Towards an environmentally – purpose designed prefabricated housing unit:
An affordable and spatially flexible housing solution

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Abstract: The movement of population is turning into a pressing challenge for architects and urban planners in places where people are relocated and who are increasingly tasked with designing new types of housing stock, to house these ever more mobile groups of people, who exist in an almost nomadic situation. Based on the above, the research team is working on a dwelling model which blends prefabrication and energy efficiency by adopting environmental design strategies and smart technologies. Cost-saving strategies - in terms of time, construction costs and overall affordability - have been employed, while high standards in architectural design and construction, user comfort, spatial flexibility, and site adaptability have been adopted. The team is confident that the proposed product will be able to keep abreast of comparable units and will be able to meet the needs posed by the current housing challenges in Cyprus and elsewhere.

Key-Words: - modular housing, sustainability, prefabrication, smart technologies, social support -

1 Introduction

Many places around the world, but more specifically the Eastern Mediterranean region have witnessed significant population shifts and relocations both as a result of natural disasters and military conflicts, and migration generated due to seeking the opportunity for induction into a system of economic production which will supposedly lead to a better quality of life [1-2]. In numerous occasions, any such trip results in increased demands for housing, whether it is generated due to an emergency or demand resulting from economic migration. By default, such housing needs to be erected expediently and inexpensively and the concept of prefabrication lends itself to both of those parameters.

At the same time, the challenges posed by increased energy consumption and increased housing needs are at the forefront of current discussions [3-4]. The use of renewable sources (more specifically solar harvesting) has become an important, almost essential parameter in the effort to reduce a building's carbon footprint, and consequently the need for prefabricated off-grid housing development becomes a necessity [5]. Additionally, the conditions due to the recent recession, have had a severe impact on the construction industry, the effects of which are going to be reflected on the housing market for a prolonged period [6]. On the other hand, the basic parameter for the construction of a house has always been financial accessibility, along with the time and ease for its completion [7].

In this context, housing prefabrication emerged as a solution providing energy and cost savings. At the same time, it is linked with reduction of environmental impacts as well as to the development of green construction practices [8]. This paper presents a new off-grid prefabricated residential model, the "Prefab Eco Smart House," which is presented as an alternative to conventional construction methods, aiming to provide an affordable, spatially flexible and site adaptable structure by adopting environmental design strategies and latest trends in construction related technologies.

1.1 The Case of Cyprus

In Cyprus, the prefabricated building industry is still at its infancy of development leading to prefabricated housing structures usually being constructed with low-cost and inferior quality materials and construction methods. The units themselves are primarily used as secondary or ancillary structures [9-10]. During the severe economic downturn on the island, the interest in prefabricated houses increased, mainly due to the low cost of this type of structure compared to what's

offered by conventional houses. This trend persists even after the rebound of the economy, but unfortunately without any significant improvements in the output of the product [9].

Having this in mind, the research team is working on a prefabricated housing unit, the "Prefab Eco Smart House" the main aim of which is to provide a competitive alternative, in terms of cost and habitation standards while offering ease of configuration and expansion when compared to conventional prefabricated housing units currently on offer or under development in Cyprus.

2 Methodology

The proposed investigation methodology is based on an extensive literature review of prefabrication methods and precedents in terms of both their design and construction, while aspects of environmental responsibility are examined through two more prongs of investigation. The first prong is provided by a sample taxonomy that delves into the investigation, assessment and categorization of existing prefabricated housing unit systems and their characteristics. The second, deals with the conceptualization of the "Pre-Fab ECO Smart House" project, i.e. for an optimized version of a prefabricated housing unit, based on the adoption of environmental design principles governed by technological excellence.

2.1 Literature Review

Housing prefabrication is offered as a solution in cases of emergency housing and to backfill and address affordable housing needs in cases where public entities and the private development sector cannot keep up with demand [11]. In the first instance, the component production cycle and the allocated budget are of the utmost importance, together with ease of transportation and assembly on- site. This also addresses short-term housing needs and the stock may then be disassembled and redeployed as needed down the road. As a result of these expectations, more time may perhaps be required for design and construction so as to afford a greater degree of flexibility both in terms of configuration and expandability of the unit as well as the configuration of clusters of units in variable morphologies and finishes.

In the Cypriot context, both of these two outlooks need to be addressed [12] as the country finds itself in an economic recovery period characterized by a demand of affordable housing by individuals and young couples and families, as well as facing the necessity to house refugees arriving on the island's shores from the conflict-ridden lands of the Eastern Mediterranean.

2.2 Taxonomy of Prefabricated Structures

As part of this project's design process, the study team emphasized the identification, study and understanding of other prototypes as well as applications of similar technologies and design approaches. The target set was the preparation of a detailed analysis to get a thorough typological understanding, upon which the team would subsequently base its design guidelines.

