Building a new sustainable preconstructed building element

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Abstract. This paper presents the primary findings of a research project, aiming to introduce an innovative building module with improved thermophysical and mechanical properties that will serve as a bearing element and/or as an internal partition wall in prefabricated residential buildings. This new building module will comply with current requirements as regards its operation and performance. For the purposes of this investigation, the overall performance of the considered building elements is ensured by the proper configuration and assembly of the involved layers and is verified through analytical and experimental analyses, as well as through measurements at accredited laboratories. The objective of this innovative building element is to establish a building envelope with a high structural, hygrothermal, energy, acoustic, fire and environmental performance, while reducing both the time and cost required to complete its construction. Evidently, the accomplishment of this objective suggests various benefits on both the business sector and the research community. Moreover, the utilization of this building module is influential in terms of social impact, as it promotes the construction of buildings with advanced energy and environmental performance that can furthermore mitigate and adapt to the climate change impacts.

1. Introduction
Industrialized building systems, developed around the central axis of prefabrication, are one of the blooming sectors of current construction technology and practice. Offering several advantages related to all aspects of the construction process, not only with regard to practical factors (e.g. reduction in cost and time, ease and speed of assembling and disassembling the prefabricated components, etc. [1]) but also to issues of wider concern (e.g. improved environmental performance and working conditions [2], reduction of construction process-related waste [3]), prefabrication represents a strong candidacy for the prevailing future building systems. On the other hand, industrialized building systems are related with disadvantages, among which a relative and inevitable inflexibility in forms and shapes and the lack of experience in several parts of the world can be listed [3].

Evidently, this construction method is not applied to the same extent across all countries, even of the same continent. Prefabricated building systems are reported to be widely used in Singapore, Japan and European countries [3]; in fact, the corresponding market share of the housing industry in Sweden may be higher even than 80% [2]. Nevertheless, in Greece, also a European country, the penetration of such systems into the construction industry is very low; the conventional building construction approaches of concrete bearing elements and brick non-bearing walls, constructed mainly in situ, prevails by far. In a similar way, the low adoption level of prefabrication seems to characterize other regions around the
Mediterranean Sea as well, e.g. Turkey [4]. This condition could be attributed to, among others, the architectural and constructional practices traditions, the lack of expertise, the absence of accurate information and of efficient communication, etc. In fact, in several Mediterranean countries, prefabricated construction was regarded as of being a solution of low quality characteristics. The focus of this paper lies on the presentation of an innovative framework for the development of a novel prefabricated building element. This component will be used as a vertical building element (load bearing component and/or internal wall) for the construction of buildings of relatively small height in Greece. The core objective of this elements’ design and development effort and process is the evolution of a building component that can be characterized by advanced rheological, thermophysical and mechanical properties, while at the same time it fulfils adequate levels of performance regarding all the safety and functionality requirements accompanying modern constructions. In this context, a holistic approach to its efficiency optimization is addressed, in terms of structural, hygrothermal, energy, fire, acoustic and environmental performance. The study of the prefabricated element is based on both analytical (calculations, simulations) and experimental (tests of several types, extending from the material level to the whole component’s scale) methods and processes. Given the background, several alternative solutions for the configuration of the element are analysed. This work is conducted within the framework of the research project SU.PR.I.M. (acronym of Sustainable PREconstructed Innovative Module), which is elaborated through the partnership of Aristotle University of Thessaloniki and the company Prefabricated Constructions Iliadis [4].

The building module under development will be capable, through the selection and the configuration of material layers forming the assembly, to meet requirements of high level with regard to the following axes of performance:

- Structural efficiency (safe response to the imposed loadings).
- 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.
- Acceptable resistance and response against the fire action, in case such an incidence occurs.
- Reduced environmental impacts during its life – cycle (i.e. favourable environmental footprint).

The monitoring of the conditions prevailing in an experimental chamber will complement the analytical calculations and the experimental measurements.

It is expected that the development of such an element will underline a comprehensive evolvement, not only regarding the scientific aspect of the issue (conduction of specialized studies) but also regarding industry adoption. Also, the effort to develop such an element could be considered as socially beneficial, as it contributes towards buildings of advanced environmental performance, and therefore towards climate change mitigation.

In this paper, the basic thematic axes and the preliminary results of the SU.PR.I.M. are presented. The research project, with a duration between June, 2018 until December, 2020, is co-funded by the European Union and national sources within the framework of the action “RESEARCH CREATE INNOVATE” of the Operational Programme Competitiveness, Entrepreneurship and Innovation 2014-2020 (EPAnEK).

