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The Function and Potential of Innovative Reinforced Concrete Prefabrication Technologies in Achieving Residential Construction Goals in Germany and Poland

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Abstract: This paper presents the role and potential of housing built using innovative reinforced concrete prefabrication technologies. The subject was presented by investigating the share of such buildings in the achievement of housing goals in Germany and Poland, where they currently constitute one of the most dynamically developing housing sector branches. The phenomenon has been presented via comparative analyses of selected designs by manufacturers from the sector and development companies. Prefabrication is essentially based on optimising architectural and structural solutions and leads to lowering financial and material cost; decreasing project completion time. At present, these goals are achieved by systematising the design and construction process and using the potential offered by building information modelling technology (BIM). This enables coordination between design specialisations and reduces the number of errors, increasing manufacturing and assembly efficiency. Innovative prefabricated technologies are solutions that are either new or are considerably improved in terms of technical specifications, components and materials, that use the latest software, are easy to assemble, durable, energy efficient, can be disassembled and reused and have a low carbon footprint and can be considered aesthetically pleasing. Contemporary prefabricated housing architecture is a combination of innovative technological solutions that enables constructing sustainable architecture and emphasizes the aesthetic features of structural solutions and solutions.

Keywords: housing architecture; sustainable development; reinforced concrete prefabrication; innovative modular systems; BIM

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1. Introduction

Among the goals outlined in European Union (EU) programmes, such as the New European Bauhaus [1], matters of housing availability, especially concerning people with incomes that prevent them from purchasing or renting a flat under commercial conditions, occupy a key place. When implementing such actions, one needs to account for the needs and wellbeing of citizens, which in this case are satisfied by accessibility to a wide range of residential unit types. This can be provided by proper subsidies and lowering building construction costs, which in this case is most successfully achieved by using system-based prefabricated construction solutions. EU economic development and construction-sector stimulation programmes highlight the necessity to pursue sustainable development, which is crucial due to the very high yearly production of construction and demolition waste in the EU, which amounts to 820 million tons [2]. In housing, this is crucial due to the scale of the phenomenon, as the construction and use of millions of homes is a major anthropogenic factor that has an enormous negative impact on the environment and the climate [3]. This paper references all these matters, demonstrating the role and potential of multi-family housing based on innovative reinforced concrete prefabrication technologies in achieving social housing goals of Poland and Germany, where buildings constructed using such systems form 6.5% and 11% of the market, respectively [4,5]. The planning and construction of modern, system-based housing buildings was illustrated via analyses of efforts by leading design firms, manufacturers and real estate development companies [6–9]. The objective of this study was to investigate optimal architectural solutions that employ reinforced concrete prefabrication systems that are innovative in material and technological terms. This paper is intended to present the results of this research, along with an analysis of the development of such systems. It also features conclusions concerning the possible future evolution and role that such systems can play in the future in the carrying out of socially important housing goals set by European countries.

Contemporary fabrication is based on optimising spatial solutions that enable the use of varied yet always functional architectural designs and the rationalisation of structure and infrastructure, which together leads to lowering material and financial costs and is conducive to the creation of sustainable architecture [10]. Research has shown that in the past two decades progress in the design of innovative prefabrication systems was enabled mostly due to new production and concrete reinforcement technologies [11–14], patents covering modular reinforced concrete structural solutions specifically applying to load-bearing structures, the thermal insulation of partitions and joint optimisation [15–18]. To achieve effective assembly and shorten construction time, it is key to introduce innovative structural connections that do not require on-site welding or concreting. Contemporary prefabrication technology utilises innovative accessories that ensure joints operate effectively, and that eliminate the flaws of monolithic joints [19]. They include point-based or linear reinforced joints that utilise steel cables [20]. Prefabricated wall panels are joined to steel clamps or loops through which a steel rod is threaded, which prevents the walls coming apart. The point of contact of the joint is filled with high-strength cement without using formwork, which cuts down on construction work. The production of prefabricated elements is also easier, as it eliminates the need for joint rebar. Point-based and linear joints available on the market can be used to join walls with a minimum thickness of 10 cm and allow connecting prefabricated walls with concrete walls on-site. It is equally important to link the technology with dry construction application in terms of walls, balustrades, floors and finishes [21]. In a future perspective, it may also turn out that the prefabricated building market can be dominated by newer technologies, e.g., those based on combining concrete or its composites without the use of steel [14], with prefabricated glue-laminated wood or even recycled materials [22]. There are also ongoing experiments with 3D printing technology, which also concerns buildings built in concrete technologies [23]. This course of action can also yield results in the manufacture of specific structural elements or small sections of entire buildings, yet appears a futuristic solution when entire buildings are concerned.

The use of the potential offered by building information modelling (BIM) [24–27] appears key to enhancing the design process. BIM allows for creating technologies and systems that include a large number of compatible elements, excellent coordination between design specialists and a reduction in errors. BIM has made design, manufacturing and assembly more effective, thereby leading to reduced cost and project completion time, in some cases resulting in a single shell-state storey taking as little as 5–6 days to complete [28].

As evidenced by the authors' research and professional experience, innovative prefabricated architecture allows for designing varied building masses and floor plans. This is possible despite limitations, such as the necessity to use standardised structural and envelope elements and unified stairwells, utility ducts and balconies. This is made possible due to the variety of all these elements and system-based joints that offer a large pool of alternative solutions [29–31]. Overall, in reference to housing, this offers the possibility of creating an array of solutions tailored to families of varying size and the expectations of different social groups [32]. As demonstrated by the cases under analysis, housing complexes and singular buildings with a great variety of forms and standards can be built: ranging from basic ones, expected of affordable social housing [33], through commercial real estate where relatively high residential unit and site development standards are employed [34,35] to flagship projects with unique spatial solutions, often sporting eccentric interior décor that exposes concrete—which references fashionable loft architecture [36].

This paper discusses issues of achieving, via prefabricated housing, the goals of sustainable development [37]. In general, such structures can meet parameters required of green buildings. They are rational and effective in terms of construction material use and provide comfort of use in terms of unit layout, microclimate and acoustics. Such buildings have spatial forms and external partition insulation parameters that allow them to meet standard energy balance requirements [38]. They are also characterised by durable structure (properly secured concrete can last indefinitely) and can be subjected to circular renovation [39]. In addition, it should also be noted that despite this potential, only in a small number of housing buildings have there been efforts to receive high-requirement certificates such as BREEAM, LEED or HQE [40], which stems mostly from disproportionately high costs of the comprehensive implementation of their guidelines in relation to commercial benefits.

In reference to the issue under analysis, there are also other debatable areas associated with the history of the first generations of prefabrication technologies. Prefabricated housing in Germany (especially in the territory of the former Deutsche Demokratische Republik and in Poland) has little in the way of positive connotations [41], which stems from errors made in the application of such rigid technologies and the construction of enormous panel block housing estates [42]. This is why the potential offered by new prefabrication techniques can be successfully employed not only under the condition of their further improvement, but also requires promotional or even psychological campaigns [43]

2. Materials and Methods

It should be highlighted that the title of this paper makes deliberate use of the term innovative technologies, thus indicating that the analyses included here cover contemporary solutions, developed recently. Among the available literature, no significant and comprehensive publication that would clearly discuss the matters featured in this paper was found. Because of this, this study is an analysis and structuring of information on the subject matter and scope of knowledge featured in academic and trade articles, official sources and online platforms used by design firms and manufacturers, as well as freely accessible statistics and political resources of the EU, Germany and Poland.

