**Discussing sustainability in prefabricated buildings**

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ABSTRACT

The paper focuses on advancing of sustainability in prefabricated buildings. The building prefabrication company Theodoros Iliadis was used as the role model in order to present the changes imposed on its initial prefabrication system through the pursuit of sustainability. More specifically, the gradual integration and assessment of the sustainability principles in the building envelope and structural framework of the prefabricated buildings of the company are presented, starting from the first schemes and reaching the most recent ones, which are purely driven from the optimization of the building performance. The latter was achieved by applying a holistic approach through the development of a new, innovative prefabricated wall element, designed to exhibit optimized structural, hygrothermal, energy, acoustic, fire and environmental performance. The methods and tools that were used for the design and verification of the new building element are presented along with the results for its performance. Beyond studying the new building element alone, it was regarded essential to examine its contribution to the sustainability of an overall building unit. Through this approach, the new building element and construction scheme are systematically assessed and the achievement of objectives is verified.

KEYWORDS: prefabricated buildings, sustainability, energy performance, LCA

## 1. Introduction

Prefabricated constructions have their origins in antiquity, as significant works of past civilizations were configured with elements constructed beforehand, which were then transported and assembled on site. In those times, prefabrication was merely a solution where there were no suitable local materials. In more recent times, prefabrication was used for covering wide scale building needs, i.e. in post-war periods, when numerous temporary and emergency prefabricated buildings, mainly houses and schools, needed to be built at minimal cost and at a very short time. However, the extensive deterioration of postwar prefabricated buildings, which eventually failed to meet minimum structural, waterproofing and fire safety requirements, contributed to the growing unpopularity of prefabricated systems worldwide (Pons, 2014).

In the past 50 years, interest has arisen in new building technologies and the industrialized construction. Emphasis is given on the added value of industrialized architecture and technologies, which includes the ability to provide higher quality within minimum construction time and costs, increased possibilities for customization and adaptability, reduced environmental impacts and advanced sustainability (Yang, Yue, 2021).

Nowadays, prefabricated residential buildings account for only 15% in Europe. Even lower penetration of prefabricated buildings designated for housing purposes is met in the Mediterranean countries (Apaydin, 2011); for example, in Greece the rate of prefabricated residential buildings ranges around 2%. However, there are signs that this rate is eventually growing, which is supported by the recently observed increasing share of low-rise residential buildings.

The main types of prefabricated building concern structures made of wood, reinforced concrete or steel, as well as composite systems, which usually combine concrete with steel elements. In low rise buildings (i.e. up to 2-3 storeys above ground) one of the most widespread prefabrication type employs the steel framework with lightweight walls, due to the easiness and speediness of site installation, as well as the adaptability of the design to many architectural morphologies.

Given that the building design objectives have been shifted in order to go along with the low-carbon, environmental protection, green and energy-saving sustainable development requirements, it is crucial for the companies of this particular building's sector to integrate such principles in their building design and construction.

In this paper, the evolution of the construction technology employed by the company Prefabricated Buildings Theodoros Iliadis is presented, highlighting the gradual integration and assessment of the sustainability principles in the building envelope and structural framework.

The optimization of the building's sustainability outline was achieved within the research project SU.PR.I.M. (SUstainable PReconstructed Innovative Module), which aimed at the redesign of the prefabricated buildings provided by the company, through the development of an innovative building wall module. In the research project academia (Aristotle University of Thessaloniki) is collaborating with an SME partner (Prefabricated Buildings Theodoros Iliadis) in order to bring innovation in the market and achieve economic development based on knowledge and sustainable specialization.

## 2. Methodology

The paper intends to highlight the changes induced to the constructional techniques of the building envelope configuration and the structural framework used in the prefabricated houses of Theodoros Iliadis' company. The examined prefabrication system has a steel framework and the transformation of the structural and building envelope configuration stemmed from the pursuit of sustainability.

More specifically, the initial building configuration of the prefabricated houses is presented, along with potential issues appearing during the use of the buildings. The wish for addressing these issues and improving the quality of the construction created the need for the building configuration's evolution. Within this framework, the new constructional approach is described and assessed in terms of structural, hygrothermal, energy and environmental approach.

The structural assessment involves the changes that are related to the load bearing system. Although the steel framework remains the main structural system of the buildings, it was considered necessary to reduce the total weight of steel components by transforming the wall elements to load-bearing ones. This new structural system would not only enhance the structural performance of the building against all imposed loads (including both static and dynamic ones) but would also contribute to decreasing the environmental impact of the construction through its life cycle.

The hygrothermal assessment entails the performance of the building elements against heat and moisture transfer. It also includes the analysis of the thermal bridging effect, which is crucial for steel constructions, as well as the thermal mass, which influences the building performance, especially in the Mediterranean climate.

