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Modular Construction and Bioclimatic Strategies: A Sustainable Approach to Building Design

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Abstract – Usually, modular construction involves the off-site manufacturing of standard building components in a factory before the components are assembled on the construction site. It is common to use terms like "prefabrication," "off-site construction," and "modular construction" interchangeably. The construction of modular constructions nowadays is flourishing all over the globe. The roots of the Albanian prefabricated constructions are extended for the first time around the 1970s. This paper will indeed analyze some recently built modular construction in Albania, considering and comparing it with international case studies.

The demand for new construction in Albania is rising rapidly. Currently, the most common structures are cast-in-place beam-column designs, driven by both traditional mindsets and industrial capabilities. However, with Albania's economic growth, there is an increasing need for affordable, quickly built, and technologically advanced buildings. Modular construction, which assembles prefabricated modules on-site, offers a solution. This method aligns with bioclimatic design principles, reducing environmental impact and optimizing resources, marking a shift toward sustainability in the construction industry.

The purpose of this article is to explore the potential integration of “modular construction techniques” with “bioclimatic design concepts” to create buildings that are environmentally friendly, energy-efficient, and multipurpose by function.

This study explores the use of modular construction techniques in conjunction with bioclimatic techniques to increase “building sustainability”. Combining these tactics encourages energy efficiency and a reduced environmental effect, making people far more resilient and weather-adaptable. The synergy between the two of them is necessary.

Keywords – modular buildings and techniques, prefabricated buildings, cast-in-place structures, prefabrication roots in Albania, bioclimatic principles of buildings

I. Introduction

For many years, modular building has been an affordable construction choice. Today, it's not just seen as a product type but as a comprehensive method of construction. Modular construction involves building structures—whether apartments, business buildings, or homes from shipping containers—off-site under controlled conditions. These structures use the same materials and adhere to the same codes and standards as traditional buildings but are completed in nearly half the time.

In traditional construction, raw materials are brought to the site, where workers cut and assemble them. However, with modular construction, significant portions of the project are fabricated off-site, sometimes in a different town or even a different country. These prefabricated modules are then shipped and assembled on-site to form a complete building.

Although some consider modular construction a modern method, it has been utilized in various industries for decades. Nowadays, it is mainly used for multi-family apartments, hotels, and commercial buildings. What makes these projects modular is that the factory-produced units are three-dimensional structures with floors, walls, and ceilings. These units come with most of the interior finishes and fixtures already installed.

In recent times, some modular companies have started incorporating traditional stick-building methods and highly automated robotic assembly lines into their processes. This evolution signifies a further advancement in modular construction techniques. Since affordable housing and faster building are essential, the flourishing of such kind of industry over the years was necessary. During the post-war era, it became more and more popular, particularly in the US and the UK. Furthermore, its popularity in the Western World began to vanish somehow, in 1968 when in the UK an apartment tower collapsed and cast doubts and concerns about the safeness of the prefabricated buildings. Meanwhile, they flourished between the 60s and 80s, in Eastern Europe (former communist countries) as an instrument to cope with the boiling housing crisis. However, they lost significance since the collapse of the Berlin Wall, because of the fragmentation of the construction industry. Nowadays, these kinds of structures are becoming again more and more widely recognized, as they are receiving new attention and financial support. Digital tools that operate in the field, have fundamentally altered the idea of modular building. There exists a stronger trend in the private sector toward building more things away from the construction site. “Modular construction” is one approach. In some other cases nowadays, there are also “multiple modular construction techniques” such as in the United States. In such cases, architects, engineers, and contractors planned to fabricate modules very far away from the site, truck them into the site, and then mount them on top of each other to complete apartment buildings. These techniques streamline the logistics of distribution and make module design easier. Also, the customer's perception of such kind of building is rapidly changing, due to more variety in material selections which enhances the aesthetic attractiveness of prefabricated buildings [1].