More specifically, fifty case studies were examined according to three prefabrication typologies: modular, prefabricated elements and containers [13]. All case studies which formed the database were chosen after a methodical selection process which examined specific energy, technological and architectural related design qualities [8, 10]. The present taxonomy began by considering building management systems (BMS). Subsequently, an investigation occurred as to whether a building may become autonomous in terms of energy, thus being able to be operated off grid. The environmental aspects were then examined and the building materials and methods of construction were analysed, followed by a structural analysis and evaluation with respect to the siting of the proposed unit.

These results were thoroughly presented in two prior papers [8, 10], and it was on these research processes that the analysis and determination of the final design strategy for the proposed unit was attained.

3 PreFab Eco-Smart House

Having obtained an understanding of the current trends in the context of the prefabricated construction industry, the research team attempts to create a "Pre-Fab ECO Smart House", an improved version of a standard prefabricated housing unit following an environmental design approach governed by technological excellence. A detailed description of the proposed design is given below.

3.1 Design Objectives

Overall, the model is governed by the following characteristics:

– Concerning its construction and according to the research, the unit will be mainly built off-site based on a "building kit" consisting of several assembled components, while the possibility for future expandability is also examined.

- Regarding the structural system, the research results indicate that this should entail a post and beam method either in a complete structural, balloon frame or self-supported system.
- In terms of the environmental aspects involved in the design, the research determined that the unit's active systems should offer an on-site energy production capability by integrated photovoltaics (PVs), or applied solar thermal systems (STSs) [14]. The unit's passive design strategies such as direct solar gains, natural lighting and ventilation, shading systems, and thermal insulation should be applied to achieve energy savings and thermal comfort for the occupants.
- Similarly, reduction of energy requirements resulting in energy savings may be met by integrating smart building management systems.
- Utilizing recycled or reused materials during fabrication and construction will help make the unit eco-friendlier.

3.2 Architectural investigations

Having defined the key points of the design process, as outlined above, the architectural investigations were initiated with the exploration of several architectural archetypes, varying from complex, modular forms to more conventional layouts, following the idea of achieving ease of unit assembly during all stages. Throughout the research, the study team understood that conventional forms following the prefabricated element typology, better match the relevant construction industry in Cyprus, as they can be better utilized given the current levels of the industry's 'know – how.'

3.3 Construction techniques

The research team made an in-depth study of a flexible construction system, always keeping in mind that design would follow the idea of a "kit-of-parts model" aiming to provide flexibility in construction by offering multiple assembly possibilities that will allow future reconfiguration and expandability of the unit.

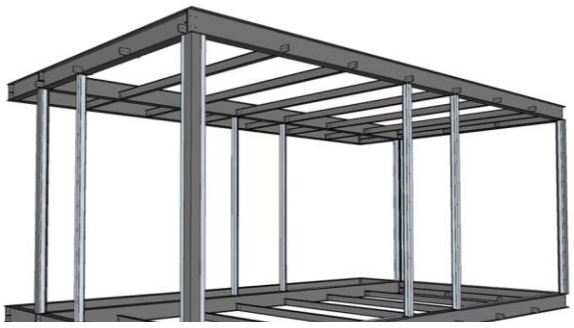

Figure 1 Three-dimensional representation of the construction system of the unit.

The design decisions led to a structural system composed of specially configured elements categorized in three main categories: (a) the primary steel structural elements, based on IPE220 which pertain to the perimeter beams of the main unit and on SHS100x8x100 at the corner column, (b) the secondary steel structural elements, based on IPE100 profile and (c) the steel construction elements which support the panels and enable their connection to the perimeter beams (Figure 1).

The adaptation of this system is expected to lead to standardization in the production process and keep the overall construction costs at a minimum.

3.4 Environmental approach

Along with all the previously mentioned design decisions, the design team performed an evaluation on the various types of bioclimatic design, which could be applied in the core unit. This evaluation covered, heating, cooling and daylighting strategies, improved microclimatic conditions aiming at creating ideal thermal conditions in the interior spaces while achieving a reduction in energy consumption and operating costs.

Natural lighting is achieved with the strategic placement of the openings so as to also ensure natural cross ventilation when required, which addresses the team's selected cooling strategy. Considering heating strategies, the design of the unit allows direct solar gains, thereby reducing the mechanical heating loads, while the passive shading systems prevent the over-heating of the unit during the summer period. More precisely, the installation of south-oriented overhangs is recommended, to make use of the best insolation and shading conditions, while for the same purpose, in the unit's perimeter, the design team installed drilled solar protection panels. The horizontal passive shading systems also act as receptors for a semi-transparent PV system, composed of PV cells. At the same time, proper thermal insulation, the creation of a thermal buffer zone on the north side of the unit and the overall air tightness of the shell, help minimize unwanted energy exchanges with the outdoors.