2. Designing the prefabricated building element
In this project, the prefabricated building element has the form of a composite panel; two lightly reinforced concrete plates, 0.05 m thick each, are positioned on both sides of a vertical (and occasionally diagonal) metal hollow element. The distance between the vertical hollow metal elements is about 0.70 m – 1.00 m and the gap is filled in with a thermal insulation material, usually expanded or extruded
polystyrene. The prefabricated panels are connected to each other and to the columns/beams with anchors, adequately settled for this construction.

The configuration of the aforementioned building element ensures an adequate stiffness to support the bearing structure and the load’s transfer, while it retains the benefits of a lightweight construction; at the same time, it has a sufficient thermal mass to restrain overheating during summer.

In order to optimize the design and the overall performance of the building element, several studies are being conducted. These studies concern the structural, hygrothermal, energy, acoustic, fire and environmental performance and they are based on analytical and experimental methods.

2.1. The structural performance

The first steps of the research 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, there are experimental tests running for the definition of 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 is given to the connection of the building panels with the main bearing organization, composed of HEA100 or HEA 120 metal beams. Two connection types are 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 are 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, are going to be tested experimentally in order to define their actual performance in static and dynamic models. The experimental measurements are still in progress, but the first ones show that the building element performs remarkably well in in-plane and out-of-plane loading.

2.2. The hygrothermal and the energy performance

As mentioned in the previous section, an insulation layer of thickness of 5 cm is located in parallel to the two concrete panels and between them, i.e. in the core of the prefabricated assembly. This layer does indeed provide a level of thermal insulation that could even be adequate for the required thermal protection at warm regions of Greece. However, the formation of the composite panels is not constant and invariable over their whole area. As explained earlier, metal beams connecting the two concrete panels interrupt the continuity of the afore-mentioned insulation layer creating areas characterized by excessive heat loss and intense 3-D heat flows. The heat flows both at these areas and through the whole building element are thoroughly studied, taking into consideration the integration of a thermal insulation layer at the external surface of the building element. In the context of the studies, different scenarios regarding the thickness of this layer are dealt with. As expected, the results of the conducted studies show that the metallic elements integrated within the structure of the examined building module induce noteworthy variations in the heat flow-related results; specifically, increased heat flows and temperature variations become evident at the areas of the metal beams. The differentiations at the areas of the metal bars in comparison to the rest of the component are reduced as the external thermal insulation layer’s thickness increases.

All the analyses related to the thermal performance of the examined elements (i.e. calculation of the coefficients expressing the thermal capacity and the thermal transmittance (U-value) of and via the examined element respectively, the analyses of the heat flow at the joints of the building elements
(thermal bridges) etc.) are conducted with the use of 2D energy flow calculation tools. This is due to the fact that the inhomogeneity of some of the layers integrated in the panels, as well as the structure of the panels itself (inclusion of metal components) create thermal fields and flows that cannot be covered by simple one dimensional calculations.

In the context of an effort to enhance even further the thermal behavior of the studied element, the possibility of using phase change materials is investigated (these materials may significantly improve the total thermal response of building elements by storing and releasing significant amounts of energy at various temperature conditions). The possibility examined is the one of the addition of PCM in the inner concrete panel. This addition is expected to be proven favorable for the control of the interior surface temperature and, as a result, for the improvement of building’s energy performance. The two PCMs, the addition of which is investigated, are in the form of powder and have melting temperatures of 24°C and 28°C. Their proportions in the concrete mixture are 10% and 20% (so that an image for different concentration cases can be acquired).

Apart from the previously mentioned computational analyses, laboratory measurements are also realized for the validation of the thermal performance of the examined element, and also of parameters related to this performance. Specifically, the guarded hot box of the certified Laboratory of Architectural Technology is used for the measurement of the U-value of the element (according to EN ISO 8990); additionally, Differential Scanning Colorimetry method and a thermal camera are used for the examination of the thermal behavior of the panels incorporating phase change materials.

The studies of this entity are complemented by the examination of the hygric performance of the element under study. A main axis of analysis is the performance of the examined component against moisture appearance and/or accumulation on its surface and in its mass related to water vapor condensation (surface and interstitial condensation respectively. Simple and more complex computational approaches are employed. The second issue regarding the studied component’s hygric behavior that is investigated is its response against rain loads. In the context of this study, and where necessary, a specialized simulation tool (WUFI 2D) is used. The hygric performance is 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) is used.

2.3. The acoustic performance
In general, lightweight prefabricated constructions are associated with poor acoustic performance for residents, since 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 contemporary acoustic study is carried out, which aims firstly at the identification of critical points or potential problematic behaviors and secondly at the proposal of measures, if indicated so by the previous step.

More specifically, the sound reduction index is calculated with the use of a leading simulation tool (INSUL), while the above index is measured in the certified Laboratory of the Architectural Technology in the Aristotle University of Thessaloniki.

