Production of Elements for an Innovative Energy-Saving Prefabricated Construction under the Project Plus Energy Prefab House

Jozef Jasiczak 1, Rene-Xavier Gerard 2, Lech Wojtasik 3, Blazej Przychocki 3, Jakub Bednarek 4, Krzysztof Cichocki 5, Jaroslaw Kolodziej 6

1 Poznan University of Technology, Piotrowo 5, 60-965 Poznań, Poland
2 GERARD Company, Krokusowa 5, 62-090 Rokietnica, Poland
3 Architectural Studio, Bydgoska 153, 64-920 Piła, Poland
4 SEZUP CLIMA Studio, Długosza 25, 64-920 Piła, Poland
5 Koszalin University of Technology, Sniadeckich 2, 75-453 Koszalin, Poland
6 University of Applied Sciences in Pila, Podchorazych 10, 64-920 Piła, Poland

jozef.jasiczak@put.poznan.pl

Abstract. In 2012, the annual International Competition Future Project Awards of the prestigious English, Architectural Review magazine, architect Lech Wojtasik from the Architectural Studio in Pila was awarded first place in the Sustainability Prize category, for the Plus Energy Prefab House project. It is a housing construction system, implemented by a factory technology of precast concrete construction, based on the use of renewable energy sources, energy efficiency, ecology and economics. The project refers to the energy and climate package for 2020-2030, first proposed by the leaders of EU countries in 2009 and later by the European Commission in 2014. Winning this international award resulted in the reconstruction of the existing architectural complex with construction designers, prefabrication technologists and engineers from the fields of effective thermal management and air exchange in the building. They developed a concept of a detached single-family house with a steep roof and passive properties. In 2016, the team received a grant from the National Centre for Research and Development (NCRD) for the implementation of a prototype building and the development of a precast production technology. The project implemented as part of an NCRD task of a prototype single-family home and adopted architectural and structural solutions with modern heating and air-conditioning systems are the subject of the presented article.

1. Introduction
Observing the development trends of housing in 21st century Europe, we can distinguish two directions of investor activities: one is associated with collective housing buildings (both exclusive and communal), and the second one is associated with the more and more attractive individual, single-family construction. The sustainable development principles apply in both cases, but multi-family construction is inherently executed with industrialized technologies, and single-family construction rather with craft technologies. It is estimated that the labour expenditure for the construction of a typical single-family house is 2000 man-hours on average, which amounts to approximately EUR 100 000 at an hourly rate of EUR 50 applicable in the EU, and that does not include material and process equipment costs. Such tendencies have been observed in Western Europe for several years, however, they are also beginning to penetrate Central-Eastern Europe.
By deemed the trend irreversible, the authors of this article commenced engineering and design works on developing an innovative housing building made of concrete pre-casts with a high finishing level, bonded on site into a whole, through a special connector system, replacing the traditional masonry method. Adopting such a system for pre-cast production and installation shall limit labour consumption for a house to 260 man-hours, and the factory production cost of such elements, as well as their installation will not exceed the execution costs of the same partitions with traditional methods.

![Figure 1. General view of a typical residential unit included in the Prefab House project](image)

Designed base building, single-storey, with a steep roof, shown in figure 1 and 2, with external dimensions 8.80x12.20m. A base module in the system is a single-storey cuboid with an 8.80x12.20m base, a steep roof and 148m² of living area, or a double-storey with the same base, steep roof and 177m² of living area. The module may be a detached house element or be appropriately matched and form semi-detached, terrace or multi-family houses. Thanks to special 11.6m long concrete roof slabs with compressed ribs, the entire length of the building may be covered, which provides the possibility of any interior division with light-weight partition walls. Storey-high external wall elements are designed as large-dimension elements, 0.41m thick, with an external facade ceramic tile cladding, polyurethane (0.15m) and polyurethane (0.18 m) insulation, 0.06m thick reinforced concrete structural elements and internal plaster. The entrance to the building is an independent vestibule, which also serves as an entrance to auxiliary single-storey facilities, covering a utility (workshop) room and a two-car garage. The closest surroundings comprise of a terrace and garage access road, with greenery taking up the remaining part of the plot. Minimum plot width for individual development is 25m, 22m for semi-detached development, 18m for terrace housing, while the preferred length is 25m, which amounts to 625 m², 550 m² and 450 m², respectively.

The building meets the requirements set for an UEiₜp₁₅ (i.e. annual, individual building demand for usable energy for heating purposes UE ≤ 15 kwh/m² per year) power standard as per the principles stipulated in PN-EN ISO 52016-1:2017-09 [1] and other official arrangements [2, 3].
Figure 2. Projection of the entire structure covering a residential building, entrance, two-passenger car garage, utility room, closest surroundings with paved surface. Riser shaft visible in the centre of the projection.

