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Design and delivery of national housing in the UAE: an alternative approach

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The provision of national housing to citizens in the United Arab Emirates (UAE) is considered a crucial topic. Over the past four decades, the process of developing national housing has emerged into multiple housing programs and schemes, all with the same aim of offering affordable and high-quality housing to citizens, in addition to meeting the needs of local families regarding spatial configurations while maintaining cultural values. However, despite all these efforts, the question has always remained: are the offered housing practices suited for family needs, socioeconomic trends, and environmental challenges? This study aims to offer an alternative approach for the design and delivery of national housing practices in the UAE. The proposed process is structured based on the following ethos: first, a conceptual approach for design flexibility toward offering customization while maintaining contextual and cultural qualities for inhabitants; second, a computational design strategy for facade optimization that illustrates the significance of incorporating environmentally conscious design strategies in response to local climatic conditions toward enhancing overall building performance; and third, a hybrid production model that relies on a prefabricated building approach that combines precast concrete systems with 3D printing technology. The efforts described in this article represent a significant phase of an ongoing research endeavor that explores how technological capacities could help rethink national housing in the UAE.

KEYWORDS

housing, design flexibility, customization, computational design, 3D printing

1 Introduction

Back in the late 1960s, when Sheikh Zayed Al Nahyan, the ruler of Abu Dhabi, came into power, he called for a new national housing initiative that aimed at building a nation, settling the nomadic Bedouin, and increasing the emirate's population. At that time, he engaged international architects and consultants to design public housing. Such an initiative resulted in multiple critical attempts that explored layout possibilities, spatial configurations, and construction techniques toward devising a viable solution for national housing. Later in the early 1970s, with the federation of the United Arab Emirates (UAE), the call expanded, resulting in a remarkable interest in exploring the potential of using modular prefabricated concrete components due to their capacity to cut construction time, thus speeding up the building process (Damluji, 2006).

During the last few decades, along with remarkable urban growth and the development of modern infrastructure across cities in the UAE, the call to deliver national housing has expanded to a wider range of its citizens. Public housing projects are being developed in every city as government bodies have invested heavily in housing developments through collaborations with the private sector in order to diversify the process and the end product, and thus deliver high-quality housing to the public (Agrawal et al., 2020).

In recent years, housing communities have been developed to meet the high demand for Emirati families, thus resulting in projects that are large in scale and complex in process. In order to orchestrate the procedures, the local housing authority has devised a series of design and construction guidelines that are set to maintain the sociocultural identity of citizens while providing housing typologies that are shaped in response to local demographics (Abu Dhabi Housing Authority, 2016). For instance, many of the recently completed projects have relied on precast concrete systems either entirely or partially, given the method's practical and economic vitality. Nevertheless, an analysis of some of these projects that have been recently completed in the emirate of Abu Dhabi has revealed a series of concerns regarding spatial configuration, design flexibility, and environmental performance. Additionally, there is an inadequacy in endorsing inhabitants' individual preferences within the design (Elkaftangui and Eid Mohamed, 2018). While housing authorities have been committed to delivering high-quality housing, we argue in this work that many of the previously mentioned concerns are due to relying on design and delivery practices that are flexible enough to accommodate possible variations in inhabitants' individualities and in being responsive to contextual characteristics. As a result, despite all these efforts, we sought to question in this work how emergent design and fabrication technologies can offer an alternative to the current housing practices. The focus is on the potential to overcome a series of challenges such as the capacity to respond to local citizens' needs, utilized construction methods, changing socioeconomic trends, and contextual specificities, through an approach of rethinking the design and delivery process.

In order to respond to the formerly mentioned questions, we propose in this work a comprehensive approach for the design and delivery of national housing in the UAE, one that relies on three ethos. First, a design flexibility scheme that could allow for various levels of customization, from spatial configuration to room blocks modification. Second, a computational design process for optimizing a self-shading facade system that aims to leverage the building's environmental performance. Finally, a hybrid production model that maintains a prominent off-site construction practice by combining precast concrete systems, integrated utility pods, and large-format 3D printing.

The proposed approach emerges in response to exploring the challenges of current practices while realizing the potential of emergent trends and technologies in the building industry. Thus, this work is structured as follows. The first section offers the background on a series of topics that aims to lay the base for the proposed approach. This includes the evolution and development of Emirati housing, various design drivers, and current housing practices in design and construction. The section leads to the identification of what we believe are the challenges being faced in current practices and the potential topics that can be explored toward devising an approach for the design and delivery of national housing. The second section outlines the proposed schemes and various strategies that we have sought to integrate, such as modularity and design flexibility, facade optimization, and prefabricated building systems. Finally, the last section gives the conclusion and future work.

The work presented in this article represents a critical phase of an ongoing research endeavor that aims to rethink the role that design and fabrication technology can play in changing national housing practices in the UAE. The goal is to develop a digitally driven workflow that relies on a series of technological procedures toward an affordable, customizable, and environmentally conscious housing system. It is worth mentioning that affordability in such a case refers to the housing authority's financial capacity to fulfill citizens' demand for housing. The focus is on devising a protocol that could potentially leverage current design and production practices while maintaining contextual attributes that are shaped by local environmental challenges, coupled with citizens' sociocultural requirements.

2 The case of UAE national housing

2.1 Background

Housing in the UAE's capital, Abu Dhabi, started off as residential clusters split tribally into quarters called *hara* or *fareej* connected by internal walkways called *sikka* (Ahmed, 2012; Boussaa, 2006; Hassan, 1972; Bani Hashim, 2016; Rashid et al., 2022). The walkways connected each quarter to distinct community facilities, such as mosques, *barahaat*, or public spaces (Ahmed, 2012; Bani Hashim, 2016). Most buildings were mainly constructed from a semi-permanent palm frond structure called *arish*, along with a few elite houses constructed from coral, mud-brick, or clay. A few of the latter contained an upper floor and a wind tower for cooling purposes (Heard-Bey, 1982; Kay and Zandi, 1991; Al Fahim, 1995; Heard-Bey, 2001; Hawker, 2008; Bani Hashim, 2016; Elsheshtawy, 2019; Rasid et al., 2022). Extended families lived in the typical household, where a rectangular fence surrounded the house and its courtyard, and each *fareej* faced north for protection from direct sunlight and attracting north wind, which provided an additional cooling effect (Bani Hashim, 2016).

On the micro-level, none of the rooms or courtyards had windows at eye level to the outside. This together with the curtain walls that were placed opposite to the rear door enhanced visual privacy (Heard Bey, 2001; Bani Hashim, 2016; Elsheshtawy, 2019). Structural frames and roof beams were composed of palm trunks. The palm branches were tied together with fiber ropes that surrounded the foot of the tree trunk, which allowed for large solid mats to be made, thus forming the walls of the house (Bani Hashim, 2016). The gaps in the walls allowed summer wind to enter the house and served as a natural ventilation. In the winter, however, several layers were added to the walls for warming effects. Furthermore, palm ponds were woven into several layers of thin mats to form the roof. Floors were made of sand, sometimes covered in the same thin palm pond mats (Heard-Bey, 2001; Bani Hashim, 2016).