The analytical study has underlined interesting results so far. 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. The introduction of PCMs slightly increases the Sound Reduction Index.

For external noises, the average equivalent sound pressure level (LA,eq)) is calculated for noise levels 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 leads to an increase of this parameter by 11% (for 70 dB) and 18% (for 75 dB). The integration of PCM in the concrete panel slightly decreases the sound pressure level.

With the laboratory measurements the above results will be validated and a parametric analysis for different thermal insulation materials with a varying thickness will be carried out. As it is clear, the results of this investigation aim to expose the importance of our decisions (design of prefabricated building module) in terms of acoustic performance.
2.4. The fire performance

The performance of the building module against fire actions is critical, as it involves metal elements that show a moderate behaviour against elevated temperatures. In this context, the resistance to fire is examined through three main criteria: the load bearing capacity (R), the integrity (E) and the insulation (I). In that respect, the load bearing capacity criterion (R) refers to the ability of a building element to preserve its mechanical characteristics and the relevant load capacity (stability) for an exact time period, during a normal fire. On the other hand, the integrity criterion (E) demonstrates the ability of a building element to restrict the passage of flames and hot gases through it and to prevent the occurrence of flames on the non-exposed side of the building component. At last, the insulation criterion (I) defines the ability of a building element exposed to fire to restrict the temperature rise at the non-exposed side above a specific level (usually 140 °C). The above-mentioned criteria can be assessed with suitable analytical and experimental approaches, while taking into account the standard and the external temperature-time fire curves (Eurocode 1: EN 1991-1-2 [6]). Special emphasis will be given to the determination of the insulation criterion (I), in that respect, thermal analyses for various building module assemblies will designate: (a) the time it takes until the temperature difference between both sides reaches to 140 °C and (b) the time it takes for the non-exposed side to reach a temperature of 180°C.

2.5. The environmental performance

The study of the environmental performance of the prefabricated building component consists in the examination of the environmental impacts that accompany its life-cycle. This examination is based on the material layers implemented in the whole element and the configuration of the final assembly. Based on the information regarding the environmental footprint of the integrated building materials, the whole module’s impact will be calculated. All the life cycle stages (raw materials’ extraction, processing, manufacture distribution, use, repair and maintenance, and end–of–life stage (disposal or recycling)) will be taken into consideration. The data that will be used for the calculations will be found in international databases listing environmental impacts; this is more a necessity than a choice as, to the authors’ knowledge, there are no available databases (at least of the required quality and extent for the conduction of such studies) for materials produced in Greece.

It is worth noting that the selection of the specific models and indicators that will be used in the context of the relative studies will be the first step of this part of the study. Indicators and models such as the ones described in methods CML-IA Baseline v.3.0.5 and Cumulative Energy Demand 1.10 will be selected, so that the quantification of the investigated impacts is in accordance with the internationally recognized and applied practices (e.g., in line with the constantly increasing in number EPDs).

3. Expected outcomes - discussion

In overall, this paper intended to present the first steps of a research project focusing on the development of a new prefabricated building element. As the outcomes of this research endeavor are still in progress, emphasis was given to exhibit the general approach of this investigation, which is part of the innovative character of this project.

The multifunctional, innovative building element that will be developed through this project will constitute the main part of the prefabricated buildings constructed by the participant company. The holistic approach followed for its development ensures its optimal performance, while the participation of the company representatives in every stage of work planning and research collaboration guarantees the achievement of a high technological readiness level of the under development building product.

The new building element and the new construction system will normalize the prefabricated element’s production, leading eventually to the increase of its efficiency, the improvement of the building quality, as well as to the reduction of time and cost of building’s erection. In parallel, the new certified and optimized performance of the building elements is expected to expand the market share of the company and increase its financial cycle, by attracting customers with higher expectations and demands. New customers and will
Additionally, the new innovative building module will contribute to the formation of an energy efficient, environmentally friendly building. The optimized hygrothermal performance will lead to the reduction of heating needs by 30% at least, compared to conventional structures, while the introduction of PCMs in the concrete panels is expected to reduce the cooling loads. Beyond the reduced energy consumption and the consequent lower energy costs, users will benefit due to superior environmental conditions, as regards both the thermal and the acoustical environment, contributing to better health and well-being.

At last, the enhanced energy behavior shows a very profound effect on the environmental performance of buildings incorporating the new building element, as the reduced energy consumption concerns conventional energy sources associated with high greenhouse gas emissions. Furthermore, the selection of the materials that constitute the new building element is cautiously chosen, so as to have the minimum impact on the environment during their whole life cycle. This is one of the main objectives of the national and European strategy for sustainability, as well as one of the main targets of SDG11 “Sustainable cities and communities”.

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