The energy performance concerns the heating and cooling loads that are required in order to sustain the desired conditions indoors. Their extent is defined by the building envelope configuration and the building's use. For the study, the heating and cooling energy needs for a low-rise single family building are estimated with the help of a dynamic simulation tool (EnergyPlus) considering various thermal insulation levels.

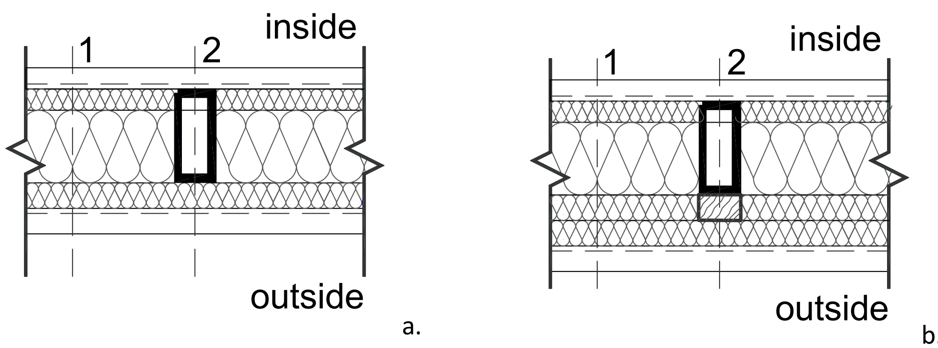
The energy consumption during the operational phase defines the impacts on the environment during this particular phase, but it is essential to apply a holistic approach and include all life cycle stages in the analysis. For assessing the environmental impact, the procedures described in relevant ISOs were applied, along with data from international databases and information from the Greek market and the company.

### *2.1. The evolution of the constructional system*

The prefabrication company started its activity in 1973. Since its foundation, the company employed a steel framework for the structural form of the buildings, composing of steel columns and beams.

Till 2009 the walls were constructed as lightweight elements, which composed of horizontal and vertical steel hollow sections forming frames, extruded polystyrene for filling in the gaps between the steel elements, woodwool cement boards, used for forming the outer surfaces of the wall, and cement mortar as their finish (Figure 1.a.). This configuration, although satisfactory for its energy performance as the U-values were adequately low, encountered thermal bridges along the steel elements, which occasionally caused surface vapour condensation during winter (Tsikaloudaki et al, 2010).

In order to minimize the thermal bridging effect of the metal frame, a simple way for mounting the wood wool cement boards was suggested (Figure 1.b.): instead of nailing the boards directly on the steel frame of the wall, a wooden element covering the area of the metal was placed between the steel frame and the wood wool cement boards. The extra gap caused by the presence of the wooden elements (3 cm thick) is filled with extruded polystyrene. By this way, the area weighted U-value of the wall element was decreased by approximately 20%, while the linear thermal transmittance that denotes the thermal bridging effect along the metal frame was reduced almost in half. Relevant changes, proposed for sensitive areas of the building envelope, as for example around the windows, lead to a significant decrease of the thermal bridging effect, as well as to a substantial improvement of the energy performance of the building envelope. However, the construction remained light weight, with moderate thermal mass (, due to the extensive use of thermal insulation materials in the building envelope, which occasionally caused thermal discomfort on hot summer days.




a.

Layers, section 1:
- Cement mortar
- Wood wool cement board
- Thermal insulation filling
- Wood wool cement board
- Cement mortar

Layers, section 2:
- Cement mortar
- Steel hollow section
- Wood wool cement board
- Cement mortar

b.

Layers, section 1:
- Cement mortar
- Wood wool cement board
- Thermal insulation filling
- Extruded polystyrene
- Wood wool cement board
- Cement mortar

Layers, section 2:
- Cement mortar
- Steel hollow section
- Wood beam
- Wood wool cement board
- Cement mortar

Figure 1. Schematical drawing of the prefabricated wall element constructed by the company Theodoros Iliadis in its lightweight form

The prefabrication company, driven through its objective for the continuous improvement of its constructions through innovation for well being and sustainability, decided to develop more its constructional system in order to further systemize the construction, reinforce the load-bearing capacity and provide even more sustainable buildings. Within this context, a change to the structural system was applied, which merely involved the transformation of the wall elements to load bearing ones and the increase of the thermal mass. The optimization of the building element with regards to its configuration, materials and performance was based on the sustainability principles and requirements.

The new wall element still entails a steel frame, but it is now formed as a composite panel, comprised of two lightly reinforced concrete plates, 5cm thick each, positioned on either side of the steel frame (made of vertical metal hollow elements). The cavity between the metal hollow elements is filled with thermal insulation boards, and the whole wall element is insulated with ETICS. The building envelope is further insulated externally with expanded polystyrene.