With the discovery of oil, and the British withdrawal from the region, in the 1960s, foreign consultants were hired to generate master plans for the city to design new residential neighborhoods, to

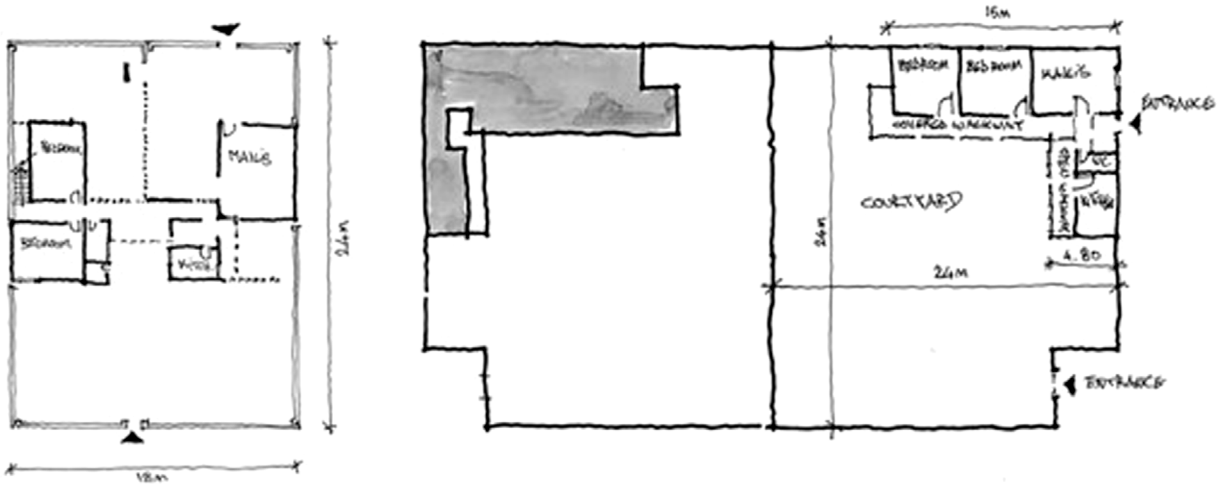

FIGURE 1
Image from the late 1960s in Abu Dhabi showing the final stages of constructing a *Sha'bi* house. Source: ADCO; Elsheshtawy (2019).

accommodate local and expatriate residents. ARABICON was hired, and national housing initiatives started to materialize, urbanize, and settle nomadic Bedouin families and tribes, who contributed to building the nation and boosting growth and social development, resulting in initiatives like the *Bayt Sha'bi* (the national house), where standard housing units made of concrete and equipped with electricity, sewage disposal systems, and running water were designed (Heard-Bey, 1982; Damlūji, 2006; Dempsey, 2014; El-Aswad, 2014; Sadik and Snavely, 2014; Bani Hashem, 2016; Bani Hashim, 2018; Rashid et al., 2022). Later, all housing and planning activities as well as the ARABICON staff were moved to Abu Dhabi City Municipality (ADM) (Bani Hashim, 2016; Kyriazis et al., 2017; Rashid et al., 2022), where the Egyptian planner Abdul Rahman Makhlouf led the planning process of modern Abu Dhabi in 1968 (Rashid et al., 2022; Bani Hashim, 2016; Elsheshtawy, 2019). Following this, national housing continued under Makhlouf's role as Abu Dhabi's Chief Planner, with traces of influence from the Japanese planner Katsuhiko Takahashi (Rashid et al., 2022; Bani Hashim, 2016). Eventually in 1988, WS Atkins & Partners Overseas (Atkins) was commissioned to generate a comprehensive development plan for Abu Dhabi and its environs. They worked on it for 2 years, and the plan was released in 1990 (Bani Hashim, 2016).

The tradition of giving every Abu Dhabian plots of land for residential, commercial, industrial, and agricultural use had already been in practice (Bani Hashim, 2016). They were now known as "*social housing*" programs, denoting the strong correlation and effect of architecture on social life (Rashin et al., 2022). Furthermore, the granting of social housing was restricted to lower income residents, and even though priority was given to households composed of 6+ family members, they were granted under the condition that the head of the household did not already possess a house or land (Bani Hashim, 2016).

Initially, houses of the Social Housing Program were built on approximately 400-square-meter plots (Al-Mansoori, 1997; Wimsatt, 2010; Leech, 2016; Rashid et al., 2022). As the building occupied only 40% of the plot, the resultant area of the house did not exceed 200 square meters (Elsheshtawy, 2019), with a 3-m-high fence (Al-Mansoori, 1997; Wimsatt, 2010; Leech, 2016; Rashid et al., 2022). The interior of the house consisted of two bedrooms, a living room—*Majlis*, a kitchen, a bathroom, a shower, and a courtyard (Elsheshtawy, 2019; Rashid et al., 2022). Furthermore, as a means of space optimization, residents used the flat roof as an additional sleeping space (Rashid et al., 2022; Elsheshtawy, 2019). Figure 1 shows a reconstructed floor plan of a *Sha'bi* house. Social living and communication were emphasized via the addition of open green spaces and courts between the dwellings, which also increased the sense of privacy among each group of houses (Rashid et al., 2022).

By the 1970s, national houses (also then known as low-cost houses) were mass-produced. This resulted in communities that lacked a clear structure, identity, and adequate community facilities (AHDA, 2014; Bani Hashim, 2016). This is evident by the replacement of traditional materials with prefabricated concrete structures, which retained heat even during the night, resulting in a dependency on air conditioning and rendering the houses environmentally unsustainable (Architectural Review, 1977; Bani Hashim, 2016; Rashid et al., 2022). Furthermore, houses were also socially unsustainable as they failed to respond to cultural needs and values, which resulted in external and internal modifications and additions to the housing units (Bani Hashim, 2016; Rashid et al., 2022). This initiated a need to encourage more environmentally sustainable houses (Al-Mansoori, 1997; Rashid et al., 2022) and increase the plot sizes over the next 20 years to reach approximately 45 m × 60 m (Abu Dhabi Housing Authority, 2014; Bani Hashim, 2016).

Between the years 1971 and 1976, over 40,000 residential housing units were built, and by 1980, more than 20,000 residents were on the waiting list, indicating the popularity of these houses (Elsheshatwy, 2019). However, as pressing needs for mass production increased, despite multiple modifications, the national housing program inside the island of Abu Dhabi stopped in the mid-to-late 1970s due to the size of families outgrowing the size of a standard national house (Bani Hashim, 2016; Rashid et al., 2022). Instead, the national houses were marked for demolition when the new development plan for the capital was initiated (Al Ittihad, 1978; Bani Hashim, 2016; Rashid et al., 2022). On the other hand, by 1985, most of the national housing projects focused on the Al Ain city and its rural areas (Atkins and Overseas, 1990; Bani Hashim, 2016). Since 1990, heritage and regeneration projects have been going through constant refinement to adapt to the rapid cultural changes caused by globalization, tourism, and interaction with expats from around the world (Rashid, et al., 2022; Hawker, 2008; Heard-Bey, 1982).

Today, stand-alone, two-story villas, marked as "Houses for the Nation," form the dominant form of national housing in the UAE. These are equipped with hot water, green-star-rated air conditioning, and fiber optic networks (Rashid et al., 2022). However, the problems with their environmentally unsustainable features remain.

2.2 Cultural and environmental drivers

In the pre-oil era (before the 1950s), the Emirati culture constituted a tribal system. At which time, tribal affiliations had influenced the building blocks of the Emirati cultural fabric (Heard-Bey, 1982; Thesiger, 1995; Trench, 1996; Rashid et al., 2022; Al Abed and Hellyer, 2001) Emiratis made their living from different professions, which included fishing, trading, pearling, and cultivating dates (Rashid et al., 2022). These professions played a crucial role in shaping the Emirati culture, even after the discovery of oil, and still do to the present day. This has resulted in the formation of the neighborhood—*Fareej*, which is made up of urban space in which houses are located.

In the Emirati culture, houses are seen as a sanctuary, that is, to be respected by people—Haram (El-Aswad, 1996; El-Awaad, 2014), which results in significant cultural value to the house as a structure (El-Aswad, 1996) and triggers a need to address the culture as a driving force that leads to the designing of residential units in the UAE. One of the main concerns when designing houses is gender-related activities. For instance, the need for two reception halls—*majlis* or *maylis*—in each unit is crucial to the Emiratis to serve each gender separately (El-Aswad, 1996). Furthermore, the tribal structure is still strong in the formation of the social fabric. This has resulted in four main categories of houses that have been identified by El-Aswad (1996) as 1) the grand palaces, which belong to ruler families, sheikhs; 2) large villas that belong to wealthy families; 3) modern, western buildings that are composed of individual apartments merged together; and 4) traditional or folk houses—*Bayt Sha'bi* (El-Aswad, 2016).