Housing and administrative building “mass production” has a long tradition in Europe, especially in the northern countries and in the United States. This type of architecture came into life for political and economic reasons, which encouraged the construction of “prefabricated structures” also in the Eastern bloc countries during the 1960s and 1970s. Meantime, Germany, Austria, and Scandinavia which had very ecological mindsets and standards, were converted into the champions of the “eco-architecture”.

Biases on prefabricated structures, which ended up somehow as the symbols of “cheap and unattractive structures”, are changing meantime. The latest technologies such as CAD/CAM/ CAE systems are archiving a wider audience and the supplies are increasing and diversified. These systems get a reduction in execution time, establish a more uniform and perfect finish, and reduce the environmental impact and occupational hazard at the site. The three more common prefabrication systems (wood, steel, and concrete) include a lower cost for the manufacturer and the customers [2].

Modular constructions are considered a preferred typology in comparison with traditional buildings because of several benefits. The decrease in the “competition time” is one of them. There are other components involved in the issue such as better “environmental performance”, better quality of life, structural flexibility, and increases in the safety of workers at the construction site. But nowadays there are still lower rates of acceptance of modular building in emerging nations.

The construction industry is indeed vital to a country's economic growth. The primary goal is to meet the housing and infrastructure demands of societies. Currently, the most common building method worldwide is “on-site construction”. Based on that the project competition time lasts longer, the quality is decreased, the construction waste is increased, the cost overruns are enhanced, and the environmental sustainability becomes inefficient [3], [4], [5].

The shift of focus toward “innovative construction techniques” in many developed countries aims to address the previously pointed problems with traditional building techniques. The procedure includes constructing the buildings and elements separately, which are produced off-site, and then transporting them to the construction site for installation and final assembly [6], [7].

Four forms of off-site construction may be distinguished: modular construction, non-volumetric preassembly, volumetric preassembly, and modular construction [8], [9]. Since 80–85% of the work involved in the building phase is completed in a factory, modular structures are the most comprehensive type of off-site construction. Meanwhile, extra ground work such as excavations, foundations, and module installation, are completed at the building site [10]. Furthermore, modular constructions benefit from the continuity of workflow [11]; reduction of construction waste [12]; reduction of project competition time [13]; reduction of CO2 [14]; and a drop in the number of contractors on-site; and improvement of the safety of workers [15].

Modular construction has many advantages in comparison to conventional buildings. So, they are being implemented in many countries and regions, including also Australia. “Modular building” has been recognized by construction companies as a critical concept for improving the state of the industry as it is now [16]. About 30% of residences constructed in wealthy nations like the UK are made by using modular prefabricated technologies. In contrast with the national average, up to 70% of residences in Scotland and Ireland are anticipated to be constructed using this technology [17]. Japan is now the world leader in off-site modular building, by constructing over 70,000 prefabricated dwellings annually. As “conventional building techniques” generate a significant quantity of refuse and carbon emissions in China, the implementation of modular construction can achieve a reduction of construction waste up to 74%, as well as a reduction of carbon emissions up to 34% [18].

The unique characteristics of modular constructions are associated with multiple complexities such as collaboration between the developers and other project participants; - like clients, main contractors, sub-contractors, designers, architects, transporters as well as manufacturers [19].

The application of modular construction has a significant initial financial expense, and the payback period could be at risk in achieving the return on the initial investment [20]. As a result of such experiences in the building sector, consisting both of failure and success, the industrialized nations seem to have acquired the ability to manage these kinds of risks.

It must be underlined that “modular constructions” are innovative constructions that have completely transformed the building sector. They have changed the manners of planning, designing, project implementation, and managing performance [21]. Reliability, durability, safety, constructability, and transportability are essential qualities for modular construction [22].

On the other hand, the goal of “bioclimatic design” is to maximize building performance by making use of the regional climate and environmental factors; as it seeks to reduce the need for mechanical systems while maximizing natural light, ventilation, and thermal comfort. Green roofs, thermal mass use, natural ventilation, and passive solar design are important bioclimatic techniques. These tactics minimize energy use and improve occupant comfort while coordinating with the local climate characteristics.