2. The concept of factory element prefabrication and their on-site installation

The project assumes factory pre-fabrication of all building elements, starting with a foundation slab, through external walls, ground-floor ceiling, riser shaft and external walls within the attic. All pre-casts satisfy the condition of high insulation, full surface finishing, reinforced concrete structure layer stability, binding through a system of patented connectors. The construction process does not provide for any wet processes, like plastering or concreting.

Composite baseplate consists of a polyurethane mould, with a reinforced concrete beam-slab element embedded in a prefabrication plant. Prior to concreting the plate, steel connecting elements of the “sinus” (plane-wise element bonding) and ”δ” type (bonding walls with the foundation) are fastened to the reinforcement. The polyurethane mould left after production is the target thermal insulation from the baseplate ground side. The mould and plate are shown in figure 3.

The multi-layer outer walls inter-bonded with “sinus” connectors and anchored in the baseplate with „δ” connectors are executed in three stages.
Figure 3. The concept of composite baseplate prefabrication. A polystyrene mould and reinforcement, and a fragment of a plate bonded with "sinus" connectors are shown. Seats for "δ" are marked on the borders.

A ceramic tile facade layer is laid on polyurethane templates, on the bottom of the mould, with a polyurethane injection insulation layer over it, blocked from the top by a steel pressure plate. A polyurethane layer with profiled cavities for reinforced concrete slab grid are glued to the polyurethane. An 0.18mx0.18m, 0.06m thick reinforced concrete wall SCC slab with a beam border is executed on such a prepared substrate (figure 6 d). "Sinus" and "δ" connecting elements are fastened to the reinforcement on the borders of the reinforced concrete beam. The principle of prefabricating walls with ready cladding are shown in figure 4.

Figure 4. Staged outer wall execution: ceramic tile cladding, polyurethane layer, polyurethane layer, reinforced concrete slab with a circumferential beam.

Composite ceiling elements are executed similar to baseplate elements, with the exception that a beam-slab element with a 6cm plate has compressed ribs, which enables covering a ceiling with an 8.20 to 11.60m span. Attic wall elements, also with ready cladding, are executed as per the principles of forming outer walls. The previously described connectors are utilized in both cases. Outer wall inter-bonding and the appearance of a "sinus" connector are shown in figure 5.

The elements sets prepared in a concrete precast plant for a specific building are either containerized (long-range transport: 2.40x2.90x12.2m sea-freight container of the 40’HCDC type) or sent in a
vertical position on trailers, adapted for road car transport up to 300 km. They are planned to be installed straight from the trailer, without additional storage at the construction site.

![Figure 5. Principle of plane-wise wall bonding. Shown connector consisting of a seat made of rigid HDPP and a “sinus” type steel wedge pressing the elements against each other. The seats are fixed to the reinforcement of adjacent pre-casts, and the bonding is through driving a steel wedge](image)

3. Description of base building calculation models
Bonded pre-cast elements form a spatial multi-connector system, and for this reason, two calculation models were developed, in order to determine the actual load bearing capacity of the elements. The calculation model for the building was developed in *Autodesk Robot Structural Analysis Professional*. The calculations were conducted on two levels: a general one, which utilized bar and bar-coating models, and a detailed one, where volume models were applied. In the general model, individual parts (building elements) were joined together pointwise with flexible connectors with a pre-calculated stiffness. The aim of this analysis was to determine the internal forces in the connectors. The forces determined in the connectors were used for the analysis of building element stresses and to perform necessary strength calculations. The subject of the analyses are the same connectors, which were modelled in the *Abaqus* software. There are ongoing empirical studies aimed at experimental determination of both the load bearing capacity of the connections, as well as more accurate strength properties of the connectors themselves. The following images in figure 6 show a set of pre-cast building elements, output data for modelling bar elements and elements in the volumetric approach.

4. Smart building - blocked installation equipment
The central part of the building has a designed riser shaft (figure 7), which contains the following equipment and systems: mechanical ventilation, water supply (cold, hot water and utility circulation), sanitary soil pipe, electrical, photovoltaics and automation, and an integrated multimedia structural system. The equipment in the shaft will include: an air handling unit, an air heat pump, electrical switchgear PV system inverter and distribution board, LAN rack and alarm central unit, as equipment of a smart building.

The building will be heated with ventilation air, heated in a duct electric heater. Supply-exhaust mechanical ventilation system with heat recovery was also designed. A 100% fresh air ventilation
system was used. Outside air will be filtrated and, depending on the needs, heated or cooled. Outside air will be heated with an electric heater in an air handling unit and a duct heater.

![Image](image-url)

**Figure 6.** Modelling output data: a) base building elements, b) diagrams adopted for the bar and bar-coating models, d) for the volume model

Air exchange will be forced via a supply-exhaust air handling unit with a rotary exchange, with a capacity of 410m³/h, DOMEKT REGO 450VE-B-EC-C4 by Komfovent. The air handling unit has a Passive House Institute certificate.

Fresh air will be drawn through a wall intake, and used air discharged by a wall exhaust terminal. The ventilation system is designed consisting of gasket-connected galvanized steel sheet Spiro type ducts. The ventilation ducts will be laid in the non-usable attic and in the riser shaft and directed to the rooms. Air supply and exhaust will be executed through air valves.