Typically, a folk house is a horizontal, single unit that has a simple, single-story layout consisting of basic functions, such as courtyard, guest reception or sitting room—*majlis*, bedrooms, storage areas, a cooking area or kitchen, a bathroom, and a seating area overlooking the courtyard—*Iiwan*. These houses are often surrounded by 2- to 3-m-high outer fences—*Jadar* and are separated from each other with a minimum of 1-m-wide vacant space (El-Aswad, 2016).

Nonetheless, the folk house has always been subject to modifications due to extended families and the ever-changing needs of its residents. Some of these modifications have been approved by the municipality, such as the replacement of exterior wooden gates with decorated steel or metal doors or the further addition of spaces to accommodate more functions (an additional bedroom, a majlis, or a garage), and they have remained connected to community acceptance and social, economic, and functional needs of the residents. Regardless of how drastic some modifications may be, the folk houses remain inward-looking, with all the original and added functions arranged around the central courtyard, emphasizing the need for privacy in the Emirati culture (El-Aswad, 1996).

The need for privacy also affects houses from the outside, where trees—more particularly, palm trees—are perceived as a symbol that offers a sense of privacy and security, along with enhancing the houses' esthetics as well as the environment. The units are often separated from their neighboring houses by a minimum of 1-m-wide empty spaces (El-Aswad, 1996; Rashid et al., 2022). Some are also surrounded by a garden. Despite the presence of garages in most houses, it is common to see cars parked in the front. Nonetheless, the entrances are perceived as an important way of protection. As a result, house entrances are not shared with anyone outside the family domain, that is, living in apartment buildings or buildings with shared entrances is not historically common in the Emirati culture. Consequently, each individual unit has two entrances: the first leading to the *majlis*—men's reception and sitting hall, while the other entrance leads to the rest of the private spaces of the house. The women's *majlis* is typically connected to the interior of the house, more specifically, adjacent to the house's back entrance (Boussaa, 2006; Coles and Jackson, 2007; El-Aswad, 2014; Rashid et al., 2022). The men's *majlis*, on the other hand, is often larger and connects the interior to the exterior world, making it a symbol of hospitality, generosity, and sociability. This renders the men's *majlis* a crucial part of the Emirati house due to its connection to the exterior and interior sides of the house (El-Aswad, 1996). The importance of the men's *majlis* calls for special attention to ornamentation and decorations on its openings (Rashid et al., 2022; Kay and Zandi, 1991; Remali et al., 2016).

The folk house's courtyard, on the other hand, represents the core and intimate side of the house, where residents, especially women, get to enjoy nature in privacy. Some women use the courtyard as an extension to the kitchen, allowing them to enjoy cooking in a natural setting while avoiding spreading unpleasant smells to the bedrooms and other spaces of the house. Children also benefit from the courtyard, as it serves as a safe outdoor playing area, away from the streets. Finally, the courtyard offers the entire family a comfortable space with natural ventilation in the UAE's hot climate (El-Aswad, 1996).

The *Iiwan* is another important component of the Emirati folk house. Having an open hall with a sitting area facing the courtyard, it is often decorated with geometric patterns. It is a roofed, centralized space between two rooms. Being open from one side, it benefits from an attractive view, making it a favored space for social interactions among family members (Kay and Zandi, 1991; El-Aswad, 1996; Hassan, 1972).

In addition to the functional aspect, attention to the little details and decorations have enhanced the esthetic appeal of the Emirati folk house. Folk decorations and paraphernalia symbolize the local culture. Doors, for instance, are painted with colors of the local folk style. Paraphernalia and decorations are inspired by nature, such as indigenous plants, flowers, and birds. The falcon is a distinctively important bird that is commonly used due to its significance in the Emirati culture (El-Aswad, 1996).

The outside area of the houses is not exempt from those decorations. Arches, crescents, stars, and domes are some elements that make up the exterior gates. Furthermore, facades are often decorated using local geometric patterns, which often include calligraphic religious phrases (El-Aswad, 1996).

Today, the influence of the Emirati culture on houses is clearly apparent in the typical house design and layout. A typical house of an Emirati still has its own entrance, at least one *majlis*, tall fences, and outside gardens. In short, the Emiratis' strong connection to their heritage implies that almost no changes can be made without a reference to their cultural heritage (El-Aswad, 2014; Elsheshtawy, 2019).

2.3 National housing practices

The public housing projects in the emirate of Abu Dhabi, UAE, which are the focus of this research, are governed by the Abu Dhabi Housing Authority (ADHA), which was established in 2012. The ADHA's goal has always been focused on delivering housing to citizens in Abu Dhabi, Al Ain, and the Western Region according to the highest standards [Abu Dhabi Housing Authority (ADHA), 2016]. Such a role has been materialized through collaborating with the private sector and establishing various initiatives and projects that have been aimed at facilitating the delivery of housing to citizens, thus speeding up the process.

As for initiatives, for instance, Bayti (2015) was launched in 2015 as a catalog of 58 housing prototypes designed by different architectural practices in the UAE. All typologies were preapproved for permitting and constructing, with the aim of speeding up the process and minimizing the risks in design, development, and construction. Housing prototypes were also designed to match standardized lot sizes within future developments. Ranging from four to possibly eight-bedroom houses (400–1,000 m^2), the catalog catered to various family needs regarding spaces, style, and amenities. Due to challenges in managing the process, in addition to dissatisfaction with the offered housing prototypes, the initiative model was set as a secondary option, and the focus transformed into a wider collaboration with the private sector toward comprehensive housing developments.

More recently, another initiative has been proposed—Teyaseer, an Arabic word meaning facilitation, and established in Abu Dhabi in order to act as a liaison between Emiratis registered in the housing program and different developers working on national housing projects. It is an optional free service that national housing loan recipients who are not very experienced with the process of building a house can use to overcome any difficulties that they might face during the process of building their homes. On their website, Teyaseer offers a catalog of housing typologies that vary in size from four to seven bedrooms (400–700 m^2) and style (modern to traditional) (Teyaseer, 2022).

Pertaining to projects, the Al Falah Community was developed in Abu Dhabi in 2015 that consists of five "villages" comprising 4,857 villas, in addition to a wide range of community amenities. The development, which is considered to be one of the largest housing developments in the capital, aimed to provide a sustainable neighborhood that serves modern requirements and lifestyles while preserving and promoting the traditional Emirati identity and preferred style of living [Abu Dhabi Housing Authority (ADHA), 2016]. The project was planned with five villages, each designed around the notion of open spaces and communal amenities and comprising a series of housing typologies and villas that had distinctive layouts and facade styles. Figure 2 shows an aerial view of the project.

2.3.1 Precast concrete industry in UAE

Concrete is one of the most usable materials in construction worldwide, and specifically in the MENA (Middle East and North Africa) region. It is considered a cheap composite due to the low cost of raw materials. Additionally, it is a strong material in compression, durable, resistant, and versatile. One of the most common applications in concrete construction is precast concrete, a production model that operates by building up offsite molds and formwork for each specific project. It is used for walls, floors, and structural elements. Once complete, these components are delivered to the construction site and then assembled by using cranes to form the building (Bachmann et al., 2012).

Over the past decade, there has been a growing interest in the use of precast concrete elements due to their superior quality, durability, ability to compress project schedules, reduced site disruptions, and improved sustainability (Sayed, et al., 2007). Villanueva (2020) argued that the precast concrete market in the UAE is anticipated to grow at a rate of 4.4% between 2018 and 2024, with structural products accounting for approximately 50% of the overall construction market value in 2020.

In recent years, the precast concrete systems have been employed extensively to realize many of the national housing projects in the UAE. In such cases, houses are built using structural and non-structural wall panels in an engineer to order fashion, in addition to hollow core slabs, beams, and stairs. Precast concrete is believed to be a faster, more durable, and sustainable technique for construction, especially for residential structures, when compared to conventional methods (Sayed et al., 2007). For example, the previously mentioned Al Falah Community project relied extensively on precast concrete systems. As a result, five villas were built per day, and labor costs were reduced by up to 25% when compared to conventional methods. Nevertheless, the project witnessed a remarkable volume of post-occupancy modification requests, directed primarily toward the spatial organization, fenestrations, and energy consumption–monitoring system. Due to the structural system employed, coupled with the design approach, implementing modifications has always been a challenge, which has led to, in some cases, dissatisfaction with the housing schemes (Elkaftangui and Eid Mohamed, 2018).