The presentation of the study's findings begins with a presentation of statistical data concerning the construction of housing buildings using reinforced concrete prefabricated technology in Poland and Germany in the years 2015–2020 [4,5] and an analysis of the organisational and technical factors that affect the dynamic of these changes, which can be used to approximate the further development of this sector in both countries. The analysis includes how housing based on prefabricated technologies in Poland was affected by programmes like Mieszkanie Plus [44] or architectural competitions organised by the Polish Development Fund (PFR) [45] and the SARP [46], and in Germany, by initiatives undertaken by government organisations such as GdW Bundesverband deutscher Wohnungs- und Immobilienunternehmen (GdW) [47].

Afterwards, the paper shall discuss contemporary systems and projects involving prefabricated housing buildings with reinforced concrete structural systems, presenting, as a representative sample, the efforts of the following companies: Budizol Sp. z o.o. S.K.A, Pekabex S.A., Firmengruppe Max Bögl and GOLDBECK GmbH [6–9]. The systems used by these companies and the building configuration approaches proposed by them were documented and analysed based on interviews, catalogues, presentations, data and written descriptions found in official sources and websites. When selecting the architectural solutions for presentation, the authors wanted to present both high-standard commercial residential units and affordable flats intended for institutional lease, which can demonstrate the flexibility and universality of contemporary prefabrication.

The following research stage consisted of analysing the role of BIM technology in prefabricated reinforced concrete housing. Among the available trade literature on BIM, most of the information focused on the technical side of this tool, only briefly discussing any architectural aspects. This is because of the comprehensiveness of BIM and the participation of various specialists in the design of buildings using the technology in question. This is why the subject was analysed from an architectural standpoint, treating specialist technical information only as a supplementation necessary to explain essential terms. The paper discusses the precept of creating a central, comprehensive 3D building model and its role in the cooperation of all project participants. Information collected on this subject in the literature was backed by cases based on the authors' personal professional experience as architects. Afterwards, the role of BIM technology in the operation of prefabrication plants and in the process of the management of a completed building was discussed. The limitations of BIM technology were also listed, with a particular emphasis on organisational barriers that exist in implementing this complex technology.

Finally, the paper features an analysis of prefabricated housing architecture in the context of sustainable development. Further development trajectories for contemporary prefabrication technologies were outlined, tied with optimisation, reuse and recycling of resources used in automated prefabricated element production. Based on the available literature, a range of innovative technical solutions was discussed, e.g., smart prefab element connectors or joints between external structural elements that ensure high-grade energy loss proofing. Development trajectories for concrete (reinforced concrete) in contemporary prefabrication in terms of lowering the carbon footprint of concrete mixes [48] were also outlined. The analysis was supported by cases of currently used concretes that do not feature primary reinforcement or that contain non-steel primary reinforcement [14].

The results of the study have been summarised in the last two sections (Discussion, Conclusion), grouping conclusions as belonging to the organisational, technical and technological planes. The findings indicate that, due to their flexibility, low cost and short completion times, these systems allow for building multi-family buildings adapted to the needs of various social groups, including low-income groups. This is why these systems have strong government backing in both Poland and Germany, which means that it could potentially form the most dynamically developing sector of the housing market. The key to the application of reinforced concrete prefabrication in housing construction lies in further organisational and technical improvement, which shall accompany the application of BIM. Progress is expected to be made in the field of new materials and patents that enhance reinforced concrete structural systems, with a strong emphasis on implementing pro-environmental solutions that reduce the carbon footprint and environmental pressure.

3. Results

3.1. Prefabricated Housing

Panel block technology in the housing sector, whose greatest development occurred in the 1970s, was based on catalogues from which architects would choose suitable elements with which to construct a building. Communication between designers and prefabrication plants was based on drawings and item numbers from these highly limited catalogues. This system contributed to the construction of panel and block housing estates in many European countries. Their architecture and low workmanship quality continue to be perceived negatively even today [41,42,49].

At present, the prefabrication industry is one of Poland's most dynamically developing branches of the construction sector in terms of innovation. In housing, this system is once again being applied, as confirmed by statistics collected based on data provided by Poland's Statistics Poland (GUS, Table 1). In past years, the percentage of delivered housing units built using prefabrication technology did not exceed 0.5%. In 2018, this percentage rose to 2.6%, and in 2019 it doubled to 5.3%. In the past year, the number of residential units delivered using prefabrication technology exceeded 10 thousand and the yearly balance was again higher than in the previous year, reaching 6.5%.

Table 1. New residential units delivered using prefabricated (large-format panel and large-format block) technology in Poland in the years 2015–2020 (third quarter). Self-elaboration, based on data [4].

Poland	2015	2016	2017	2018	2019	2020
Residential units in total	143,014	157,977	173,489	180,897	203,458	154,297
Large panel Large block	181	247	481	4677	10,791	10,045
Percentage share	0.1%	0.2%	0.3%	2.6%	5.3%	6.5%

The situation of the prefabricated housing industry presents itself differently in Germany (Table 2). In 2015, the percentage of residential units delivered using prefabrication technology in Germany was slightly above 9%. In 2016–2020, this percentage remained at a steady 10.9–11.9%, which means that just slightly over one-tenth of residential units delivered in this timeframe was built using prefabrication technology.

Table 2. New residential units delivered using prefabricated construction technology in Germany in the years 2015–2020. Self-elaboration, based on data [5].

Germany	2015	2016	2017	2018	2019	2020
Residential units in total	216,727	235,658	245,304	251,338	255,925	268,774
Large panel Large block	19,720	27,985	27,970	28,140	27,812	28,101
Percentage share	9.1%	11.9%	11.4%	11.2%	10.9%	10.5%

The conclusions drawn from macroeconomic studies and statistics are as follows (Figure 1). In Germany, the number of residential units delivered each year oscillated around 250 thousand and has been growing only slightly in recent years. The share of prefabricated construction was also relatively stable and amounted to 11%. This balance in housing will probably change due to growing deficiencies in skilled workforce resources and the increasing disparity in material and labour cost in the construction sector. The growth of prefabricated technologies is also expected to be aided by government programmes, or the organization of architectural competitions, with the GdW having already started hosting them [47]. In Poland, a positive trend can be observed, both in relation to the global number of residential units (ca. 10% per year) and an even greater growth of the share of prefabricated buildings. From slightly below 200 units delivered using prefabricated technologies in 2015, this number increased to over 10,000 units in 2020. The primary cause behind this significant change is that leading Polish companies in the prefabrication sector that previously operated on the Swedish and Norwegian markets [6,7] decided to grow their operations domestically. This was tied in with the increase in competitiveness of prefabricated systems in relation to conventional construction technologies, which are currently facing the challenge of qualified construction sector workforce shortages and central and local government promotional campaigns, in the form of competitions organised by the Polish Development Fund (PFR) [45].

