Innovative Component in the Creation of the Most Outstanding Greenhouses in the World of XIX - XXI Centuries. At the Junction of Architecture and Engineering

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Abstract. The article examines the innovative contribution of architects and engineers to the design and construction of "translucent architecture". Examples of the most outstanding greenhouses since the middle of the XIX century to the beginning of the XXI century, as well as materials on projects, realizations and modern use of these constructions published in the public domain are considered. Particular attention is paid to the facts of professional success from the biographies of architects, engineers and entrepreneurs who created innovative buildings of "translucent architecture" during this period. It is concluded that the latest architectural and constructive solutions are connected with the paradigm shift in the XXI century, modern scientific achievements and high-tech engineering. The source of inspiration for the transfer of natural principles in architectural solutions are the factors of the latest innovative achievements of architecture and civil engineering.

1. Introduction

The term "innovation" was first introduced by an Austrian-American economist, Professor Josef Schumpeter, in the 1920s. According to his definition, innovation is the unification of all innovations available to the manufacturer – materials, production methods, opportunities to introduce products to the market and the creation of new markets [1]. Innovation is interpreted by Schumpeter as a new scientific and organizational combination of production factors, motivated by the entrepreneurial spirit of a special type of entrepreneur – "innovator". The key feature of innovation is novelty, but innovation is not just novelties, but the causative factors of production and production functions. The most important innovations are the introduction of new products and new production methods (commodity and technological). Basic innovations (large inventions) create the preconditions for the formation of new generations of equipment and technology, initiate secondary (small) innovations that develop the primary idea.

The term "innovation", born in economics, has become very popular. In authors’ opinion, it can be used when considering the development of architectural and construction business in general as well as its individual segments. Professional publications traditionally emphasize historical, morphological and stylistic descriptions of objects. In the twentieth century, the publication of author's design concepts was added to this list. The innovative component is rarely the focus of architectural researchers.
The purpose of this work is to study the innovative contribution of architects and engineers to design and construction on the example of the most prominent greenhouses in the world since the mid-nineteenth century to this day.

2. Literature review
The work is based on the history of design and construction of greenhouses [2-8], published photographs, drawings and descriptions of famous architectural projects, their implementation [3; 9-14] and modern use [2; 10; 11]. Particular attention is paid to the facts from the biographies of architects, engineers and entrepreneurs – the creators of outstanding examples of "translucent architecture" [4; 7-9; 12] – and the role of innovative component in the history of their professional success.

3. Materials and methods of research
The main method of this research is a comprehensive and comparative study of various sources on the issue (drawings, photo materials of famous greenhouses, literary and biographical sources). The most iconic greenhouses of the late XIX – early XX centuries are analyzed from the position of identifying the innovative contribution of their creators to various fields of architecture, construction and engineering. As a result, the characteristic features of the work of architects were revealed, as well as a number of aspects of the activities of civil engineers and designers – from the sole creator to large design teams and engineering companies. It is noted that among the builders of greenhouses an important place is occupied by entrepreneurs manufacturing building structures.

4. Results
A notable example of innovation in architecture and construction business is the Crystal Palace by Joseph Paxton [2]. Under this name the exhibition pavilion that housed the first World's Fair entered the history of architecture. Joseph Paxton was not an architect by profession; he was a gardener and built greenhouses [3].

From Wikipedia it can be learnt that “Crystal Palace in London's Hyde Park was built in 1850-1851 of iron and glass for the 1851 World's Fair. Exhibition hall with an area of over 90,000 m², 564 m long and up to 33 m high was built under the direction of Joseph Paxton and accommodated up to 14,000 visitors. The palace was built in less than a year, thanks to the innovative idea of J. Paxton. It consisted in the use of modular iron and wooden structures. 5,000 people took part in the construction (no more than 2,000 people were on the site at a time). The glazing for the palace was made by the famous English company Chance Brothers. In total, more than 84,000 m² of glazing were produced” [4, 5].