During the winter time, air treatment is limited to just heating its temperature up to +39°C, thus mitigating the energy loss component in the thermal demand balance of ventilated rooms, and heat losses resulting from its penetration through construction partitions.

A C6.1 controller by Komfovent will be an element responsible for controlling the unit. The controller will maintain the supply temperature in the exhaust temperature function at +20°C, measured with a duct sensor upstream of the air handling unit, adequately adjusting with the power of an electric heater embedded in the unit and a duct electric heater, and by selecting the rotations of a rotating exchanger.
The hot water source for the designed system is a BASIC air heat pump by Galmet, with an integrated domestic hot water heater with a capacity of 200 l.

A heat pump will be included in the mechanical ventilation system. The air handling unit will be a sufficient air source for the heat pump. During the winter, the heat pump will draw the heat for the used air exhaust duct. During the summer, the heat pump will draw heat from the air supply duct - the heat pump, if heating water, additionally cools the air by ca. 5–10°C relative to the outlet air.

Thanks to the use of a Home Centre central unit, the user receives an option to adjust the intensity of heating, ventilation, controlling additional devices such as a TV, tuner amplifier, Blue Ray, from a tablet or a smart-phone level. Additionally, thanks to the use of appropriate sensors, the system will inform about flooded rooms, particularly exposed to uncontrolled water impact, such as bathrooms, the kitchen or laundry room, and about the detection of carbon oxide or a fire in the kitchen or the attic. The design also provides for remote opening of the door and gate, controlling roller shades, LED lighting, on/off of individual equipment plugged in via relevant adapters to power sources, as well as a smart and multi-functional video-interphone, enabling connection with the owner and a view of the building from anywhere in the world.

5. Conclusions
National Centre for Research and Development (NCRD) financing allowed us to implement a vision of a single-family building, trying to meet the current and future requirements of limiting or eliminating traditional energy carriers. The authors of the article, forecasting growing difficulties with obtaining professional construction labour force, concentrate on full factory prefabrication of elements with high insulation properties and a high finishing degree, meeting all the future requirements regarding functional comfort. In principle, the building is to satisfy the £UE≤15 (i.e. annual, individual building demand for usable energy for heating purposes $UE \leq 15$ kwh/m$^2$ per year) energy passive standard, while having a high standard of process equipment, also meeting the criteria of a smart facility, which is also economically competitive relative to facilities executed with traditional technologies.

After completing a prototype building and practical verification of adopted solutions, it will be possible to expand this technology onto multi-family, two- and three-storey buildings, with bonding elements via special connectors as an installation principle, while eliminating wet processes. The fact that these are not utopian solutions is proven by Polish experience from the period of 1973-1978, when the traditional installation of concrete pre-casts in multi-family building with concrete connectors was
replaced by steel plates with indentations, driven into gaps on the borders of slabs, allowing steel rebars with a diameter adapted to the indentations in steel plates to pass through them. These experiences were described in the papers [4, 5, 6]. “Sinus” and „δ” connectors for the currently designed Prefab House system are, of course, much more technically advanced than the ones from 1978, nonetheless, it would be beneficial to find a reference level for innovative solutions.

The evaluation of residential buildings made of concrete pre-cast after 40 years of operation, which was conducted over the recent years, confirmed the durability of connections and the rightness of the solutions adopted at the time [7].

Acknowledgements
Elaboration within the framework of Intelligent Development Program, project No. POIR.01.01.01-00-0133/16 financed by National Centre for Research and Development

References
[1] PN-EN ISO 52003-1:2017-09, “Energy performance properties of buildings - Indicators, requirements, assessment and certification - Part 1: General aspects and applications of overall energy performance properties”.

[2] The determination of basic requirements, necessary to achieve expected energy standards for residential buildings and the manner of verification for designs and inspecting the executed energy-efficient houses. STAGE I - Guidelines for the verification of residential building designs, as per the NFOŚiGW” (National Fund for Environmental Protection and Water Management]) (in Polish).

[3] “Directive 2010/31/Eu of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings” (amended version).

[4] J. Mikoś, “Selected issues of prefabrication technology”. Warszawa 1987. (in Polish).

[5] J. Mikoś, J. Kajrunajtys, J. Kowal, PRAS-BET structural-installation system. Zeszyty Naukowe Politechniki Śląskiej, seria Budownictwo, Z51, 1980, s.91-106. (in Polish).

[6] Patent PRL -79209: dated 8/6/1973. Prefabricated construction elements, especially with sandy borders, pre-cast construction elements installation method and a connector for joining prefabricated construction elements (in Polish).

[7] J. Jasieczak, K. Girus, “Maintenance and Durability of the Concrete External Layer of Curtain Walls in Prefabricated Technological Poznan Large Panel System”, WMCAUS 2017, IOP Conf. Series: Materials Science and Engineering 245, doi: 10.1088/1757-899X/245/3/032015.