In both countries, it was crucial to implement innovative prefabrication technologies that were constantly being improved in specialised design firms, manufacturing plants and with the participation of companies with elaborate research infrastructure. The growth of the housing sector will probably be enhanced by the COVID-19 pandemic, as a result of which demand for service buildings (e.g., offices, hotels and commercial buildings) has greatly declined, while the demand for housing has increased. This demand also includes flats that allow for working from home. These trends shall probably carry over into an even greater pursuit of innovative solutions in the housing construction sector, solutions that can enhance rapid and affordable construction in relation to pro-environmental solutions and offering suitable finish quality.

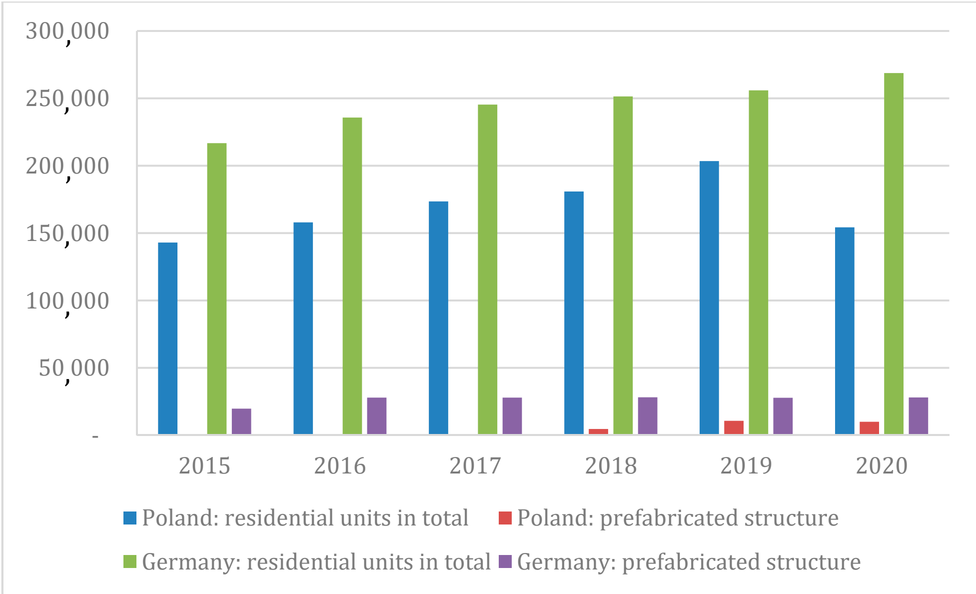

Figure 1. Comparison of the number of newly delivered residential units made using prefabricated construction technology in Poland and Germany in the years 2015–2020. Self-elaboration, based on data [4,5].

3.2. Contemporary Prefabricated Housing Systems and Projects

There are currently excellently organised companies on the construction market that, apart from manufacturing prefabs, also offer building design services, technical consultations, transport and assembly of prefabricated elements. The configuration of structures in these companies is typically performed via an interactive planning catalogue that includes prefabricated modules with assigned properties. Despite the application of standard components, 3D technology allows for the design of bespoke modules depending on a given project's needs. The comprehensiveness of services offered as a part of a single company's operation is facilitated by the use of the same software, which greatly simplifies data exchange and limits export errors. In addition, the cohesion of design processes and the coordination of all building information within a single database minimises the amount of planning and reduces cost. Systematised planning also enables the quick formulation of alternatives, while data visualisation greatly shortens the decision-making process concerning the building. Examples of companies that offer comprehensive services in housing prefabrication include Budizol Sp. z o.o. S.K.A. and Pekabex S.A. that operate on the Polish and Scandinavian markets, and Firmengruppe Max Bögl and GOLDBECK GmbH that operate on the German market [6–9].

Budizol Sp. z o.o. S.K.A. manufactures reinforced concrete prefabricated elements for housing construction. Among the benefits of using prefabrication technologies, the company lists ease and rapid assembly of prefabs, the high thermal insulation values of the elements, elimination of errors at the construction site, and the freedom to design any type of building massings and indoor spaces. The prefabs produced by the company have high insulation properties and structural strength, which increases the capacity of buildings to accumulate heat during winter and maintain cool temperatures during summer. In addition, Budizol stresses that prefabrication technology allows performing assembly work during poor weather conditions, thus shortening overall construction time [6]. One of the most well-known projects by this company in Poland is a mixed-use housing and service building at 4 Sprzeczna Street in Warsaw, designed in 2015 by BBGK Architekci [34] and built in 2017 (Figure 2). This project provided a testing ground for and a demonstration of the potential offered by contemporary prefabrication. In this case, the atypical conditions of the site, oriented at 45 degrees relative to the street, and placed amid compact downtown development, between nineteenth-century townhouses, proved to be a challenge. This demonstrative project made use of as many as 250 types of prefabricated elements [50], which made the project architecturally original but also costly relative to what is expected of prefabricated housing. However, the project's goal was to demonstrate the entire potential within this technology and present differences in the quality of such architecture relative to the one known from the second half of the past century.

Figure 2. Multi-family residential building at 4 Sprzeczna Street in Warsaw, Poland, constructed in 2019 by Budizol sp. z o.o. S.K.A. using prefabricated technology and designed by BBGK Architekci [34].

In 2017, the prototype building at Sprzeczna Street became an important step for innovative prefabricated construction in Poland and propelled Budizol S.K.A. and BBHK Architekci to realise other commercial-standard projects in the years that followed, such as the Wave office complex in Gdańsk [51] and much simpler tenement houses, as in the case of a competition prize for the design of model buildings for the Mieszkanie Plus programme [52] or even modern, pro-environmental prefabricated single-family houses under the Budihome brand [53].

Another company that engages in the manufacture of reinforced concrete prefabricated elements and other products for housing construction is Pekabex S.A., which for over thirty years has been successfully building prefabricated buildings in Norway and Sweden, where close to 65% of multi-family buildings are built using prefabricated technologies (from wood and concrete). Pekabex has been building 1–1.2 thousand modular residential units in these countries on average every year [7]. One example of a Sweden-based project by the company is the Linaberg 19 housing complex located in Stockholm. It consists of 19 buildings with a total of 370 residential units. The company's share of work included the design, manufacture, delivery and assembly of prefabricated elements [54]. Another example is the Kv Duggregent complex of four residential buildings, constructed for Skanska Sverige AB in Stockholm. In this case, the company was responsible for the design, 3D modelling, manufacture, delivery and assembly of prefabricated elements as well as monolithic concreting work [7]. Over 10 thousand prefabricated elements were produced for the construction of both complexes [7,54].