When compared to conventional construction methods, modular construction has fewer environmental drawbacks such as less waste from materials, less energy use, and a smaller carbon footprint. Furthermore, the regulated manufacturing environment enables more economical resource usage.

II. REFLECTIONS ON MODULAR CONSTRUCTIONS

Below are some reflections on (dis-)advantages based on local and international experiences of the modular way of construction.

1. The advantages of modular construction:

- Saves time - It permits certain work to be completed in a factory while foundations and site construction are being done at the location at the same time. The advantage of saving time is that it accelerates construction while maintaining project schedule efficiency. The modular method can reduce the entire timetable by thirty to sixty percent.
- No weather delay - The modules are manufactured in a controlled environment, thus building modular structures is not affected by severe weather. It offers more pleasant and safe working environments for employees. They become more proficient and more productive. The majority of the appliances are included with the modules once they come on-site including flooring, cabinets, countertops, plumbing, and electrical fixtures.
- No need to archive components: Staging and moving materials on a small urban site, like in Tirana, can be challenging. This often leads to clutter, slower production, and concerns about theft. When modules

are constructed in a factory instead, building sites can stay safer and cleaner. This also provides more space for workers to move around freely.

- Lower Labor Costs - One major but sometimes debated advantage of modular construction is its impact on labor costs. Today, skilled construction workers are in short supply in many countries, and in some cities, their services are very expensive. This makes it difficult to complete building projects within budget and on schedule. With modular construction, however, skilled workers can operate in fixed, controlled, and safer environments. Modular plants can draw in top talent and take advantage of easy access to raw materials and transportation links like highways and railways. This method can potentially lower construction costs by up to 25%.
- Reduced waste volume: Recent building experiences in Tirana's downtown area demonstrate that modular building and restricting the quantity of trash on each project may achieve up to a 90% reduction in materials. Even in the factories that assemble the construction components, recycling is being maximized.

2. The challenges of modular construction:

- Mass production vs. Limited Variety: On a large scale, the modular mass manufacturing technique promotes increasingly homogeneous and repetitious areas and goods. For this reason, investors choose a modular strategy when developing hotels and residential buildings, provided that each unit can be standardized and stacked. Unique or non-repetitive construction shapes significantly reduce time and cost benefits for suppliers and buyers.
- Higher number of complex decisions -vs- Front loaded design – The majority of choices and design/engineering work must be finished initially according to the modular method. It necessitates that contractors and architects/engineers understand the nuances of the modular manufacture and construction phases. Additionally, this pushes owners and purchasers to make final decisions considerably in advance of the building's completion, yet last-minute alterations can be quite problematic.
- Independent of how they are built, the approval procedure can be challenging since requirements for compliance with local and federal building standards and laws must be met. However, some countries have more favorable laws for modular production than others. Meantime building inspection systems could also vary a lot and might complicate both the approval and execution phases.
- Few suppliers continue to carry the majority of the risk. While firms that produce commercial and multi-family goods are expanding, their ability to grow depends on other factors such as liquidity. Manufacturers of modular houses are primarily focused on building single-family homes. Before signing a contract that transfers all risks to them, buyers and contractors must exercise adequate caution. Halfway through the project, changing manufacturers might also be disastrous.
- Transportation costs and risk - There is also the risk associated with transporting the modules, as they are prefabricated in a factory far from the construction site. These modules need to be either transported directly to the site or staged at a nearby location for later relocation to the site. However, mistakes during the transportation of the module could lead to serious damages, repair needs, or replacements. This needs previous extra work for planning and tracking the transportation itinerary and its best timing, to avoid situations like bridges, tight turns, traffic problems, crane setup, and temporary road closure permits. This imposes extra costs and expertise on insurance issues.
- Difficult financing process - Since modular construction involves purchasing materials on a faster timeline, the bills tend to be much larger earlier in the construction process than what investors and bankers are typically accustomed to. Therefore, is needed more patience to understand the amounts and timing of the foreseen funding, making sure that the work is not disrupted. This means making sure to explain well investors' building plans via the site and factory visits [23].