2.3.2 Reflection: challenges and opportunities

There are not many publications on the designing process of national housing in the UAE, given that it is a topic of practice rather than research. Furthermore, most of the work published has been focused on analyzing the existing strategies and projects. To mention a few, Agrawal et al. (2020) evaluated the effectiveness of housing programs in Ras Al Khaimah, one of the UAE's seven

FIGURE 2
Aerial view of the Al Falah project and facade of one of the housing units (source: Gulf Precast website, 2022).

emirates. Ahmed (2017) analyzed factors that contributed to sustainable community development and planning (Bande et al., 2019), and examined the relationship between spatial layouts of housing units, their orientations, and accordingly, the cooling loads of the housing units, while maintaining factors of local culture. Ahmed et al. (2022) also explored digital tools toward preoccupancy evaluation.

Based on exploring previously mentioned strategies and relevant challenges, observing recent housing practices and reviewing some of the research produced in various areas, we sought to question the possibility of proposing a new protocol for the design and delivery of housing prototypes. The proposed approach highlights a series of opportunities that stem from precedent efforts in housing designs that include, for instance, design flexibility and customization (Schneider and Till, 2005; Habraken, 1972; Duarte, 2001), facade and opening optimization (Caldas and Norford, 2002; Tuhus-Dubrow and Krarti, 2010; Kirimtat, et al., 2019), prefabricated building strategies (Kieran and Timberlake, 2004), and 3D concrete printing (Bos et al., 2016). We believe that such ideas offer a resilient medium to overcome current practices.

It is important to mention that the rationale of the presented research emerges based on two considerations: first, working closely with housing authorities, thus establishing a critical appraisal of implemented initiatives and offering housing catalogs, and second, examining one of the major housing projects delivered using precast concrete in order to understand various implications that limit flexibility.

3 Design and delivery scheme

The proposed design and delivery scheme stem from critically understanding the challenges that current national housing practices face. Nevertheless, it is important to mention that such a proposition does not seek to replace current practices but rather highlights the potential of applying a series of strategies that could overcome some of the challenges and thus offer an alternative. In that sense, the proposed scheme focuses on three main drivers: first, design for flexibility toward customization; second, optimization of facade openings toward better building performance; and third, utilization of prefabricated building systems based on precast concrete systems, combined with 3D printing. The following sections underline how we anticipate the integration of these drivers toward a comprehensive approach.

3.1 Design for flexibility

The study of national housing projects, specifically ones realized using precast concrete components, reveals the challenges in offering design flexibility and variations due to the pursued design approach, combined with the construction method. In that sense, one of our goals in this research is to offer a strategy for the design of housing prototypes that could allow for a certain level of flexibility and customization. As a preliminary scheme, we explore the notion of implementing a modular design approach. Modularity in design supports multiple configurations by using repetitive elements toward scaling and scope. This enables accommodating design variations on multiple levels, which is considered a core criterion in offering flexibility (Kieran and Timberlake, 2004). We propose devising an approach to spatial configurations, that is, based on a scalable modular grid system of 3.0 m × 3.0 m modules for generating floor layouts. In that sense, all of the interior blocks start with a minimum dimension of 3.0 m or its increments. This also informs exterior wall panels. For further flexibility, we incorporate half a module, 1.5 m, to allow for expanding spaces. The proposed architectural grid stems from design guidelines set by authorities for national housing developments in Abu Dhabi [Abu Dhabi Housing Authority (ADHA), 2016], which forms the basis for many of the spaces, according to their proportions.

Following various iterations for the spatial layout and in order to offer choices to homebuyers, we came up with three different variations for the typical plot: compact, atrium, and courtyard

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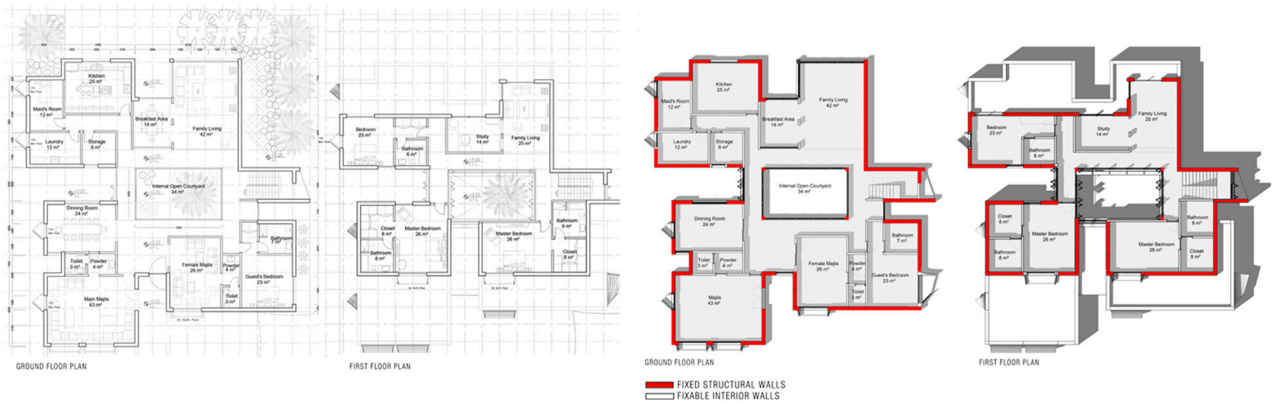

FIGURE 3
Typical plans for one of the proposed housing prototypes, the "courtyard house," in addition to the structural proposal where load-bearing walls are marked in red.

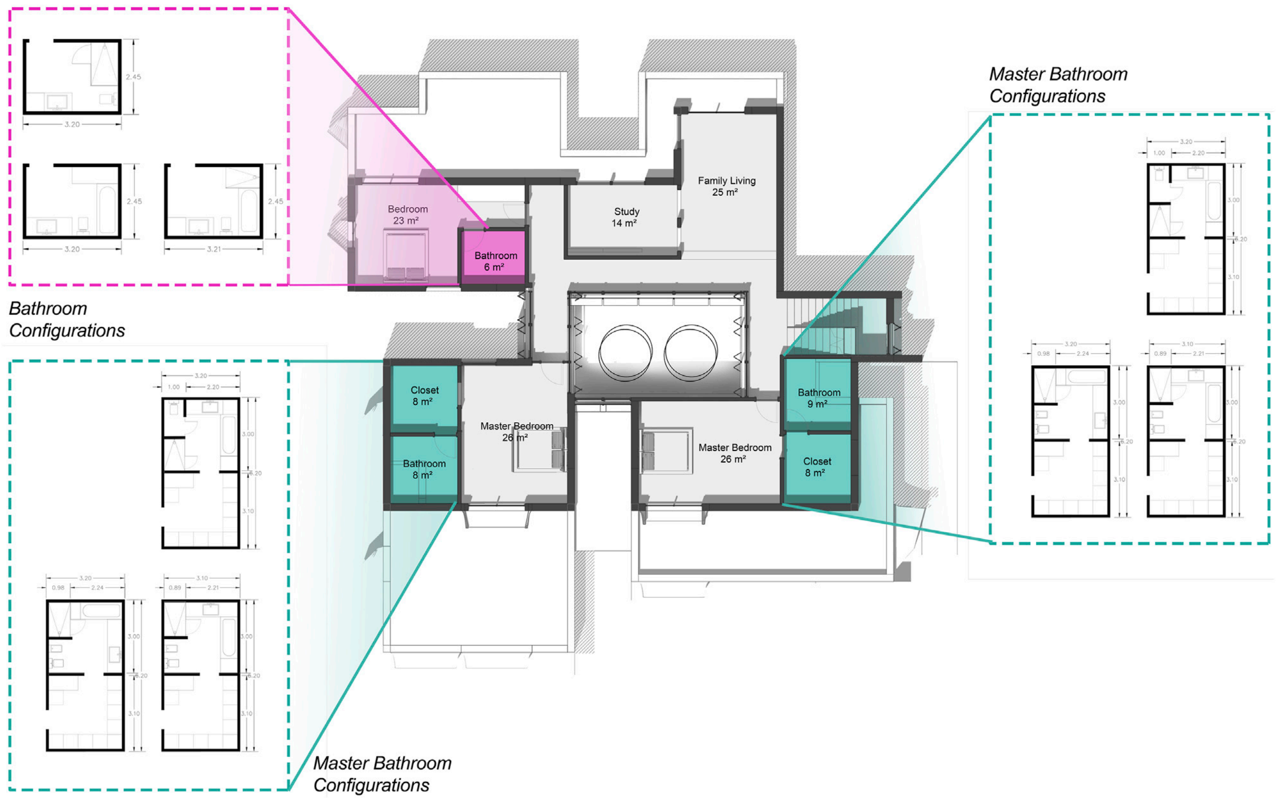

FIGURE 4
Micro-flexibility and customization in the upper floor of the "courtyard house" and exploring the possibility of various layout possibilities for the bathroom block.