Pekabex lists the following as the primary benefits of using prefabrication systems: the potential to achieve a higher apartment floor area indicator while preserving the same total floor area, a project completion time reduced by as much as 50% relative to conventional technologies, lower construction costs, no need to plaster walls and ceilings, high prefab quality, and the possibility of assembling elements under practically any atmospheric conditions [28]. The prefabricated elements most commonly produced by the company for housing construction include walls, ceilings, stairwell elements and balcony elements. The company offers single, double or triple-layer walls. External triple-layer walls are supplied to a construction site with completed façade finish layers and mounted windows and doors. The company's system features the following façade finish options in triple-layer walls: concrete façade (painted concrete, plastered concrete), with texture (painted concrete, plastered concrete) and with cladding (brick, clinker, stone). External double- and single-layer walls allow for the use of other façade solutions, such as panels. The manufacturer lists the following benefits of prefabricated walls: high element surface quality without the need to apply plaster to walls, quick and easy assembly, high acoustic insulation, lowering construction time by eliminating formwork and reinforcement, reducing construction site infrastructure by supplying elements in a state ready for assembly [28].

Over the past three years, due to increased interest in prefabrication, the company has also been carrying out housing projects in Poland. This began in 2018 with a project involving a model complex of six five-storey multi-family buildings at 9 Jasielska Street in Poznań (Figure 3), with a floor area of 8475 m^2. The buildings were designed with attention to high-quality architectural composition and excellent technical parameters. Residential units (two-, three- and four-room units) were equipped with spacious balconies and terraces. Construction on the complex began in 2018 and was completed in 2020 along with its infrastructure and green surroundings [35]. Pekabex was the main contractor and developer of the project.

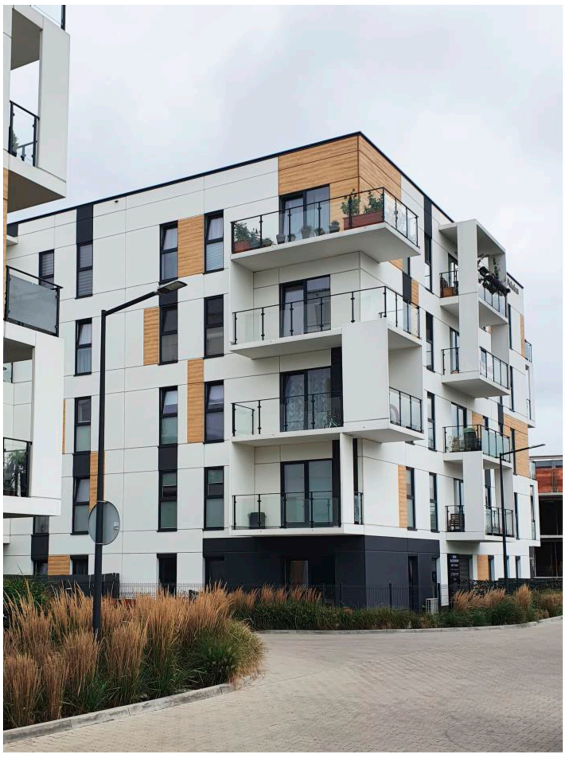

Figure 3. Multi-family residential building at Jasielska Street in Poznań, built in 2020 by Pekabex S.A. and designed by Adam Mikulicz Architekci [35].

The success of the 'Jasielska' housing estate in Poznań, which garnered considerable publicity in trade press and the mass media, resulted in a range of successive prefabricated housing projects by Pekabex in Poland, with examples being a complex of eight buildings at Okólna Street in Toruń, designed by S.A.M.I. Architekci and built as a part of the Mieszkanie Plus government programme. This project, which began in 2018, had a commercial character, but the companies involved and the tenants receive substantial financial support from the PFR, which means that it is classified as being in a segment of residential units available to a wide range of social groups. Initial assumptions also affected the rather purist composition of the housing estate and modest building façades. The standard of single, two- and three-room residential units did not deviate from solutions typically seen in flats delivered by real estate development companies [33].

The German market, similarly to most European markets, is currently facing the problem of a shortage of affordable residential units and the lack of a qualified workforce required to erect building structural systems and finishes using wet technologies [21]. This is why innovative concepts of system-based architecture are seen as a new way of building affordable flats over a short time period without compromising their quality. The German market is dominated by two companies: Firmengruppe Max Bögl and GOLDBECK GmbH, which offer comprehensive services in housing prefabrication and direct their systems to meeting its demands.

Firmengruppe Max Bögl lists the primary benefits of prefabrication as high quality and precision assured by the in-factory manufacture of elements, a reduction in planning costs, short element production and assembly times, reducing construction duration times, preventing waste generation and energy savings due to effective logistics [8]. The company's system can be applied to every type of housing architecture: both the stairwell blocks, tower blocks, corridor and deck access buildings. This allows adapting a design proposal to a planned project's urban context. The system assumes that units are created using modules with a specific size: a length of 6.36 m or 7.15 m, a width of 3.18 m and a height of 3.15 m, offering a daylight unit height of 2.5 m. The modules: living room, bath and kitchen, bedroom with WC and pantry, are connected to each other, creating, depending on the need and building type, unit variants with between one and five rooms (Figure 4). The company's system features one bathroom type, situated directly near the kitchen so as to create a shared utility shaft for both spaces [55].

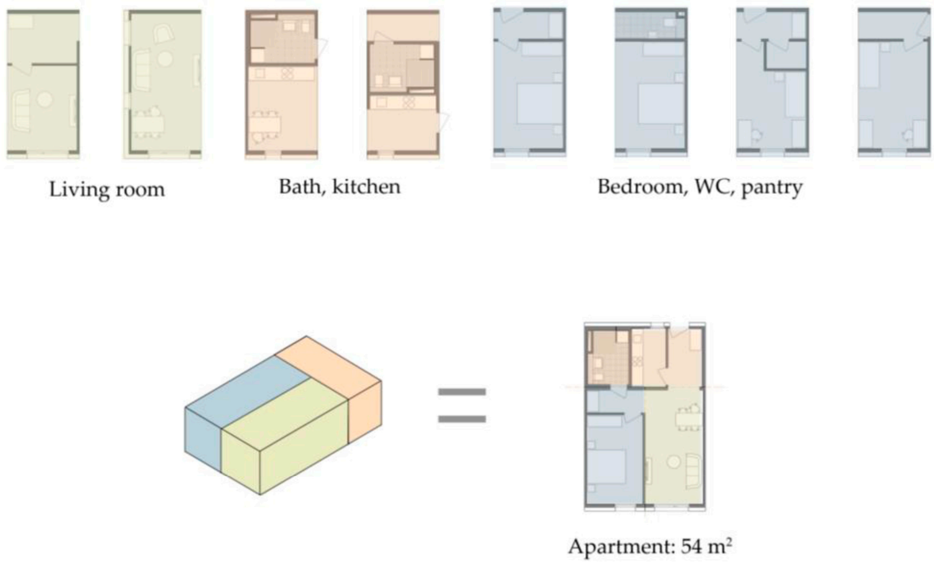

Figure 4. Residential unit design based on system-based modules by Firmengruppe Max Bögl/maxmodul (self-elaboration, based on data from [55]).

The unit modules are manufactured entirely at the company's plant. Finished elements, fitted with all the necessary installations, are transported to construction sites, where they are used to assemble entire buildings using cranes. This system allows the construction of a single storey within a week, which significantly reduced overall construction time and minimises any nuisance caused by construction.