III. METHODOLOGY

The methodology is based on the historical, descriptive, and comparative manner of implementing the principles of bioclimatic architecture into modular constructions in some European cases, considering also the Albanian case study as a developing country. In Tirana, prefabricated buildings have a brief historical heritage. Tirana needs to gain experience from international case studies to further advance.

IV. INTERNATIONAL CASE STUDIES

The objectives of bioclimatic techniques and modular building are similar. They emphasize efficiency, sustainability, and less environmental effect. By combining these strategies, structures may be designed that are not only quickly constructed but also naturally energy-efficient and ecologically conscious.

Here are some international examples of modular constructions using some of the bioclimatic principles:

1. School in Leknes, Norway

The school is located in the Norwegian archipelago of Lofoten, a part of the Arctic Circle. Its topography includes dramatic landscapes and mountains, open sea views sheltered bays, untouched land, and beaches.

The prefabricated modules that are used represent the latest advanced technology in the Scandinavian market. The modules are from Cramo's new C90 series. As a result of 30 years of extensive experience in the field, the outcome is categorized by a modern design with a focus on functionality, work environment, and energy consumption. Also, the transportation by ships from the Estonian Factory is completely environmentally friendly and integrated within the green philosophy. The building was completed in a record time. 74 prefabricated modules were positioned within one week. The building has three floors. On the ground floor and first floor are positioned the classrooms; meanwhile on the third floor are positioned the rooms for school administrators and teachers. The building meets all the requirements of a modern school [24].

Fig.1 School in Leknes, Norway [24].

2. Sustainable prototype. Studio 804 (University of Kansas, School of Architecture and Urban Planning), Greensburg, KS, USA.

The project was conducted one year after a devastating tornado in the Greensburg area. The sustainable prototype uses active and passive systems as the main core for the environmental strategy, based on bioclimatic principles and passive sustainable strategies. The building uses recycled materials in full interaction with nature [2].

The Sustainable Prototype became Kansas's first LEED Platinum building. The main goal was to construct a structure that would be open to the town and the southern sun while shielding the artwork from the sun's UV rays. This would prevent the artwork from deteriorating and also create a pleasant viewing area. Studio 804 got in touch with a supplier of airplane hangar doors to find an adaptable simple-to-use and manually controllable method of opening and closing the south wall. The door was designed so that, when closed, it creates louvers to block the sun and, when open, it allows gatherings to spill onto the large buffalo grass lawn to the south [25].

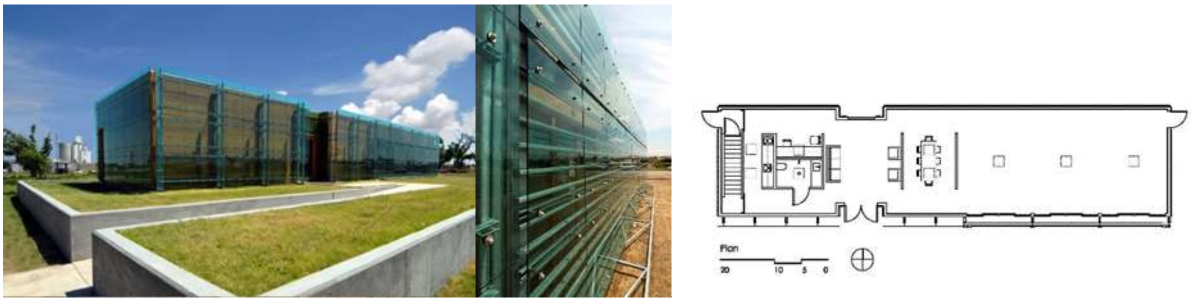

Fig. 2 Sustainable prototype [25].

3. Hedge Building. Atelier Kempe Thill Architects and Planners, Rostock, Germany.

The building is composed of a rectangular floor plan, with dimensions of 6.5x20x10 m. It has a monolithic structure. Within the structure are included two 4m high doors and high ceilings topped with polycarbonate sheets. The volume has a close nature and the green walls fuse it with the exterior [2].