Recycled materials were widely used in the ceiling, cladding and flooring surfaces, as well as in the unit's furnishings (OSB). The main ecological strategy of the unit's design however, is that it offers the ability to actually reuse the same modular elements of the building, via a process of transforming or redesigning it based on possible changes in the needs of the occupants, something which is also enabled by the dry assembly of the kit of parts.

3.5 Automation system and software

The term "Smart-House" is addressed with the installation of sensors which constantly record relative environmental parameters, passive elements (openings and overhangs) as well as heating, cooling and lighting components. The installation of a smart automation system to regulate and assist in the efficient energy management of the unit leads to controlled energy consumption and at the same time ideal conditions for minimizing excesses. Another element defining the PreFab Eco Smart House is the automation of the unit via passive interaction with the user and by building-in a user profile based on recording behavioural patterns.

3.6 Design brief

The design decisions described above, led to a core unit of 21m^2 due to a seven by three grid of one-meter intervals with a shell created by 80-millimeter thick Ecopanels. The shell of the unit is formed by assembling panels, which may be installed and disassembled by a relatively straight-forward procedure, making the unit very flexible in terms of assembly (Figure 2).

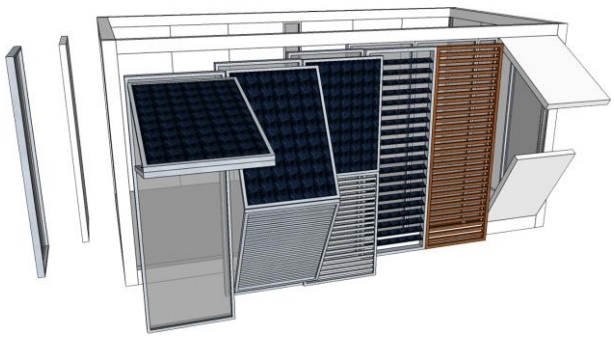

Figure 3 Illustration of the shell of the unit; formed by assembling panels.

The structural system as described in paragraph 3.3, allows the proposed unit to expand in both horizontal and vertical axes up to two floors, thereby giving the option to adopt several layouts which could result in a unit of 40m^2 or 60m^2 depending on the needs of the prospective users.

Figure 2 Three-dimensional photorealistic representation of the result.

The team is currently in the process of developing a prototype, which also allows for the formation of clusters, as it consists of two main units which form a small family house (Figure 3, Figure 4).

Figure 4 Images of the assemblance process of the structural frame of the units, which is consisted by two main units, thus forming a small family house.

To provide a quantitative account of how the unit performs, preliminary computer simulations were carried out using the official software of the Republic of Cyprus, iSBEM CY and daylighting performance analysis software. The proposed housing model was certified with an "A" rating, the highest classification level, which reaffirms that the proposal is an energy efficient building with low operating costs. To confirm these results, a subsequent step will be to undertake a more extensive evaluation on the actual prototype.

This proposed unit should be able to meet the needs for users varying in profile from emergency housing for migrants, to housing for young couples or families, or anyone seeking to manage a household of moderate means with the added advantage of a reduced construction timeframe, lower construction and life cycle operational costs, and a high level of adjustable, bioclimatic-oriented building components.

4 Conclusions

The proposed off-grid prefabricated residential model, the Pre-Fab Eco Smart House, was designed to improve the day-to-day life of its users, while at the same time to contribute to environmental protection policies and act as a stepping stone towards a sustainable Cypriot housing policy which will take no shortcuts when it comes to architectural design standards. The team's aim - concerning cost reduction - is to ensure that the proposed unit will raise the bar compared to the conventional prefabricated housing units currently produced in Cyprus when examining its overall operational and life cycle costs. All challenges the team came across to this stage, have been faced in terms of optimizing the overall design performance to lead to an affordable, spatially flexible and site adaptable construction.

Lastly, the originality of the design, as compared to comparable units on an international scale, has several advantages when it comes to reducing construction time, future unit maintenance, and curbing operational costs, while also ensuring ease of configuration and modular unit expansion.

4.1 Further research

During the construction of the first prototype, construction details which could not be fully evaluated through the preliminary design stage will be further explored and finalized. The research team plans to perform on-site analysis of the unit's environmental behaviour. This will be achieved by utilizing specialized sensors which will be strategically installed. The data obtained from these sensors, will be used to calculate the necessary heating and cooling loads to maintain thermal comfort for the users. Parallel to the above, a lighting analysis will be performed to determine the unit's ability to offer increased comfort to its potential users. At this stage of the research the final design while also undergo a more thorough cost estimation and market analysis.

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