One example of a modular multi-family housing construction project by Firmengruppe Max Bögl is a complex of three residential buildings that were completed in December 2018 in Westring in Frankfurt am Main. The design was commissioned by Vonovia, one of the largest real estate development companies on the German market. The buildings feature a total of 36 units built out of 201 modules. The project's goal was to deliver affordable tenement units, which was reflected in the complex's functionalist composition and modest façades, which were only accentuated by self-supporting balconies [8].

GOLDBECK GmbH is another company that engages in the construction of multi-family housing residential buildings on the German market using prefabricated technologies. The company's goal is to manufacture modular, affordable tenement units while maintaining proper quality and construction standards. The system-based design assumptions by the company allow for the construction of every type of residential building, with the maximum height being eight storeys. The GOLDBECK system assumes a perpendicular structural axis layout, with each axis being a multiplication of a module 0.625 m long, with a minimum span of 3.125 m and a maximum span of 6.25 m. Transverse and stairwell walls have a thickness of 21 cm, while the longitudinal walls have a thickness of 14 cm [56]. Standard, system-based residential units consist of a day section that includes a living room and kitchenette and a bathroom that abuts it, with a span module of 6.25 m. A module with a night-time zone is placed beside the one with the day section, and the night-time module's width depends on the number of bedrooms planned. For example, a two-room unit can be built using a day zone module with a span of 6.25 m and a night-time zone module with one bedroom and a storage space with a span of 3.75 m. A three-room unit can have a day zone module with a span of 6.25 m and a night-time zone module with a span of 5.00 m with two bedrooms and a storage space (Figure 5) [57].

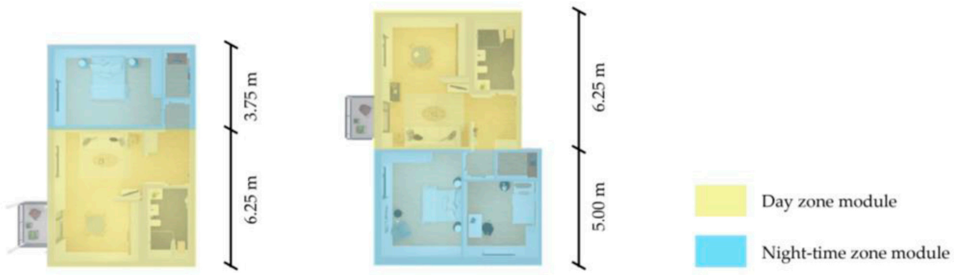

Figure 5. Floor plans showing a two-room and three-room units by GOLDBECK GmbH with day and night-time zones marked (self-elaboration, based on data [57]).

In its projects, the company prefabricates elements that form the structure of the building, such as walls, ceilings, modular lift shafts, stairwells and pre-made sanitary modules with all the necessary utilities and a complete set of furnishings, all assembled in its own plants. The modular bathroom and toilet system is the most effective when a specific number of basic sets of their type is assumed, and which can be repeatably integrated into the floor plans of a given building. For this reason, the company has limited itself to building three types of modular sanitary cubicles, chosen depending on the size of the residential units. Prefabricated sanitary cubicles considerably accelerate construction due to their quick and easy assembly and a production process independent of construction work [56].

GOLDBECK's system features a steel and aluminium balcony structure supported by structural columns that is affixed directly to a building's external walls. The deciding arguments in favour of this solution are lower costs relative to prefabricated balconies and there being no need to prepare custom architectural details of the joints between the balcony and the external wall. In addition, the assembly of steel and aluminium balcony elements takes place after the completion of a building's entire façade, which considerably facilitates construction. The abutting balcony structure is currently most often used in the revitalisation of buildings and is rarely encountered in new housing. For this reason, in one of its projects, GOLDBECK developed a proposal in which the steel structure of the balconies was integrated with the massings of planned buildings, creating a cohesive architectural layout (Figure 6). In the first building, the shape of the letter L along the outline of the massing was retained by adding a sequence of balconies from the side of the main road, as a continuation of the balcony sequence of the first building. In other parts of the massing, certain sections were set back, and balconies were placed within, thus maintaining the L-shaped outline.

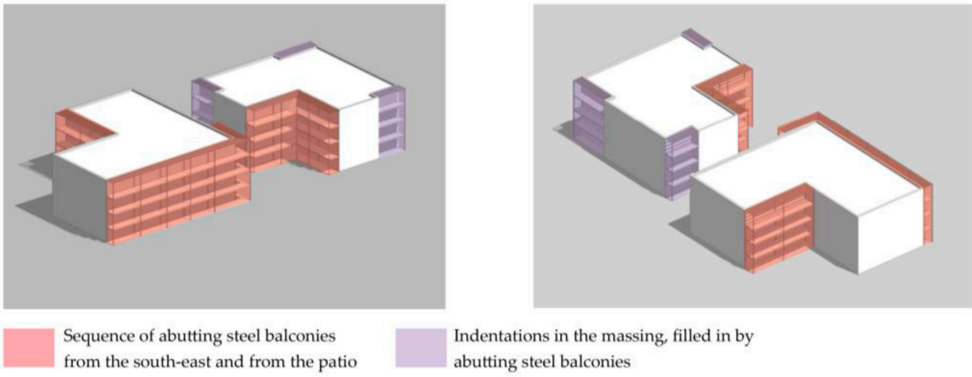

Figure 6. Design proposal that assumes the application of abutting, self-supported balconies by GOLDBECK GmbH. Original work based on materials supplied by GOLDBECK.

3.3. BIM Technology in Prefabricated Housing

Since the second half of the twentieth century, there has been a significant increase in the importance of information technology solutions used to transfer, store and generate large amounts of information [58]. This phenomenon is also observed in the construction sector, which has been developing dynamically over the past few years. The prefabrication industry, in which standardisation allows for greater production automation, is a leader in innovation in construction [26,59,60]. BIM is a method of design that integrates all project participants based on its cohesive, comprehensive spatial model, recorded in digital form [58].

BIM technology is used across all stages of a building's creation, ranging from the initial conceptual phase, through design, construction and managing a complete building [59]. BIM technology is based on a central, comprehensive 3D model of a planned building recorded in digital form in a common data environment. The central building model consists of interconnected models prepared by specialists from various fields of engineering which are transferred separately in the Industry Foundation Classes (IFC) format [58,61]. The central model is a set of all crucial information about the building, and can be used to perform key analyses, formulate schedules, bills of costs and prepare design documentation [27]. It enables the efficient cooperation of all project participants, providing them with enhanced work effectiveness and a reduced number of errors. Designers who work on their 3D architectural model can combine it with models from other specialisations as needed. For instance, to assess potential clashes with ventilation ducts inside the building, the 3D architectural model is combined with a 3D HVAC design model (Figure 7). Should clashes be detected, it is possible to quickly exchange information between specialists and correct any errors in the model instead of doing so at the construction site, which can save considerable cost and time. Models of the structural system, electrical installations, etc., operate using the same principle.