The architects' goal in designing the pavilion was to explore the poetic possibilities inherent in the logic of Dutch agriculture, which is characterized by absolute rationality and industrialization. They attempt to provide a romantic touch to the pavilion solely via objective and logical ways.

The ivy hedge on the smart screen is cultivated in Dutch glasshouses. It is manufactured in garden pieces that are 1.2 by 1.8 meters in dimensions. These plants are essentially industrial products that may be used to construct "green walls." Ivy often takes years to develop to the point where a green building is created. The growing phase of the construction process is shortened by smart displays. A typical wall of ivy has an organic design; which a wall of "smart screens" does not. Rather, it is made up of several almost similar parts, which highlights its industrial nature. The pavilion is like a pergola. Its small size of 4-meter-high doors, and its roof, give it the appearance of an enclosed "house" [26].

Interesting lighting conditions dominate the room. It has the feel of a traditional museum room thanks to light coming in through the ceiling, and more light comes in through the surrounding hedges. An intriguing interplay between the inside and exterior is the end product [26]. The smart building uses bioclimatic principles by creating a heat trap during the winter season and shading with green walls during the summer season, self-efficient in terms of internal thermal comfort.

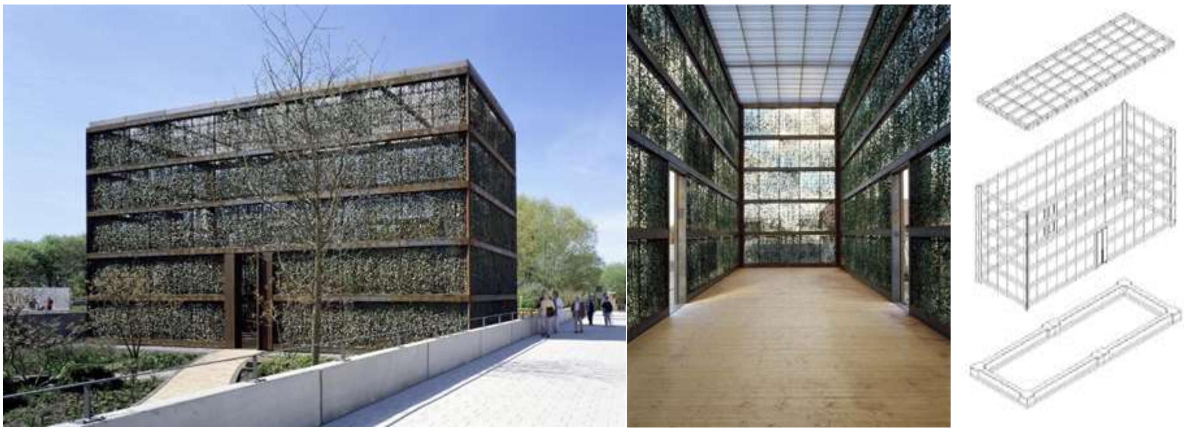

Fig. 3 Hedge Building [26].

V. The Case Study of Tirana, Albania

Due to the war's devastation of cities, the housing crisis following World War II became a pressing national emergency in the first 2 decades of the post-war period. To meet urgent demands, the first homes were constructed by building brick-made blocks, or by using temporary supplies donated voluntarily by other countries. The overtly neoclassical Russian school dominated the architecture of the time for both: the new individual buildings ore the construction of massive and sturdy structures. The motifs of such architecture were ostentation, domination, and pomposity. The majority of the new buildings constructed between 1950 and 1970 used silicate or red-coated bricks for the retaining walls. The growth of the building materials industry also contributed to the standardization of architectural elements. By bringing the design aspects together, this method significantly aided in the typification of homes and the unification of housing morphology. Many of these systems received criticism in the late 1960s and early 1970s for their compositional remedies for the social repercussions of forced expropriations, for encouraging antisocial conduct, and for rejecting the city's building customs. The kitchen space that was connected to the living room was reduced to adhere to the primary building cost-cutting philosophy. Often, plastering and other elements of the facade were also eliminated to further reduce costs. During this period, the National Architecture and Design Institute created a variety of dispersed and repeatable models to feed local housing initiatives, that had no relation at all with national or local customs, culture, or climatic circumstances, all over the country [27], [28], [29].