houses; each one is a four-bedroom dwelling unit that can be expanded to seven. The proposed layouts follow typical design strategies for national housing in the UAE and incorporate all the required spaces while respecting cultural and social values. For instance, the separation between public male and female zones, considerations for aging in places in the form of future expansions, and provisions of adequate spaces for services. Nevertheless, the proposed layouts have been formalized around two notions of flexibility: macro and micro. On the one hand, macro-flexibility allows for spatial expansion as per the design brief that requires considering the notion of aging in place. In order to achieve the aimed flexibility, the structural system informed by the

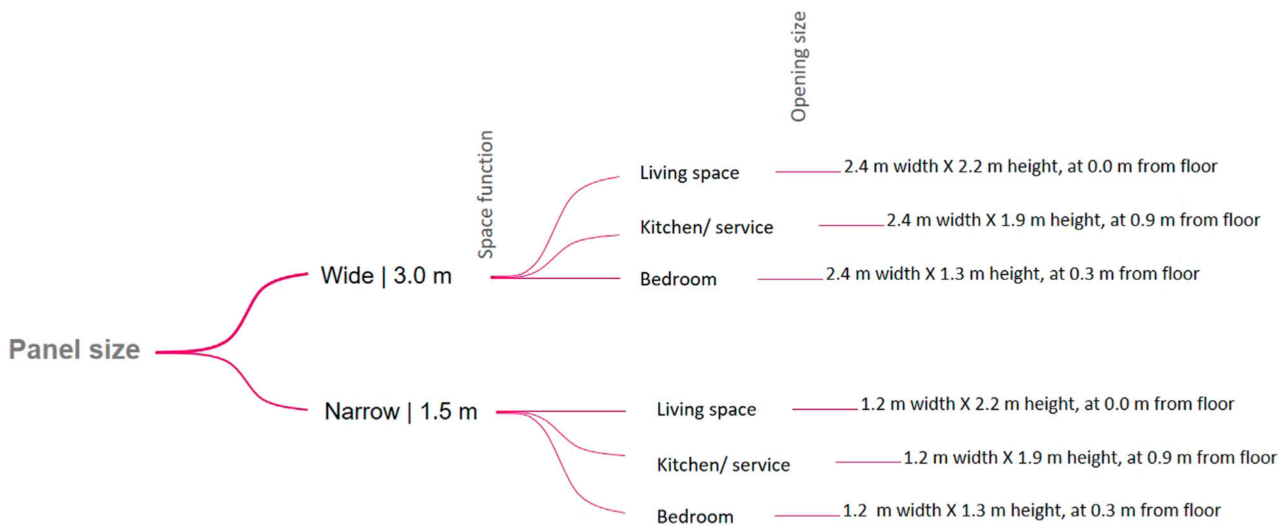

FIGURE 5
Classification of wall panels. Panels are designed based on a series of assumptions derived from examining residential design trends in the UAE, with a specific focus on opening size in relation to allocated function.

use of precast concrete components and following the proposed architectural grid is designed where only peripheral walls are allocated as load-bearing walls while the interior ones are set as lightweight partitions, as shown in Figure 3. Accordingly, homebuyers would be allowed the possibility to customize the spatial configurations of the housing units by moving, shifting, or removing some of the interior walls.

On the other hand, micro-flexibility allows for internal layout manipulation through the manipulation of utility spaces, kitchens, and bathrooms, thus offering room block modifications. These blocks have been initially designed and integrated within the three prototypes based on the notion of commonality. Commonality refers to the possibility of using a component both within the same product and between different products. The combination of modularity and commonality leads to a configurable product platform that can contribute to reducing costs (Tseng and Piller, 2003). Figure 4 represents customization possibilities for bathroom blocks.

3.2 Facade system

One of the major factors that has to be considered while designing buildings in the UAE is harsh conditions in the form of high heat and humidity during the summer. In order to cope with such conditions, buildings tend to rely extensively on active systems to achieve comfort within indoor spaces. However, these systems represent a significant portion of the construction cost and energy requirements, in addition to their environmental impact (Awadh, 2014). In order to cope with such a challenge, we propose a process for the design of a facade system that would contribute to the environmental performance of the housing units, thus becoming the first layer of protection against climatic conditions.

The facade system is composed of two typologies: insulated solid panels and window-hosting panels; both following the previously described modular strategy, with a basic panel that is 3.0 m wide and a sub-module that is 1.5 m wide. The purpose is to accommodate various possibilities for fenestrations as per spatial requirements, follow market standards, and leverage typology-based flexibility. Figure 5 demonstrates the classification of panel sizes according to the assigned spatial function.

While the solid panels follow industry standards regarding composition, the window-hosting panels integrate self-shading elements that are optimized for daylight through computational logic. We sought to employ a computational design logic based on an evolutionary generative algorithm toward devising unconventional solutions. Evolutionary algorithms are employed due to their capacity to simulate the processes of natural selection and reproduction, thus shaping the evolution of solutions in response to a problem (Bentley, 1999). In architecture, optimization applications through evolutionary computation have been explored since the late 1990s toward various types of design problems. To mention some of the early works: exploration of the matter of computers and assisting in the creative process (Gero, 1996), form finding (O'Reilly and Ramachandran, 1998), lighting and thermal performance optimization (Caldas and Norford, 2002), and opening size (Tuhus-Dubrow and Krarti, 2010). Commonly, when the case relates to building performance, the optimization model is combined with a simulation engine to ensure adequate solutions.

3.2.1 Optimization of window-hosting panels: developing panel taxonomy

Window-hosting panels are sought to play an important role in the environmental performance of the housing unit by being a potential source of heat gain. Accordingly, providing shade is