The construction of the Crystal Palace went beyond the traditional construction practice of the time, which gave rise to new forms and aesthetic principles in architecture. With its new aesthetics, innovative design, organization and construction technology, the building belonged to the architecture of the future, the symbol of which it became. Design innovations have had an even stronger impact on the further development of construction equipment than external forms [6]. It can be stated that modern architecture "made of glass and metal" owes its origin to the Crystal Palace – and greenhouses.

Greenhouses are a special type of building that has certain requirements: year-round full illumination of the room at a sufficiently high height, lack of a large number of supports, and ideally – their complete absence, the possibility of ventilation, repair and replacement of light-transmitting coating, the ability to maintain temperature and humidity. When considering the experience of construction of these structures, it can be observed that the aforementioned requirements have become the basis for the search for new expressive forms and construction solutions, which continues today.

Until the middle of the XIX century, greenhouses or hothouses, as they were then called, were the subject of prestige for rich and influential people. The second half of the XIX century is the golden age of greenhouses. With the beginning of the widespread use of metal in construction, the construction of large-span structures became real. The largest greenhouses were built in England during the Victorian era.
One of the prominent and successful figures in the construction of greenhouses is Richard Turner (1798-1881). He was a manufacturer of iron products, one of the leading designers and builders of greenhouses in the Victorian era. Turner was a brilliant innovator who boldly expanded the construction capabilities of his time. The most famous of his surviving works is Palm House, the world's first building of such a scale with a wrought iron frame, not supported by columns (the so-called "Turner design construction") [7; 8]. The palm trees greenhouse built in the 1840s has become a hallmark of the Royal Kew Botanical Gardens. The greenhouse project for palm trees and other tropical and subtropical plants belongs to Demim Burton, and the realization is owned by Richard Turner. Before that, no one had ever built greenhouses of this size, so the architects used shipbuilding technology. The Palm House also looks like an inverted skeleton of a ship. The combination of technical and architectural skills has qualitatively changed the possibilities of botanical gardens.

One of Turner's first major buildings in London, Winter Garden in Regents Park, completed in 1846, no longer exists. And it was the first greenhouse in all of Europe open to the general public. It also became the prototype of a palm greenhouse in the gardens of Kew. The Winter Garden in Regents Park existed until 1932.

Turner worked extensively in Ireland, where he was born and grew up. One of Turner's most famous works, which has survived to this day, is the Curvilinear Range [7] in the Glasnevin Botanical Garden in Dublin. The garden was founded in 1795, it took several decades to form a collection, and then the question of building a permanent greenhouse for heat-loving plants arose. Work began in 1843. The Curvilinear Range of Glasshouses was built in the spirit of its time - from elegant metal structures with high vaults, a striking form with smooth curved lines. The large size of the greenhouse – more than 100 meters in length – did not prevent it from looking very light and almost airy. By 1995, when the botanical garden was celebrating its 200th anniversary, the Curvilinear Range of Glasshouses had been so carefully renovated that it received the Europa Nostra Prize from the European Union for its high skill in preserving architecture [8].

The first half of the XX century is a difficult period in human history. Two world wars, economic and industrial crises, revolutions, social upheavals... These were not the best times for such fragile buildings as greenhouses. At the same time there was the active development of science, technology, industry and bold social experiments, which are impossible without innovation in many areas, including architectural and construction business. The ideological and economic competition between the two systems, the capitalist and the socialist, which took place throughout most of the XX century, was also a stimulus for innovative discoveries and their implementation.

After the Second World War greenhouses were experiencing a renaissance; their construction uses technological achievements of previous stages and the products of latest advances in the construction industry. There were various constructive decisions in the practice of erecting greenhouses in the second half of XX century: two-sloped core designs of a covering with glazing, pyramidal translucent designs, arched and frame systems with total glazing, cable constructive systems with the suspended frame elements, mesh covers. The latter turned out to be the most potentially variable direction in the creation of engineeringly innovative and artistically expressive structures of "translucent architecture".