In fact, the configuration of the building element is very similar to its previous form, but two substantial changes have been imposed: (i) the woodwool cement boards that formed the outer surfaces of the wall have been replaced with the reinforced concrete panels, adding thermal mass to the component, (ii) the building element has acquired load-bearing capacity, as the reinforced concrete panels are connected to the steel sections and participate in the structural performance of the building.

The main structural framework of the building consists of metal beams and columns. The connections between the wall element were studied in detail; firstly the joints were designed considering welding between the joining parts, but later bolting was employed, in order to systemize the construction. Lately, a composite connection is being used, through which the main steel elements are connected with the wall elements both through bolting and casted concrete.

In this way, a new wall system was designed, optimized and validated through a process that involved both laboratory and field tests, as well as analytical simulations, covering all aspects of sustainable building performance, i.e. the structural, hygrothermal, energy, fire, acoustic and environmental performance.

## 3. Design, assessment and validation of the new wall element

The objective governing the building module's development is to create a wall system that will be capable, through the selection and the configuration of material layers forming the assembly, to meet high level requirements regarding (Tsikaloudaki et al, 2020a):

- Structural efficiency (safe response to the imposed loadings and load bearing capacity).
- Advanced thermal behaviour (i.e. thermal performance enhancing the whole building's energy efficiency; in this light this advanced behaviour will contribute towards the construction of nZEB, which represent current trends in the respective regulations).
- Excellent hygric performance (avoidance of surface and interstitial water vapour condensation, effective response against driving rain/rain loads).
- Efficient sound insulation levels.
- Reduced environmental impacts during its life – cycle (i.e. favourable environmental footprint).

### *3.1. The structural performance*

The first steps of the study were to configure the basic form and estimate the dimensions of each specific part of the composite panel, in order to cover specific requirements. The analysis was made through simulation, using the finite element method, and included the basic parts of the building module, i.e. the metal hollow elements, the concrete panels, the connections between the metal hollow elements and the concrete panels, as well as the connections between consecutive building modules and between the main bearing structure and the wall elements.

The initial study indicated the properties of the main parts of the building element. The analysis of the basic form of the building element was tested against buckling and fire. Apart from the analytical calculations, experimental tests were run for defining the mechanical and physicochemical properties of the concrete panels for different compositions, as well as the performance of the whole building element as regards its strength and its performance against static and dynamic loads.

Special attention was given to the connection of the building panels with the main bearing organization, usually composed of HEA100 or HEA 120 steel sections. Two connection types were studied: welding and bolting, with the latter being considered as more appropriate in order to guarantee high quality joints made in situ. For both connection types, special joints were designed and tested in praxis for their easiness and feasibility of construction through real size samples.

Both the building element and the whole structural system, including the building element, the steel columns and beams, were tested experimentally in order to define their actual performance in static and dynamic models. The experimental measurements showed the load bearing capacity of the wall and indicated that it performs remarkably well both under in-plane and out-of-plane and dynamic loading (Nikolaidis et al, 2020).

More specifically, it was found that the overall performance of the wall system was significantly enhanced due to the presence of the steel mesh reinforcement and the embedded shear connectors, which prevented a potential brittle failure. The obtained maximum capacity was 22 kN under out-of-plane bending loading, and 13.0 MPa under concentric axial compression. The maximum shear resistance recorded under diagonal compression was equal to 3.0 MPa.

### *3.2. The hygrothermal and the energy performance*

The basic form of the building element contains a layer of thermal insulation, 5 cm thick, located on the core of the composite panel, between the hollow steel sections. However, at the areas of the metal beams the lack of thermal insulation causes excessive heat loss and intense 3-D heat flows. These phenomena were studied thoroughly, even after the integration of a thermal insulation layer on the external side of the building element. The special studies showed that the areas around the vertical and diagonal steel sections are characterized by increased heat flows and significant temperature differentiations, which were decreased as the thermal insulation thickness increased.

These phenomena caused by the presence of the steel elements on the composite panels and the inhomogeneous layers composing the panel, necessitated the use of special methods in order to estimate the thermal performance of the building element, i.e. the calculation of the thermal transmittance (U-value) and thermal capacity coefficients, the analysis of the thermal bridging effect on the joints of the building element, etc. All analyses were based on 2D energy flow calculation tools. In order to validate the thermal performance of the building element, laboratory measurements were also employed.

The hygric performance was also studied in detail, with a special focus on the phenomena of surface and interstitial condensation, as well as the performance of the building element against driving rain. For this study a specialized simulation tool (WUFI 2D) was used.

Additionally, the energy performance of low-rise residential buildings that employed the new wall system was improved when compared to conventional buildings. More specifically, the energy needs of the prefabricated building were found lower by 2–15% than the ones calculated for a relevant conventional building (Tsoka et al, 2020). The difference in energy needs varied as a function of the thermal insulation thickness; it is interesting to notice that as the thickness of the thermal insulation increased, the difference in energy needs between the two wall configurations became lower.