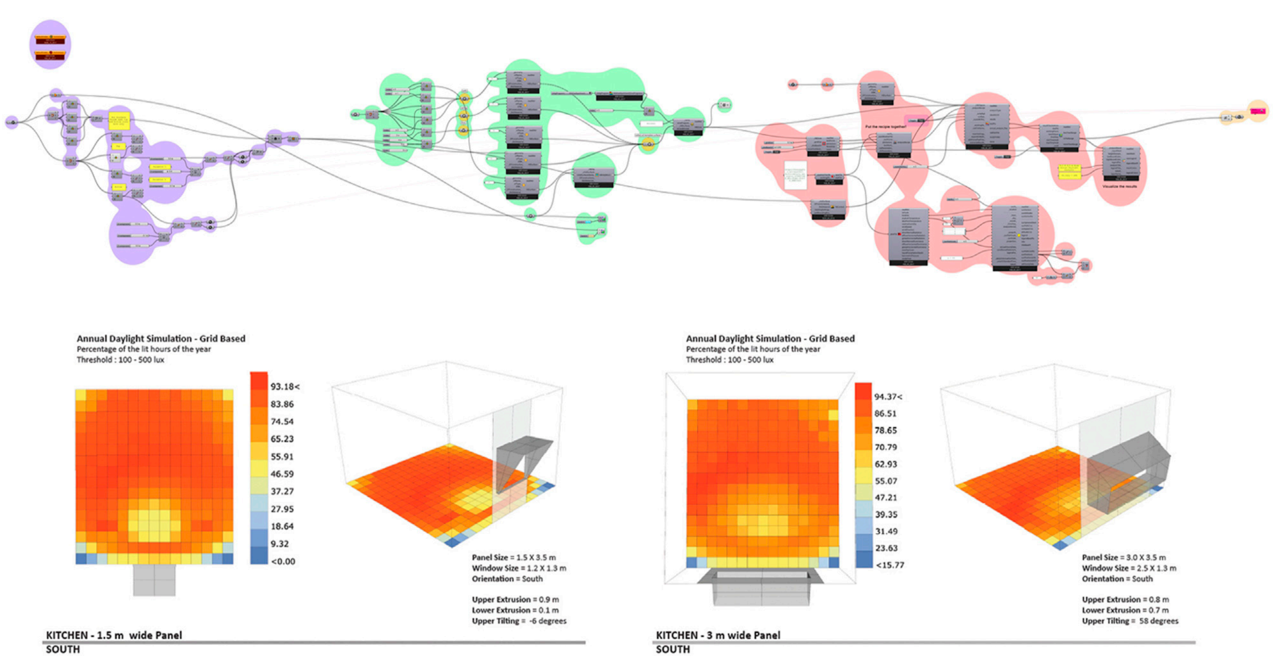

FIGURE 6
Above: the optimization process realized though combining a series of computation tools. *Below*: the outcome of optimizing a south-oriented 1.5-m-wide window-hosting panel when compared to a 3-m-wide panel. Color codes indicate the annual percentage of achieving optimal heat gain and lighting conditions for each grid square of the layout.

inevitable. The proposed self-shading element is integrated within the panel, thus taking advantage of the plasticity of concrete. As a starting point, the self-shading element is set within a predefined volume and controlled by a series of parameters in the form of vertices in the x, y, and z directions. The purpose is to allow for flexibility in performance optimization through manipulating parameters in response to orientation. Additionally, in order to control the generation process, a set of constraints related to opening guidelines in the UAE were involved, in addition to the modular grid.

The optimization process is initiated by devising a typical room model in the Rhinoceros (Rhino3D) software with one glazed opening, hosting a non-uniformly extruded virtual shading element. While the shading element is set to be computed as a dynamic component, it follows the perimeter of the fenestration at this stage. This generic configuration is then fed into the Grasshopper, the visual programming platform, where the optimization process occurs. The Grasshopper definition interprets the basic geometry and identifies it within the digital model's bounding elements: walls, floors, ceilings, and glazing zones. It also enables the input of orientation as a predefined parameter: south, southeast, east, southwest, or west. Then, the shading element parameters are established. Being a core feature in the Grasshopper, the process is characterized by building up associative relationships with a clear set of parameters and a range for their values. This dynamic setup is then optimized by manipulating extrusion parameters in the x, y, and z directions for the sake of optimizing the configuration of the shading element to the fittest according to orientation, using carefully calculated fitness criteria between annual illumination levels and solargain levels to achieve the most efficient performance.

Running the optimization requires the use of Grasshopper plugins and components, each performing a very specific task within the whole process. Galapagos, the evolutionary solver, is utilized to orchestrate the process of searching within a pool of solution space for the fittest solution with regard to the shading system parameters in the x, y, and z directions, thus resulting in a specific configuration. To ensure adequate performance, the process is combined with Honeybee, Ladybug, EnergyPlus, Radiance, DaySim, and OpenStudio, a series of necessary components in the Grasshopper for building energy and daylight simulations. These components act as normalizing media for the form-finding process, hence ensuring the minimum annual heat gain possible inside a space while maintaining adequate illumination levels (between 300 and 500 lux). In that sense, the results from the analysis becomenbsp;the fitness factor for the optimization process. Figure 6 illustrates the Grasshopper definition of the optimization process and outcome regarding the self-shading element.

The outcome of the process is a taxonomy of window-hosting panels with integrated self-shading elements that are optimized in response to a predefined orientation. The variations in panel sizes and corresponding fenestrations extend the potential for residents to configure the facade appearance through the selection of sizes and relocation of the panels, in addition to window positioning. Moreover, the

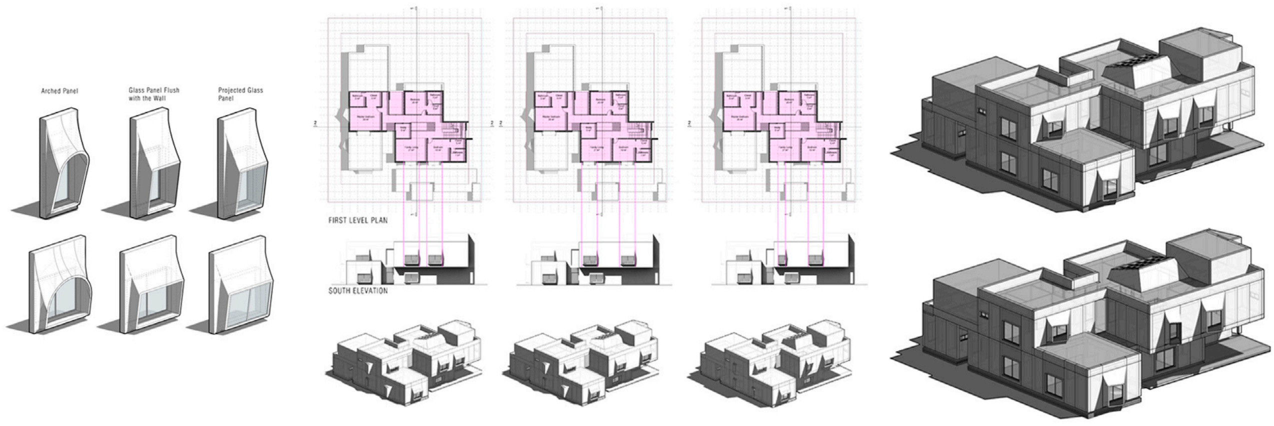

FIGURE 7
Variations in panel size, window, and corresponding self-shading element and its application according to two different orientations: south and west.

