to validate this study's results through actual testing of the prefabricated construction methods using controlled experiments. This research constitutes an essential input for affordable housing stakeholders and researchers to better understand how to evaluate the sustainability of different building materials and methods to not only keep up with the Net Zero targets (2030 and 2050) but enabling cleaner production to significantly enhance the social, environmental, economical of affordable housing in a whole of lifecycle manner.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Alireza Moghayedi reports financial support was provided by Royal Academy of Engineering.

Data availability

The data that has been used is confidential.

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Appendix

Sustainability and green assessment systems

Tool	Year	Origin	Targets	Main categories
BREEAM	1990	UK	Buildings, Interiors, Infrastructure	Energy and water use, Health and well-being, Pollution, Transport, Materials, Waste, Ecology, Management processes
LEED	2000	USA	Buildings, Interiors, neighborhood development, Cities and communities	Sustainable Sites, Water efficiency, Energy and Atmosphere, Materials and Resources, Indoor Environmental Quality, Innovation in Design, Regional Priority
IGBC	2001	India	Buildings, Interiors, Residential Societies, Cities and Communities, Villages	Sustainable Architecture and Design, Site Selection, and Planning, Water conservation, Energy efficiency, Building Materials and Resources, IEQ, Innovation and Development
CASBEE	2001	Japan	Buildings, Interiors, Cities	Energy efficiency, Resource efficiency, Local environment, Indoor environment
Green Globe International Standard for Sustainability	2002	International	Accommodation and hospitality	Energy, Indoor Environment, Site, Water Resources, Emissions, Project & Environmental Management
Green Star	2002	Australia	Communities, Buildings, Interiors	Management processes, IEQ, Energy, Transport, Water, Materials, Land Use Ecology, Emission, Innovation
BCA Green Mark	2005	Singapore	Buildings, Interiors, Districts, Infrastructure	Energy efficiency, Water efficiency, IEQ, Green and innovative features
STAR Community Rating System	2007	USA	Cities and Communities	Built Environment, Climate and Energy, Economy and Jobs, Education, Arts, Community, Equity and Empowerment, Health and Safety, Natural Systems, Innovation, Process
GSAS	2007	Qatar	Buildings, Districts, Infrastructures	Energy, Water, Indoor Environment, Cultural and Economic Value, Site, Urban Connectivity, Material, Management and Operation
Green Star Tools	2007	South Africa	Buildings, Interior, Precincts	Management, IEQ, Energy, Transport, Water, Materials, Land Use and Ecology, Emissions, Innovation
DGNB	2007	Germany	Buildings, Interiors, Urban districts	Environmental Quality, Economical Quality, Sociocultural and Functional Quality, Technical Quality, Process Quality, Site Quality
GPRS	2009	Egypt	Buildings	Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, IEQ, Innovation in Design Regional Priority
Green Star NZ	2009	New Zealand	Buildings, Interiors, Communities	Management processes, IEQ, Energy, Transport, Water, Materials, Land Use, Ecology, Emission, Innovation
HK BEAM Plus	2009	Hong Kong	Buildings, Interiors, neighborhood	Site aspects, Material, Water, Energy, IEQ, Innovations
GreenSL	2010	Sri Lanka	Buildings	Management Awareness, Sustainable Sites, Energy and Atmosphere, Materials and Resources, IEQ, Process, Innovation, and Design, Social and Cultural
GBI	2010	Malaysia	Buildings, Interiors, Township	Sustainable Site Planning and Management, Water Efficiency, Energy and Atmosphere, Materials and Resources, IEQ, Innovation in Design

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Tool	Year	Origin	Targets	Main categories
GRIHA	2010	India	Buildings, Large Development, Cities	On-site Sufficiency, Water, Energy, Solid Waste Management, Development Quality, Site Planning, Energy, Water, Wastewater management, Transport, Solid Waste Management, Socioeconomic
PBRS	2010	UAE	Buildings	Integrated Development Process, Natural Systems, Livable Communities, Precious Water, Resourceful Energy, Stewarding Materials, Innovating Practice
EDGE	2012	World Bank Group	Buildings	Energy, Water, Materials
ARZ BRS	2012	Lebanon	Buildings	Energy performance, Thermal energy, Electrical energy, Building envelope materials, IEQ, Water conservation, Operations and Management
HQE	2013	France	Buildings, Urban Projects	Energy, Environment, Health, Comfort

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