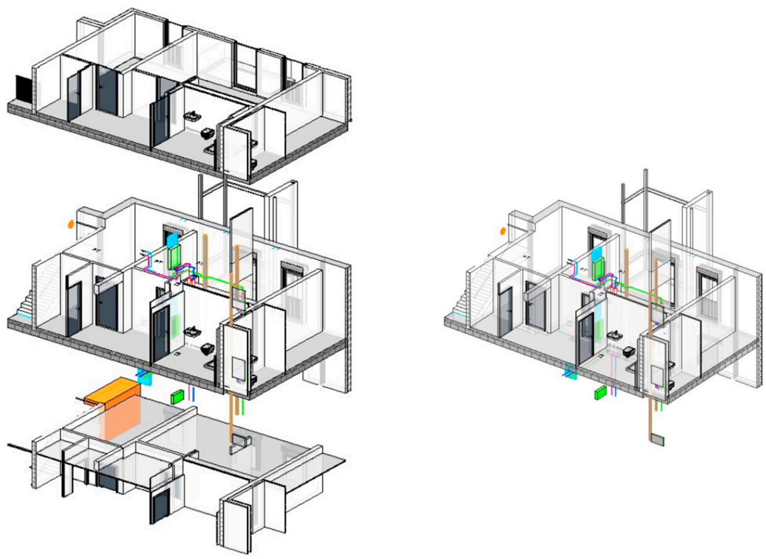

Figure 7. Central 3D model of a residential building consisting of prefabricated elements manufactured by GOLDBECK GmbH. Original work based on materials supplied by GOLDBECK.

In the case of contemporary prefabrication, 3D modelling is an exceptionally useful tool that has given it an entirely new dimension. Prefab manufacturers who use BIM technology possess complete models of their products with all the required properties and characteristics already pre-assigned [24]. This allows designers of prefabricated buildings to already make use of prefabricated 3D elements during the conceptual design stage, enabling them to avoid clashes.

The 3D model makes the work of prefab manufacturing plants much easier. On the one hand, the visual model facilitates interpretation of a given building and the solutions employed, while on the other it verifies the correctness of the elements selected and their joints, minimising the risk of manufacturing errors. The model is used to generate lists which allow the production plant to obtain information about the type and number of prefabs used, which allows for greater production automation. BIM technology also allows for a more effective planning of the transport of elements to a construction site and their proper assembly. Every prefabricated element has its own identifier within the 3D model, accompanied by information about its location within the build, mode of transport and assembly [58].

BIM technology is also used in the management of completed buildings [62,63]. Design documentation, generated based on data from the 3D model, features an overview of the materials and elements used to erect the building, making the building administrator's work easier, e.g., in the case of the need to adapt the building due to changes in use [64]. BIM is a method that has introduced a completely new standard in planning, design, construction and management of prefabricated buildings, giving it an entirely new dimension.

As mentioned previously, the experimental mixed-use housing and service building at 4 Sprzeczna Street in Warsaw by BBGK Architekci is among recognised and multiple-prize-winning projects from Poland that feature system-based housing built using a prefabricated reinforced concrete structure. Based on the building's 3D model, its designers analysed the building and the project site, which allowed the application of the most suitable and effective design solutions [34]. These analyses were used to, among other things, design triangular balconies and openwork terraces on both sides of the façade, intended to continue the regulation line of the street's front. The building was built using prefabricated elements, designed and manufactured by Budizol Sp. z o.o. S.K.A. [6]. All of the reinforced concrete structural elements and façades were designed using a 3D model in BIM technology (Figure 8), which allowed for the coordination of project participants and an increase in planned effectiveness and a reduction of errors in design documentation.

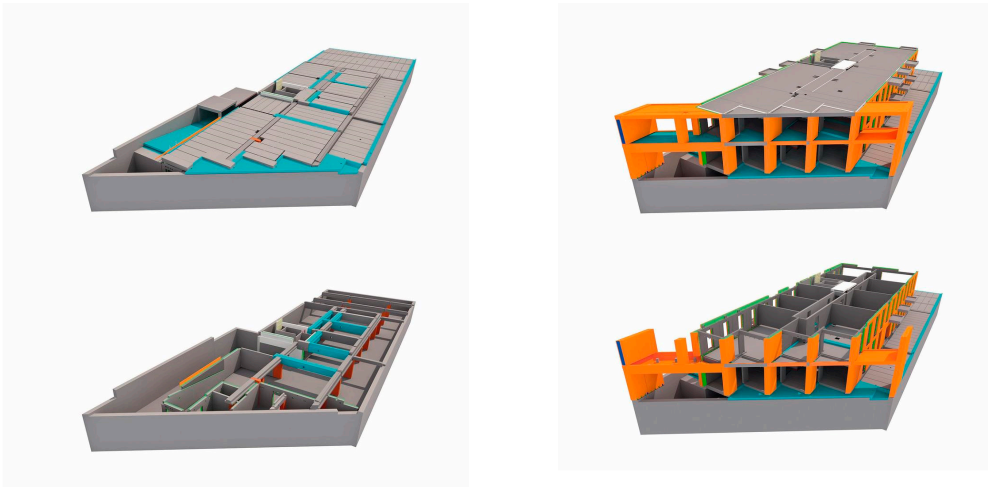

Figure 8. Scheme of the 3D model of the mixed-use residential and service building at 4 Sprzeczna Street in Warsaw, prepared using BIM technology [34].

Apart from the benefits listed, BIM technology also comes with certain limitations. The primary assumption behind BIM is based on ease of data exchange between project participants, the contractor and developer via the use of suitable software that allows, among other things, for building a 3D model of a building. Applying software that enables one to work in a BIM environment is a laborious process that requires the user to master a range of skills so as to make effective use of its tools [65]. Every project participant who works using BIM technology generates an enormous amount of data that is shared during various design stages. The free flow of this information can be disrupted when a given object is created using different systems from various developers, which can pose a problem with the compatibility of working files. Opening and saving files in a different program can lead to loss of data [66]. Despite constant development of BIM technology, the possibility of preparing assembly drawings, including those of architectural details, remains limited. Data exchange in this respect is typically done using 2D drawings which are a necessary supplement to a building's 3D model. In addition, software that allows one to use BIM technology is constantly being improved, in part due to the continuous development of the technology itself [67,68]. It is thus necessary to regularly update it. This is tied with the need to acquire new abilities and master tools offered by the software.

3.4. Significance of Prefabricated Housing in Sustainable Development

Contemporary innovative prefabrication technology should be inseparably tied in with the notion of sustainable development. At present, ecological awareness is increasing. This is why solutions with the least possible negative impact on the natural environment are pursued in construction. According to various estimates, this industry is responsible for emitting between 36% and 51% of CO_2 from anthropogenic factors in Europe and produced 820 million tons of construction and demolition waste [2]. Due to the scale of the phenomenon, it can be assumed that every form of 'green architecture' becomes a small contribution to protecting the natural environment. Likewise, contemporary innovative housing architecture based on prefabrication technology contributes to sustainable development. This is performed through material savings and lower energy expenditure for heating and cooling during use, which is facilitated by compact masses of buildings that optimally perform as housing and external partitions with low heat transfer coefficients and joints without thermal bridges.

The in-plant, automated manufacturing of prefabricated elements allows for optimising resource consumption and thus generates much less waste. One of the foreseeable trajectories of prefabrication technology development is reducing the weight of elements and increasing the share of recycled materials which would include the use of waste from prefab manufacturing and the recycling of industrial by-products [22].