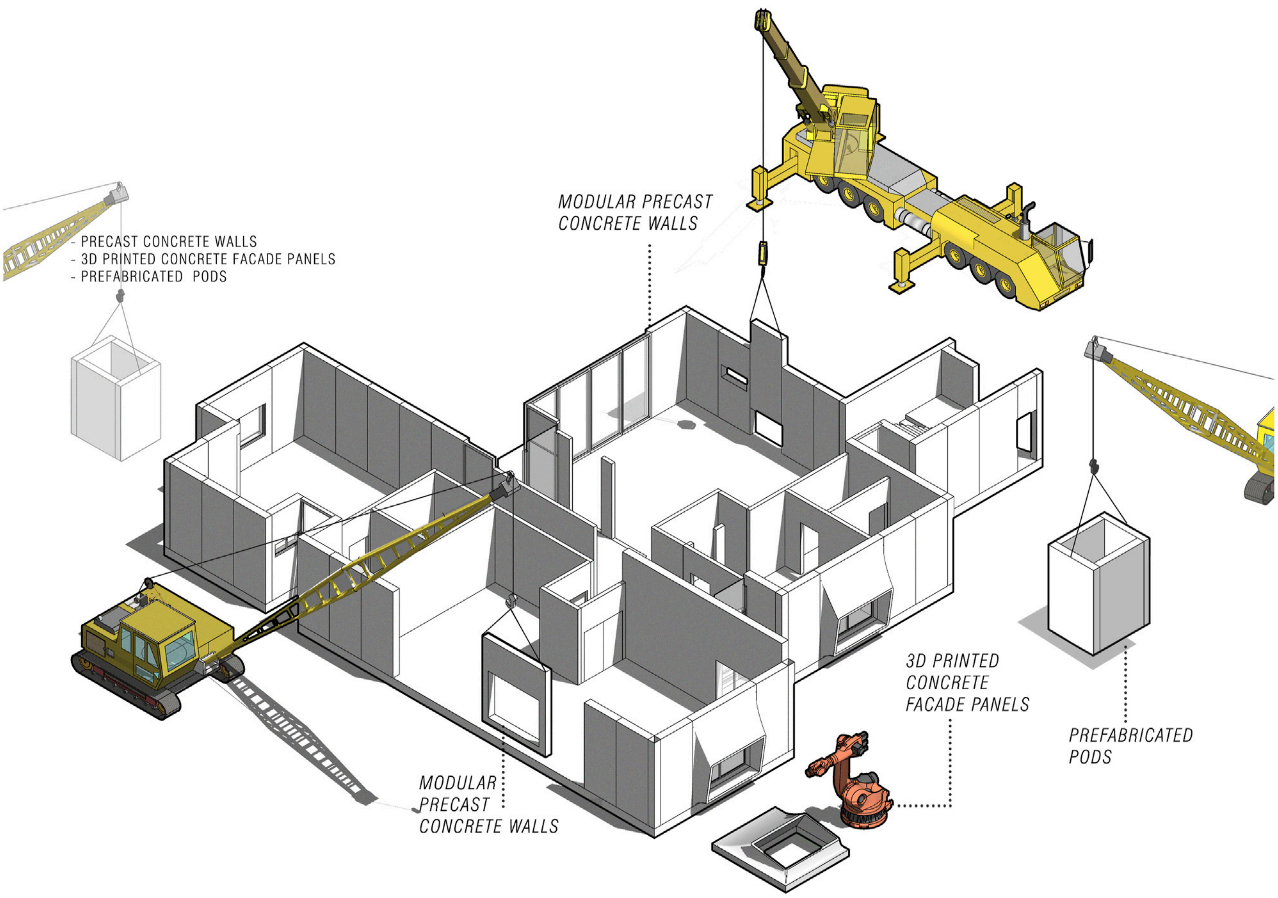

FIGURE 8
Hybrid and collaborative construction process combining precast concrete, prefabricated pods, and 3D printing window-hosting facade panels.

self-shading element leverage privacy thus borrows from the original idea of the *mashrabeya*. Figure 7 represents the possibilities of south-facing panels and their possible applications within the facade of one of the house prototypes. We also represent facade variations in the case of west orientation.

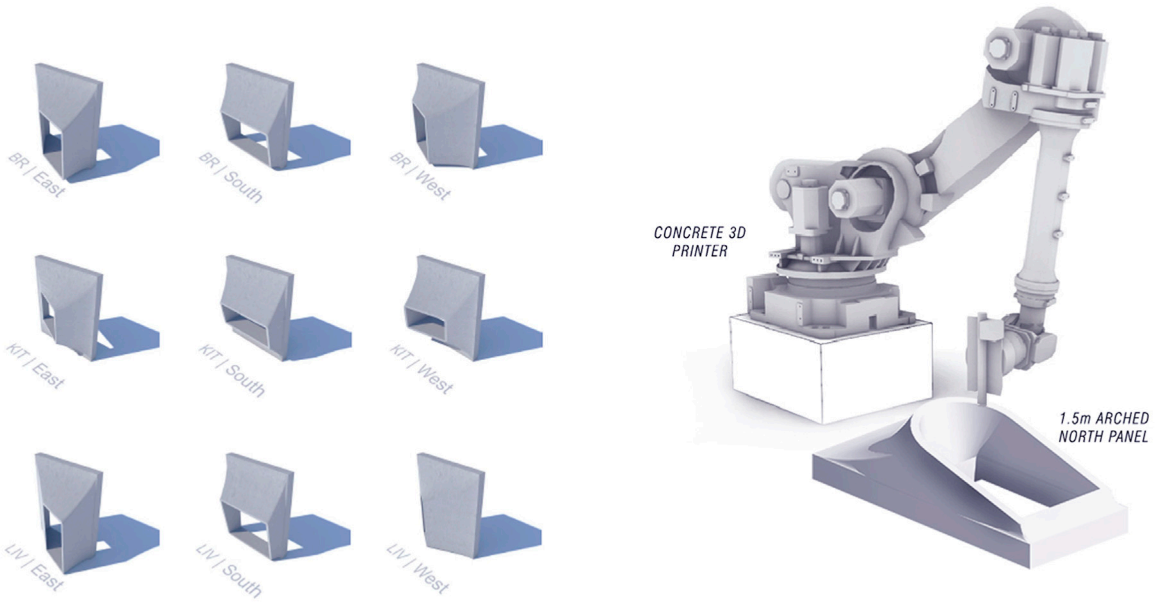

FIGURE 9
3-m-wide window-hosting panels and their variations according to orientation and spatial function.

3.3 Hybrid production approach

The proposed housing prototypes are intended to rely on three different production techniques: first, precast concrete for standard solid panels, structural components, stairs, and floor slabs. Second, modular prefabricated bathroom pods, an approach that has been utilized in the UAE construction market (Lumb et al., 2009). Finally, we anticipate the use of 3D concrete printing for window-hosting panels due to the possible tremendous variations in their shapes as per the orientation. 3D concrete printing has been an active area of research and practice as it is believed to provide enormous potential for the construction industry. It has been argued that 3D concrete printing allows for several improvements in the construction industry regarding the reduction of cost, time, and defects while offering design flexibility. It is also assumed that it can minimize environmental impacts (Hager et al., 2016).

We consider a design to fabrication workflow that can save time and cost. Figure 8 shows a possible production and assembly scheme for a housing unit, relying on the previously mentioned techniques. Figure 9 represents 3-m-wide window-hosting panels and their variations according to the orientation and spatial function. The panels are intended for 3D printing, as per the diagram.

In order to realize the design scheme, we employ a Building Information Modeling (BIM) strategy toward implementing parametric and customizable product families that can be shared between the manufacturer and other component producers throughout the building process. Such a scheme entails standardizing the structure of object information beyond geometry to include specifications for selection and use in analysis, along with material properties. Additionally, the capacity to establish a multiuser environment enables efficient collaboration and data exchange within the design and production teams.

Furthermore, we rely on interoperability for data transfer given that the development of the housing prototypes rely on various digital tools to establish a comprehensive digital model that can incorporate architectural and structural components. For instance, optimized panels are exported as mesh components to Autodesk Revit and then redefined under one parametric family with different types to accommodate all possibilities of orientation, function, and opening size. The purpose is to establish an integrated process where panels can be modified within one approach according to spatial function and orientation toward performing environmental performance simulation.

In order to explore the capacity of such a process, we studied inserting various panel typologies within the skin to evaluate the flexibility and adaptability that is required to respond to various contextual conditions. Accordingly, Revit demonstrates the possibility to investigate the panel materiality, where layers of concrete and insulation are introduced with specific properties, following industry standards. The goal is to develop a digital model that can be effectively simulated for environmental performance.