### *3.3. The acoustic performance*

In general, lightweight prefabricated constructions are associated with bad acoustic performance, as the light panels do not contribute to the protection of the interior space against noise. In order to ensure the optimal performance of the building element in a holistic way, a special acoustic study was conducted, which aimed firstly at the identification of critical points or potential problematic behaviors and secondly at the proposal of measures, if indicated so by the previous steps.

More specifically, the sound reduction index was calculated with the use of a special simulation tool (INSUL) and measured in the certified Laboratory of the Architectural Technology of the Aristotle University of Thessaloniki.

The analytical study presented interesting results. As regards the air-born sound, the noise protection capacity of the building element is found equal to 51 dB, with the minimum value set at 50 dB. For external noises, the average equivalent sound pressure level (LA,eq)) was calculated for noise level equal to 65 dB, 70 dB and 75 dB. In all cases the parameter ranged below the threshold, which is 35 dB. It is interesting to notice that the increase of the exterior noise level by 5 dB lead to the increase of the parameter by 11% (for 70dB) and 18% (for 75dB).

With the laboratory measurements, the above performance indicators were validated and a parametric analysis on different thermal insulation materials and thicknesses was conducted, in order to investigate all alternative configurations of the building element and their acoustic performance (Tsirigoti et al, 2020).

### 3.4. The environmental performance

The environmental performance of the wall system aimed at the estimation of its footprint during its first life stages, i.e. from raw material extraction through materials processing and manufacture (from cradle to gate). The study expanded to the building level and included all building elements composing a single family residential unit throughout its whole life cycle, i.e. from all raw material extraction and processing, manufacture, distribution, use, repair and maintenance, as well as disposal or recycling.

The environmental impact, within the system boundaries was calculated according to the principles of ISO 14040, ISO 14044, EN 15804 and EN 15978. Ecoinvent database provided the environmental (LCI) data, while all remaining information and inputs derived from the building construction plans, the Greek market and from personal communication with the prefabricated building manufacturer.

As regards the analysis on the building level, the results indicated average contribution to the total life cycle impact for the upstream processes (A1-A3; raw material, supply, transport, manufacturing) of about 40.0%, while for the core processes (A4-A5; transportation, building construction) this value is low (0.55%). The replacement of materials and components (B4) contributed with ca. 30% to the total life cycle impact and the energy use-operating phase (B6) with a total of 28% (heating 1.9%, cooling 10.6%, DHW 15.7%). The shares of each life cycle change with regard to the climate context of the building's location (Tsikaloudaki et al, 2020b).

Considering only the embodied impact, the results highlighted as the main average impact contributors the windows, the steel sections, the heating and DHW system, the XPS insulation and the cooling system.

## 4. Conclusions

The paper intended to present the evolution of the constructional system used by a Greek company for prefabrication buildings, which was based on the pursuit of sustainability. Beyond the description of changes that were merely related to the optimization of the structural, hygrothermal, energy and environmental performance of the wall element and the building envelope, emphasis was given to the presentation of the holistic approach which was employed in the research project SU.PR.I.M. in order to maximize the sustainability of the constructions and gave extra innovative character to the project.

The multifunctional innovative building element that is developed through the SU.PR.I.M. project is now the main part of the prefabricated buildings constructed by the participating company. The optimality of the project's results was ensured by the continuous participation of the company in every stage of the research, which guaranteed the achievement of a high technological readiness level.

The new prefabrication system has resulted in the systemization of the elements' production and buildings' construction, leading eventually to the increase of its productivity, the improvement of building's quality, as well as the reduction of time and cost of building's erection. The new constructional system offers high adaptability to any climate or regulation requirements regarding the structural, thermal and energy performance. Additionally, the robustness and the advanced performance of the new prefabrication system, along with its certification and systematic analysis, has attracted new consumers and it is expected to increase the financial cycle of the company.

Beyond the benefits of the company, the new prefabrication system leads to an energy efficient, low carbon, sustainable building. The energy needs during its use is lower than the ones derived for conventional buildings, resulting to lower environmental impacts and lower operational costs. The environmental impact is not only minimized during the use phase of the building, but carefully studied to cover the whole building life cycle. Additionally, the enhanced indoor conditions, considering not only the thermal but also the acoustic environment, contribute to the health and the well being of the building users.

In that sense, the new prefabrication system developed through the research project SU.PR.I.M. and applied through the prefabrication company Iliadis brings the most positive impacts to the company, the environment and the society in general.

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Acknowledgements

This research has been co-financed by the European Regional Development Fund of the European Union and Greek national funds through the Operational Program Competitiveness, Entrepreneurship and Innovation, under the call RESEARCH – CREATE – INNOVATE (project code:T1EDK-03042).