At present, innovative, smart prefab joints are available on the market, offering ease of element assembly that does not make use of welding and concreting [69]. It also allows for their disassembly, which is particularly helpful in the event of demolition, remodelling or adaptation. Examples of such modern wall joints are steel connectors (Figure 9). The system consists of 'female' and 'male' connectors, which are fitted directly to the prefabs and placed in formwork during the production of prefabricated walls. The wall element with the female connector is slid into the element with the male connector, forming a joint that does not require shuttering or concreting. This system allows the disassembly of the elements without damaging them, which is crucial as it allows for the reuse of the prefabs [39,70].

Figure 9. UNICON connecting system by Munitec GmbH [39].

Contemporary buildings constructed using prefabrication technology have very good external partition parameters, which carries over to a beneficial energy balance. At present, efforts are made to ensure even better insulation via flat roofs and external walls: examples of this include the Intelligent Development Operational Programme (POIR) 2014–2020 [71] that is being implemented by Budizol, and which is to follow European Union guidelines concerning nearly zero-energy buildings (NZEBs) [72]. The high precision of door, window and external sill assembly guaranteed in all advanced solutions, performed at automated production plants, allows for the proper design of zones around apertures, and thus the elimination of thermal bridges. Modern connections between prefabs also provide high protection against energy loss [31]. Joints between external structural elements such as prefabricated balconies, loggias or terraces and the load-bearing structure are also primary sites of thermal bridge occurrence. Thermally insulated joints, e.g., for reinforced concrete balconies, called thermal break connectors or Isokorbs, are modern solutions to this problem. The rebar in thermal break connectors is made from stainless steel, which, due to its properties, assures corrosion proofing and reduces thermal conductivity via the rebar to a minimum [39].

The technology of manufacturing reinforced concrete prefabs requires substantial use of concrete and steel. The development of materials in contemporary prefabrication aims to reduce the carbon footprint of concrete mixes. At present, there is low-emission concrete available on the market. It can reduce the carbon footprint by 48%. There is also zero-emission concrete, which has a carbon footprint of zero [48]. In order to limit the use of steel in prefabrication, it has become increasingly popular to use concrete without primary reinforcement [11] and concrete with non-steel primary reinforcement, such as glass fibre reinforced polymers (GFRP) [14].

4. Discussion

Innovative systems of prefabricated construction, due to their flexibility, low cost and short completion times, allow for the building of multi-family residential buildings suited to the needs of various social groups. This is why they are the most dynamically developing segment of housing construction in several European countries and can be one of the primary drivers in achieving the goals of the New European Bauhaus initiative that first started in 2020 under the head of the European Commission, Ursula von der Leyen [1]. The objective of this project is to, among other things, pursue solutions that aid the creation future-oriented, affordable and universally accessible housing spaces.

During this study, it was determined that the full use of the potential and possibilities offered by contemporary prefabrication is tied in with improving this technology and organising multi-branch design processes using BIM. This allows the design of both unique experimental and demonstrative buildings, as well as mass-produced ones akin to the corporate real estate development model, as a part of large projects employing public and commercial standards.

The key benefits of prefabrication technology include precisely planned prefab manufacturing, transport and assembly. At present, manufacturing plants, due to considerable technical and technological progress, do not need to worry about restrictions on the size, type and form of prefabs. This allows the construction of housing with any type of architecture and any standard. Concrete prefabricated systems are effective in terms of comfort and type of use. This is due to the possibility of tailoring the size and layout of residential units, ensuring high-standard insolation and a microclimate suitable for allergy sufferers (while ensuring proper ventilation). Such buildings guarantee safety in terms of load-bearing capacity and fire resistance of their primary structural system and offer good acoustic insulation. To prevent the spread of impact sounds, floating floors and acoustic breaks are used to separate stairwells, as are proper internal and external wall layouts.

The future of multi-family housing lies in linking the benefits of constructing the main structural system using prefabricated reinforced concrete technology, effectively assembled on-site, with the installation of segments pre-made at manufacturing plants, such as: utility blocks, lift shafts, stairs, bathrooms and kitchens, and utilising interior finishes in dry construction. This applies to wall, balustrade, floor and carpet finishes, as well as doors and windows. In effect, this considerably lowers labour cost, shortens overall construction time (while using proper materials) and ensures good finish quality.

The process of planning buildings from prefabricated elements has been fully digitised, opening up new potential in terms of visualising design proposals or inter-specialist communication [24,27]. BIM technology allows one to achieve a completely new standard in planning, design, construction and building management. Its application in the present-day prefabrication industry lowers the amount of planning, cost and completion time [25], which is crucial when constructing residential buildings. BIM is a tool that coordinates and enhances the efficiency of all design stages and allows their effective integration with other project phases.

Today, ecological awareness among users is increasing. This is why it needs to be explained that innovative system-based architecture proposals are not only an effective means of building affordable housing over a short period of time but are also an important element of sustainable architecture. Buildings erected using such technologies have compact masses and good external structural partitions, which lowers heat loss and has a potential to significantly reduce CO_2 emissions. Erecting prefabricated houses also means much less waste produced (in comparison to traditional technologies), and when proper materials are chosen (concrete, wood, glue-laminated wood, glass), they can be recycled up to 100%.

In determining the tasks placed before innovative solutions for prefabricated reinforced concrete housing, coordinating architectural aspects (concerning function, aesthetic and safety), structural and technological aspects (which define efficiency, reliability and quick assembly) is crucial. The optimisation of function-spatial solutions is not a problem when employing experienced design teams and can be successfully implemented in compliance with user needs and suitably to the standard assumed, whether it is for municipal or commercial housing. Considerable progress in housing quality is achieved by enhancing modular bathrooms and implementing systems that allow for making façade structures more attractive while also featuring the option to easily attach balconies. In this situation, the primary challenge for and limitation of such systems are currently existing technical imperfections that are being addressed based on new joints, materials and technologies. Gradual progress in the quality of residential unit spatial solutions could be achieved by implementing structural layouts that grant greater flexibility in interior arrangement, which would require a partial abandonment of wall-and-slab systems and the use of decks with greater spans. Prefabricated construction is tied with the psychological problem of widely recognised flaws associated with panel and block technologies. It is being overcome in Germany and Poland by the initiative of informed manufacturers who offer pilot projects that demonstrate the wide-ranging potential of prefabrication technology. These projects are partly experimental and have been promoted in the media, business and trade press, where information highlighting the strengths of model houses and complexes were presented in a digestible manner [43,73]. So far, this method has been successful in convincing central- and local-level government decision-makers, which has resulted in architectural competitions and low-interest loans meant to incentivise developers and citizens. In the case of prefabricated concrete structures, there are also other types of challenges in the potential negative effect of this material on human health. At present, due to the use of technologies that prevent the emission of allergenic substances from concrete, progress is made in overcoming reluctance towards concrete housing, which is seen as a healthy living environment [36]. Multiple attractive architectural projects in which concrete acted as an original interior design element also contributed to overcoming the stereotype that concrete is a low-quality and aesthetically unpleasant building material [74].