3.4 Evaluation and environmental performance analysis

As of September 2010, the Pearl Rating System for Estidama Program (Department of Urban Planning and Municipalities (DPM), n.d.) was introduced as a mandatory requirement for all buildings in Abu Dhabi, which is linked to the Abu Dhabi Municipality building that permits the process. Estidama ratings range between 1 and 5 Pearls, where 1 is the lowest and 5 is the highest, depending on a set of clear criteria related to the environmental and energy performance of buildings and

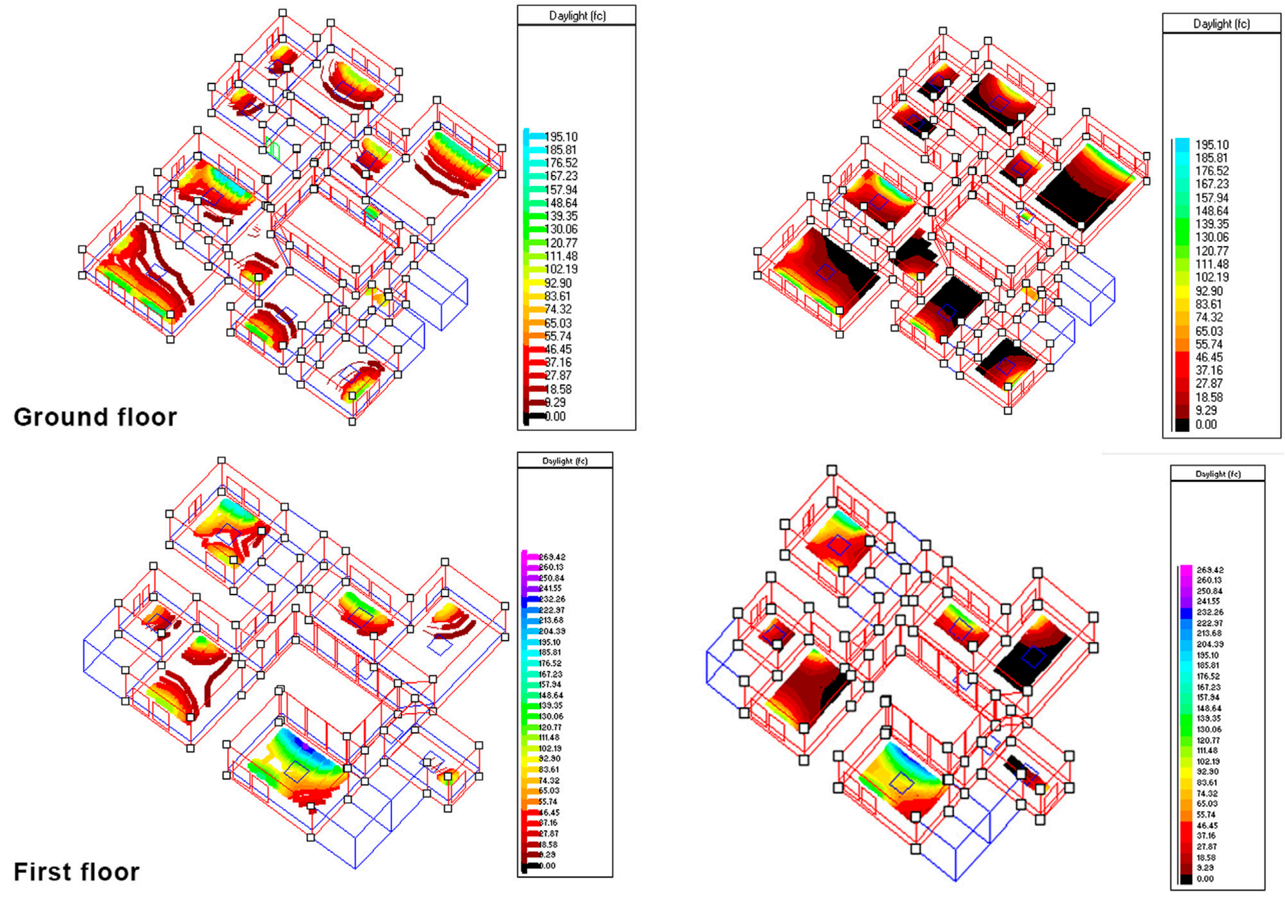

FIGURE 10
Lighting visualization analysis (daylighting).

communities. While the principles of sustainability in Estidama are very similar to the Leadership in Energy and Environmental Design (LEED) criteria, the Pearl Rating System has been regionalized to emphasize the particular concerns relating to Abu Dhabi, with a specific focus on indoor quality, energy saving, innovative design and production practices, and regional and cultural practices.

Given that our proposal is for national housing, we devised a series of strategies to achieve a high level in the Estidama Pearl Villa Rating System for Abu Dhabi—"3 and 5 Pearl." The proposed design strategies focused primarily on the following: first, minimizing construction waste through implementing a modular approach, coupled with employing prefabricated components; second, reducing energy consumption through optimizing window-hosting facade panels; and finally, taking advantage of precast concrete systems to leverage the performance of the building envelope.

In addition to the previously mentioned strategies, more measures have been incorporated and evaluated to achieve the intended Pearl rating, such as

- employing high-performance double-glazing window systems and
- minimizing lighting loads by using energy-efficient light fixtures, occupancy sensors, and dimming controls

3.4.1 Lighting visualization and analysis

Following the implementation of the self-shading facade panels, it was crucial to evaluate the impact of such an approach on the overall quality of natural light within the regularly occupied areas on the floors. This analysis aimed at determining the amount of natural daylighting that would be available in the building based on the previously explained design approach. Given that we had concerns regarding the prioritization of minimizing heat gain over natural lighting quality, it was crucial to perform a natural lighting simulation and analysis for the courtyard housing prototype based on the data of the city of Abu Dhabi. The aim was to determine the levels of natural daylighting and compare these with municipality standards and requirements.

As per Abu Dhabi standards, the acceptable daylight levels range from a minimum of 27.87 foot candles (300 lux) to a maximum of 278.7 foot candles (3,000 lux). For this analysis, the following input parameters were assumed as per typical finishing standards approved by housing authorities:

- reflectivity for floor finishes—20%,
- reflectivity for wall finishes—30%,
- reflectivity for ceiling finishes—50%,
- VLT for glazing—40%, and
- lux level range—minimum 300 lux to maximum 3,000 lux.

Figure 10 offers a graphical representation of the analysis, revealing that adequate levels of daylight without glare have been achieved. It can be noted that the maximum daylighting levels for the ground floor are 195.10 foot candles and 269.42 foot candles for the first floor, which ensures the comfort of the occupants. The peripheral areas of the villa get the desired daylighting level without the inconvenience of any glare. In this sense, we were confident in the approach of integrating the self-shading panels and the role these played in leveraging the buildings' environmental performance by maintaining adequate daylight levels while minimizing natural energy use.

4 Conclusion and future work

There is a remarkable interest in the MENA region and specifically in the UAE to build affordable and environmentally conscious housing projects. Such an interest has been manifested in developing large-scale integrated communities to serve the increasing demands of citizens. However, after working with authorities for 2 years, learning about various challenges, and analyzing some of the projects, we came to the conclusion that the employed design and delivery process is more focused on fast-paced delivery toward the end product rather than on the flexible delivery model that could adapt to accommodate the ever-changing requirements of future inhabitants.

In this work, we present a conceptual approach for the design and delivery of national housing in the UAE that can be considered an alternative approach to the current practices. The proposal is intended to highlight opportunities rather than offer solutions. We believe that there is significant potential in taking advantage of the state-of-the-art design and fabrication technologies, coupled with a critical understanding of the contextual and cultural qualities of dwellings in the region, toward implementing a process that can lead to affordable and customizable housing. Accordingly, the presented approach is shaped by three main strategies: first, a modular design approach that can act as a reference to develop flexible and scalable housing solutions; second, a computational statement for facade optimization toward more efficient building performance; and third, a comprehensive relationship between design and notions of prefabrication that combine precast concrete, modular utility pods, and 3D concrete printing toward exploiting its potential in efficiently realizing buildings.

While we believe that the presented work is successful theoretically, there are a series of drawbacks that can be identified. First, the outcome of the optimization process, as represented, has been validated theoretically for printability but has not yet been realized. We are in the process of establishing a 3D concrete printing laboratory to experiment with the topic and investigate the development of a smooth transition from design to fabrication. Second, we have not yet performed a comprehensive energy analysis to investigate the validity of some of the design decisions, as we only focused on the performance of self-shading elements and their impacts on the lighting quality. Finally, we have not had the chance to evaluate the cost-effectiveness of the proposed housing prototypes, which can play a major role in realizing such an approach. Nevertheless, we aim to continue working on issues related to affordability and flexibility of housing through the application of cutting-edge technology toward housing that can respond to global challenges.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material; further inquiries can be directed to the corresponding author.

Author contributions

BM was responsible for conceptualization of the research project, writing of the manuscript, and reviewing the design approach. ME orchestrated roles between authors and wrote the review on Emirati housing, and helped with environmental performance analysis. RZ worked on modeling, developing drawings and diagrams, and computational designing and simulation. RH helped with the review of the article, developing the literature review, and putting various sections together. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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