The first mesh covers and load-bearing structures based on them appeared during the height of the "first metal revolution". The inventor of this type of construction was the famous Russian engineer V. G. Shukhov (hanging mesh coatings at the industrial exhibition in Nizhny Novgorod, 1896) [9, 10]. It was he who first came up with the idea of using a joint static system of metal rods that intersect in two directions. In this design, the coating works as a whole, and all the rods carry approximately the same load, which allows to utilize rods of the same cross section. Later, architects of the high-tech movement – the famous Buckminster Fuller and Norman Foster – finally introduced mesh covers into modern construction practice. The study of the possibilities of mesh systems led to the appearance of the geodesic dome of B. Fuller (1950s), and then to the surfaces of double curvature in numerous variants [11].

In the middle of the XX century a new constructive discovery – a geodesic dome – made a great impression on the architectural community. A geodesic dome is a spherical structure assembled from
tetrahedra, rods connected in a special way. In each of the nodes of the structure, three ribs of slightly different lengths converge, forming a geodesic structure, one of the strongest structures in the world. Richard Buckminster Fuller is considered to be the inventor of the geodesic dome. He had no higher education, and before doing his research, served as a naval officer and worked as a director of a construction company. He is called an architect, an engineer, an inventor. But he himself proclaimed the following: "In architecture, "form" is a noun; in industry “form” is a verb. I'm trying to connect them with each other" [12].

The first spherical grid was developed by engineer Walter Baurfeld in 1925. However, Fuller studied the shape of the sphere independently and in the 1950s patented the design of the geodesic dome and received several orders for its construction. This was the beginning of one of the most successful humanitarian design projects in the history of architecture of the twentieth century.

Geodesic domes brought Fuller international recognition. According to his project, a "golden dome" was built for the American National Exhibition in Moscow in 1959. In 1967, Fuller designed the US pavilion at the World's Fair in Montreal, Canada, which now houses the Biosphere Museum [13]. Fuller's innovative design has inspired designers around the world to create unique architectural objects. Geodesic domes have even appeared in futuristic designs of earthlings’ settlements on other planets.

Greenhouse designers also showed attention to Fuller's invention. In 1960, the Climatron was built on the grounds of the Missouri Botanical Garden in St. Louis, which became the world’s first greenhouse made of plexiglass with a completely artificial climate. The diameter of the dome is 53 m, height is 21 m, the frame is made of aluminum pipes. It was designed by architects Murphy and Mack (T.C. Howard, Synergetics, Inc., Raleigh, N.C.) [14]. In 1961, the creators of the Climatron received the Reynolds Award for successful use of aluminum structures. In 1976, the greenhouse was named one of the 100 most significant architectural achievements in the history of the United States.

The world's most famous new dome-type structure is the Eden Project (2001), an indoor botanical garden in Cornwall, United Kingdom. The greenhouse complex is based on two huge geodesic domes, each of which consists of several translucent plastic spheres, divided into many hexagons and pentagons, which not only allow creating huge spherical surfaces, but also provide rigidity. The greenhouse complex is designed in the reclaimed areas of the quarry. Round domes of greenhouses are embedded into the existing landscape. Around the greenhouses a park area for walking and contemplation of the surrounding areas is organized. The idea belongs to Tim Smith, a project is designed by architect Nicholas Grimshaw and the engineering company Anthony Hunt & Partners. Project developer is David Langton. MERO company has designed and built greenhouses [15].

The architecture of the XXI century saw an emergence of new issues and guidelines related to the crisis at the turn of the XX-XXI centuries and a paradigm shift in modern architecture. Scientists distinguish “five metaconcepts: avant-garde architecture, architectural technicism, neohistoricism, megalandscape architecture and quasi-architecture” [16]. Along with the rapid development of civil engineering, the ecological ideological direction and the issue of sustainable development, as well as the issue of preserving life on the planet came to the fore in architecture and urban planning.