One of the greatest challenges to architecture is ensuring it remains neutral to the environment, which is achieved both during their construction and operational phases. These energy savings are the essence of prefabrication systems, and further progress is achieved by lowering the weight of structural members, the use of low-emission concrete or the use of local resource deposits in construction, which reduces material transport costs. This is a key challenge due to the mass scale of housing projects and the fact that inhabiting a house that meets ecological standards is of educational benefit, as it familiarises users with sustainable development.

5. Practical Implications

Innovation is an extensive term, which covers activity in the spheres of engineering, economics, finance and organisation. How this innovation is achieved and what drives and slows it down depends on the distinctive features of each of these fields [75]. The construction sector is constantly labelled as conservative and resistant to change. It is assumed that shared innovation metrics such as research expenditures and research and development personnel count, combined with the number of patents, are not necessarily the correct measures of innovation in the construction sector [76]. Just as in all service sectors, here it is also necessary to intensify efforts to obtain clients and react to change in the environment, forcing the pursuit of innovative solutions [77]. Prefabrication meets those expectations, and is commonplace in all industries, and is currently enjoying its heyday as a competitive technology in service, industrial and housing construction sectors.

The construction sector is characterised by a number of distinctive features that can influence how innovation is or can be achieved. Contextual characteristics, such as the legislative environment [78] and project organisation, which can be both an obstacle to and a driving force for innovation [79], have a strong impact on how innovation is supported or hindered. Another complicating factor is the complexity of the construction process itself [80], which is coordinated by the lead designer during a comprehensive technical design stage, with said designer typically being the architect. During the execution and assembly phase, this responsibility is distributed and covers the cooperation of multiple specialists at several decision-making levels, with varying economic logics, and which must become involved in the innovation process at the same time.

This investigation showed that the main reasons for pursuing innovative solutions in systematising the design and construction of prefabricated housing is improving them so as to enhance their architectural potential and competitiveness in the face of traditional systems. This necessitates the optimisation of all functionality and safety of set parameters while also lowering capital and material expenditure, as well as shortening project execution times [81]. The harmonious achievement of all these goals is possible, yet it requires excellent organisation and the ability to achieve a consensus on the abovementioned vectors, which can be opposing. There is a feedback loop between enhancing a prefabricated building's flexibility and comfort of use that leads to the system becoming complicated and thus more costly to implement. In turn, prioritising the effectiveness of industrialised production and assembly leads to enhancing the technology's competitiveness, but can constrain attractiveness and the potential to offer alternative solutions at the complex, building and residential unit levels. Praxis has shown that solution quality and optimisation is facilitated by large-scale and repetitive projects, where the bespoke design of optimised project-specific structures and prefabricated elements is profitable. On the German market, such an approach is applied in the construction of municipal and for-rent housing projects by Max Bögl Modul AG and Goldbeck GmbH. The fact that such commissions are possible and even commonplace is a result of developer strategies and is moderated by government agendas that support housing programmes with loans or by organising architectural competitions. This is why an increasing number of European construction companies choose prefabrication, and many specialists also reference relevant studies on enhancing and standardising components as a field of renewal and innovation [82].

In housing construction, the application of prefabrication is often automatically associated with social or tenement housing, in which cheap solutions are the most desirable. Using this technology in such buildings does have positive aspects, such as a simplified and quick design process due to following a pre-selected structural system, lower construction costs due to there being no custom solutions (such as corner windows, conventional reinforced concrete balconies) or a short completion time which translates into completing a single story in as little as one week. Certain limitations also apply, such as the lower flexibility of the interior layout due to modular dimensions and the structural system, the relatively high number of internal structural walls, the limited number, type and layout of modular bathrooms. This leads to there being little variety in residential units and in some cases floor area is lost due to the standardisation of primary structural members or staircases. Because of this, in the case of system-based housing construction, at the initial design stage it is necessary to perform an analysis of the potential of a given system in relation to the developer's expectations, which are a consequence of the project site, and the building's standard. The projects by Pekabex S.A. and Budizol Sp. z o.o. presented in the paper are proof that prefabricated multi-family residential buildings do not always need to be orientated towards low construction cost, but can also be cases of competitive architectural solutions in the commercial housing sector.

6. Conclusions

In 2013, the subject of the 158th international Karl Schinkel competition (158. Schinkel-Wettbewerb) was the revitalisation of extensive post-industrial areas of the Tegel Airport in Berlin, with the intent to reuse them as housing. The first prize (Schinkelpreize) was awarded to Dagmara Sietko-Sierkiewicz and David Weclawowicz, diploma candidates of the Faculty of Architecture of the Wrocław University of Science and Technology, who worked under the supervision of Professor Paweł Kirschke [83,84]. They designed a futuristic district featuring buildings with prefabricated, skeleton-based structural systems that allowed the arrangement of various types of residential units and the placement of hybrid mixed-use production and service uses. The proposed structural system allowed for the rapid assembly of the buildings and the reuse of steel and reinforced concrete elements. This innovative design was a contribution to the propagation of the then-flourishing prefabricated housing sector, which is now being implemented on a large scale in Scandinavian countries, Germany and Poland.

Primary studies and analyses of the effects of application research by companies involved in the development of prefabricated reinforced concrete housing, as well as personal knowledge of the authors collected during their professional praxis as architects, allowed the formulation of the following conclusions.

There is a stable demand for the construction of several dozen thousand relatively affordable residential units per year in both Germany and Poland, which is and shall continue to be successfully achieved using prefabricated reinforced concrete technology.

The key to the use of reinforced concrete prefabricated elements in housing is their continued improvement, via new technologies, materials and patents, and which shall occur with the application of BIM.

There is a natural susceptibility for prefabrication technology to implement pro-environmental solutions (which reduce carbon footprint and environmental pressure), which can contribute to their preferential status in the future, albeit under the condition that the housing sector shall be supported via subsidies in the same manner as it is done for 'green' public and commercial buildings.

7. Future Research

The development of prefabricated construction in the sphere of multi-family housing shall be linked with an even more improved coordination based on BIM and the enhancement of available construction systems, combined with the elimination of existing imperfections in technological processes and assembly. It can be presumed that the main focus shall be placed on investigations concerning:

a. Applying the potential of structural layouts that differ from commonly used wall- and wall-and-deck-based systems;
b. Introducing prefabricated decks with greater spans that can enhance the organisation and adaptability of indoor spaces;
c. Increasing the share of pre-made furnishings and fittings already attached to prefabricated segments and interior furnishings based on dry construction;
d. Implementing modern technologies during prefabrication, using components, such as wood, glue-laminated wood and glass, which are 100% recyclable;
e. Improving joints in layered walls so as to improve stability and protect the façade layer;
f. Applying modern joints for internal prefabricated structural elements that can withstand high loads and reduce the occurrence of thermal bridges;
g. Limiting the number of prefabricated element joints, reducing their visibility or completely eliminating them;
h. Using varied materials, textures, patterns and colours that improve the aesthetics of façade layers;
i. Limiting standardisation and simple repetitiveness in commercial designs in favour of bespoke prefabricated elements that are task-optimised;
j. Pursuing innovative insulation materials for prefabricated external walls;
k. Unconditionally ensuring environmentally friendly building disassembly by improving joint systems;
l. Using prefabricated hollow core decks to trace HVAC ducts.

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