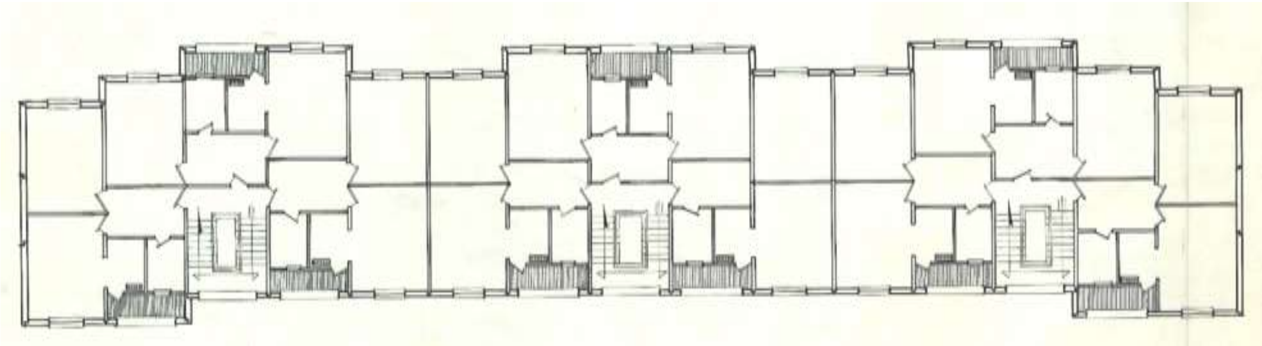

Fig. 4 Prefabricated building in Albania during the 1970s. Typical plan [30].

Albanian authorities of the time invested in the building materials production industry. Therefore, a building materials factory "Josif Pashko" began operations in Tirana for the first time in the country by the beginning of the 70s. However, this factory featured a consistent structure with load-bearing panels, based on Russian and Chinese building technologies. Precast reinforced concrete panels allow rapid construction of residential buildings. The leading institution was the architectural bureau of the “Institute of Design No.1” in Tirana. The Institute developed four different typologies/techniques of intervention, considering precast panels (four different types of modules). These modules could be combined into linear schemes. Furthermore, buildings starting from 2 up to a maximum of 6 floors could be created. The central staircase of the four modules consists of two ramps and two platforms. The intermediate platform is open and shaped like a lodge, and one staircase provides access to two or three apartments per story [31].

Generally, to combine linear plans and to construct urban complexes, the prefabricated structures were mainly made up of four distinct planimetric modules featuring two blind-side walls and bilateral exposure [32].

During the period of socialism, there were constructed a lot of prefabricated buildings at country scale. These buildings often had prefabricated reinforced concrete panels covering them and a concrete core (staircase). They were joined together via the welding of iron/metal parts. The building panels were created by using such materials, while the staircase's reinforced concrete was poured straight onto the building site. They were built quickly and effectively, but hardly provide comfortable temperatures indoors owing to thermal air infiltration and thermal bridges at their sites of interaction [33].

Generally, from the bioclimatic point of view, these buildings were positioned randomly in the area without taking into consideration the solar orientation of the building to maximize the benefit from the sun during the winter. This resulted in a considerable reduction in heating loads [34], [37].