It is natural that due to the new understanding of the botanical garden and greenhouses as a public, multifunctional space in the XXI century, both an eco-botanical and at the same time technological complex, the creation of these objects is becoming an increasingly complex process. It no longer involves individual architects, engineers and entrepreneurs-innovators, but project groups, bureaus and companies, often several. The competitiveness of modern engineering solutions and the success of new buildings and complexes provide a new ideology, the innovative approaches to construction design.

In the Gardens by the Bay park project (2010) in Singapore a fantastic symbiosis of technology and natural diversity has been created. A unique garden of the future, eco-technological botanical complex offers solutions to many problems: from the preservation of natural biomes to the ecology of the modern metropolis. There are two giant domed greenhouses in the park complex - the Flower Dome and Cloud Forest. The greenhouses (covering about 1 hectare) developed by Wilkinson Eyre Architects are a clear example of the use of arch-frame structural system with a mesh cover. The design has no additional
supports. Its base is a giant steel mesh, which carries 3332 glass panels and 28 metal arches mounted on the outside of the domes on top of the greenhouses. The design is actively aimed at minimizing environmental impact. Rainwater is collected from the surface of the greenhouse and circulates in the cooling system, which is connected to the so-called "supertrees". In "supertrees" water is used to cool hot air and circulating water [17].

According to the Plasma Studio project in 2013, a grand greenhouse was built in the Chinese city of Xian [18]. The glass building with a metal frame is partially sunk into the hill and resembles an exquisite crystal, shining in the sun with sharp edges. This impression is due to the faceted roof formed by triangular fractures that converge at different angles. Visitors enter the main hall of the building through a curved slot-tunnel that crosses the main facade like a crack. The interior of the greenhouse is divided into three main sections, dedicated to different climatic zones and landscaped with plants that are characteristic of these zones. The horseshoe-like shape of the object plan forms a large internal open-air space - it is the natural center of the complex, which connects other parts of the building in the open air.

In the XXI century the construction of individual greenhouse complexes has repeatedly become an event in the architectural world. A number of modern greenhouses with various innovative components, stunning design and architectural solutions are currently built around the world.

5. Conclusion

The flourishing of the most spectacular modern architectural and engineering ideas that we see today began long ago, during the formation of industrial society. This event has a distinct beginning, even a date – the First World Industrial Exhibition in London in 1851. It is marked by the construction of the Crystal Palace, the idea of which belonged to the innovator J. Paxton, and which together with the development of civil engineering, technology and materials, gave impetus to the birth of a relevant trend – called "translucent architecture".

Innovative developments in the field of architecture, engineering and construction technologies of past epochs were actively used in the XX century during the construction of greenhouse complexes. Along with the new interpretation of traditional structural schemes, innovative constructive solutions were invented, an example of them being a geodesic dome. With the use of the latest technologies, more and more opportunities emerged for the implementation of increasingly ambitious tasks that opened up new horizons for the development of architecture. Greenhouses with their requirements, special expressiveness and innovative methods of design solutions have repeatedly become symbols of the latest achievements in architecture and civil engineering of the last century.

In the XXI century the ecological ideological basis which directs possibilities of modern building technologies acquires urgency as the latest architectural trend. Today, the ideas of conservation of resources, sustainable development of settlements and the like give rise to new competition in the construction of unique translucent structures that become symbols of cities and countries worldwide. Avant-garde architectural designs of greenhouses, their chimeric bionic forms that appear more and more often, clearly show the possibilities of implementing innovative developments of modern engineering in the natural environment. Scientific achievements become a source of inspiration for the transfer of natural principles in the architectural solutions of modern greenhouses. Thanks to the combined efforts of today's innovators from various fields of science and construction, today we have the opportunity to implement projects based on the latest ideas, various technological innovations, unique and sometimes fantastic creative concepts.

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