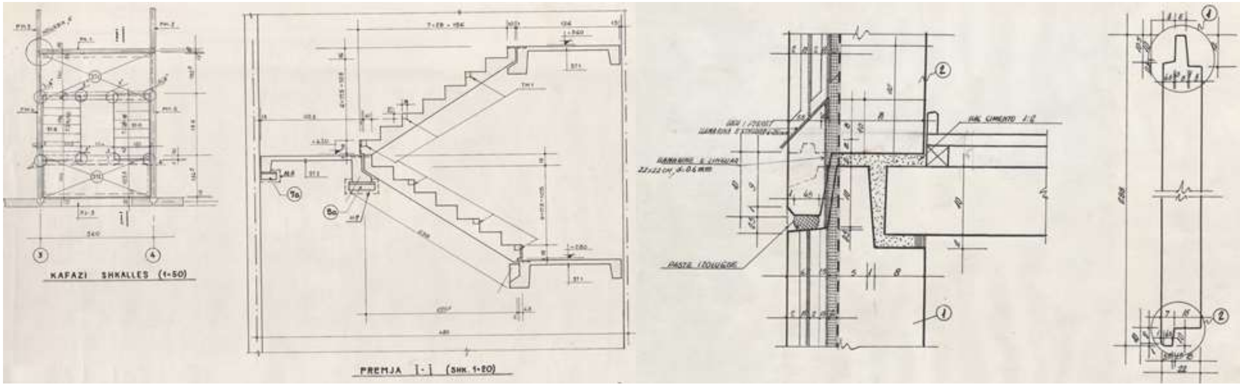

Fig.5 A. Staircase, plan, and section; B. Vertical section of horizontal joint and vertical cut of external panels [30].

Nowadays, the construction of modular buildings in Albania is not so present. Regrettably, despite their limitations in the past, prefabricated initiatives, now are rare in the Albanian construction sector and receive insufficient attention as a result of prejudice, inadequate organizational goals, lack of infrastructure and expertise, and fragmentation of the building industry. Albania has to work more with education and training institutions, industry players, and government regulations, to encourage the adoption of contemporary and new prefabricated and modular building technologies, to meet past and current difficulties [35], [36].

One of the recently built semi-prefabricated buildings in Tirana is a multifunctional one located in the main national infrastructure and economic corridor which connects the capital Tirana with the international airport, and the main port city of Durres. The structure of the NOVA Company building (designed by Arch.4 Studio in Tirana) is a combined one: a cast-in-place beam-column structure, and a prefabricated one (metallic structure). Recently, such kind of structures have gained more popularity in Tirana at least.

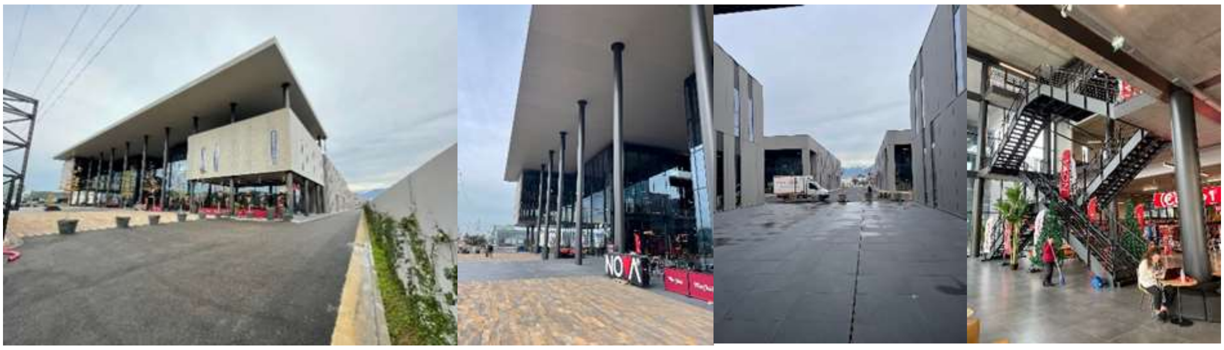

Fig. 6 Semi-prefabricated NOVA building, Tirana, Albania (Source: Authors).

The main building facade faces south, and the overhanging shading platform is designed to provide shade during the summertime. The smart glass facade is withdrawn from the first line of construction to protect against overheating and benefit from solar radiation during the winter season, using bioclimatic principles. The outer coat of the building is realized using prefabricated panels.

Another typical example of a metallic prefabricated structure is at the POLIS University building in Tirana, Albania. The added volume of the existing building was designed by Metro-Polis Architecture Studio of the university and was finished in 2010. The architects involved in the project were Arch. Fagu, E; Arch. Marku, E; Dr. Aliaj, B; and Dr. Dhamo, S. The structural engineer was Eng. Sula, B; and the mechanical engineer was Dr. Alushaj, R. The prefabrication of the metallic structure of the building was carried out by an Italian company "Mangili & Associati" SpA, transported via ship, and then assembled directly on the construction site. The walls and ventilated façade were implemented by FB-ART Shpk Tirana, in cooperation with the German company "Moeding Keramikfassaden".

The orientation of the main facade that was added to the existing warehouse is located at the back of the building toward the south. The principles of bioclimatic design are also applied here to the newly added volume/structure (serving now as the main entry hall of the university). The thermal trap (smart glass facade) faces south and has a direct benefit from solar radiation (as part of the implemented bioclimatic strategies) and is combined with the thermal mass of the ground floor platform. During summertime, the façade is protected from overheating through aluminum shaders positioned in the structural glass facade. The maximum angle of the sun on the summer solstice in Tirana (21 June) is 75°, hence the shaders were calculated purposely considering such a problem. Meanwhile, on both sides of the glass facade, ventilated facades have been created to increase the thermal performance of the building, and protect it from east and west. A study conducted by Xhexhi, K, and Aliaj, B reveals also that the thermal performance of such type of facades is much higher compared to an external standard wall [38]. The overhanging shader on the top of the building protects further the building, especially in the summertime from solar radiation. The quality of the glass structural facade is essential to be discussed. The glass implanted reflects the sun's rays to avoid overheating during summertime.

Fig. 7 Polis University's semi-prefabricated building, Tirana, Albania (Source: Authors)

VI. DISCUSSIONS

It is imperative to acknowledge the importance of incorporating "bioclimatic concepts" into these initiatives. The case studies that have been examined, including the ones from Tirana, demonstrate a definite tendency to respect nature by employing a variety of construction techniques and materials that both significantly benefit the environment and have no adverse effects on it, starting from the early stages of construction.

The use of bioclimatic concepts is constantly being expanded, particularly in "modular structures" to lower energy consumption, carbon footprint, building time lag, and reducing costs, to create a more sustainable future.

The case of Tirana and the other international case studies is a need and also a demand to change the synergy between bioclimatic architecture and modular buildings, making possible a fusion between them. The symbiosis between the two must be real and necessary.

VII. CONCLUSIONS

The primary goals of bioclimatic techniques and modular building are similar mainly because they emphasize efficiency, sustainability, and less environmental costs or effects. By combining these strategies, structures may be designed that are not only quickly constructed but also naturally energy-efficient and ecologically conscious.

It is important to consider the involvement of economic issues when merging modular construction and bio-climatic design into one entity; this involves complexities of design, constraints on funds and the regulatory environment. Collaboration between bioclimatic technologies and modular buildings necessitates careful consideration of policy proposals, scientific improvements, and industry stakeholders' cooperation. The success of the development process is dependent on resolving these difficulties.

The combination of modular construction economy and the environmental adaptability inherent in bio-climatic design results in a holistic and sustainable approach to building. The recent merger is a big step toward designing more durable, flexible, and environmentally friendly structures that can fulfill the needs of our modern society. As construction techniques evolve, there is an exciting opportunity to increase sustainability by merging modular building approaches with bioclimatic practices. This fusion has the potential to result in more environmentally friendly constructions and innovative technology.

In countries like Albania, where urban reconstruction is still in its earliest stages, there is much to learn from more prosperous countries' successful initiatives as well as their mistakes. However, it is critical to customize these principles to our specific circumstances. Tirana, Albania's capital city, demonstrates this trend by investigating the incorporation of bioclimatic design principles into modular construction. Furthermore, these structures should fulfill several functions to ensure their maximum utilization in the future.

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