Applications of Innovative Elements of Industrialization in the Field of Construction Industry and Wood-based Buildings

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Abstract

The industrialization of construction has accelerated significantly in recent years thanks to automation, prefabrication, digitalization and sustainable solutions. In the field of timber construction, these innovations are reflected in more efficient and environmentally friendly production and construction processes. Timber construction plays a key role in sustainable construction, as wood is a natural, renewable and carbon-neutral material. In combination with modern technologies and innovations, they become even more environmentally friendly, energy-efficient and durable. The purpose of this manuscript is to point out, within a limited scope, the principles and aspects related to the above-mentioned topics, both in terms of raising awareness of the given topics and also to initiate new research tasks for increasing the performance of the construction industry as such. Because, for example, innovations in the industrialization of timber construction enable faster, more precise and more sustainable construction. The combination of prefabrication, digitalization, automation and smart solutions is creating a new era of wooden buildings that are not only environmentally friendly but also competitive with traditional building materials.

Keywords: *Construction Industry; Efficiency; Innovations; Wood-based Buildings*

1. Introduction

Construction industry is one of the oldest industries in human history, yet it is constantly undergoing innovation and technological advancement. Past industrial revolutions have fundamentally changed the way buildings are designed, manufactured and constructed, from the mechanization of manual labor to the digitization and automation of construction processes [1],[2]. Today, we are witnessing the fourth and fifth industrial revolutions in construction, which are bringing about breakthrough technologies such as robotics, artificial intelligence (AI), Building Information Modeling (BIM), 3D printing, prefabrication and sustainable materials. Industry 4.0 brought automation and digitalization, while Industry 5.0 focuses on connecting technology with human creativity, personalization and environmental responsibility [3]-[6].

Nowadays, the construction industry is facing increasing environmental and economic challenges that require innovative and sustainable solutions. In this context, timber constructions are proving to be a key alternative to traditional construction methods, as they combine ecological sustainability, high energy efficiency and modern technological innovations [7],[8]. Developments in wood processing, prefabrication, digital technologies and intelligent systems not only enable faster and more precise construction, but also significantly reduce the carbon footprint [9],[10]. Thanks to innovative materials such as CLT (cross-laminated timber) and LVL (laminated veneer lumber), timber constructions offer high strength and durability while maintaining low weight [11].

The aim of this manuscript is to present, within a limited scope, modern approaches to industrialization as such, but also in the field of timber construction and their impact on sustainability. Below, topics are addressed in connection with key innovations, such as the principles of industrialization, the differences between industry 4.0 and 5.0, intelligent building systems, digitalization and the circular economy, which make wood the material of the future.

2. Difference between Industry 4.0 and Industry 5.0 in the Field of Construction Industry

Industrial revolutions are fundamentally changing the way we manufacture, build and innovate. Industry 4.0 has brought about the digitization, automation and connectivity of manufacturing processes through the Internet of Things (IoT), artificial intelligence (AI) and robotics. This transformation has enabled smart factories, where machines communicate with each other and optimize production in real time.

Despite technological progress, however, there is a need to move industry to a higher level, towards Industry 5.0. This concept emphasizes the humanization of technology, sustainability, and human-machine collaboration [12]. Industry 5.0 does not aim to replace humans with robots, but rather to create a synergistic system in which technology supports creativity, personalization, and environmental responsibility [13],[14].

2.1. Industry 5.0 in construction industry

Industry 5.0 is a relatively new concept that focuses on the synergistic combination of advanced technologies and the human factor [15],[16]. In the field of construction, especially in wood-based construction, Industry 5.0 can bring several innovations that improve the efficiency, sustainability and quality of construction. The key aspects of Industry 5.0 in this area are:

Personalization and customization - Industry 5.0 places emphasis on customizing products and services to individual needs and requirements. In the field of timber construction, this means that technologies such as 3D printing, CNC machining or robotics can enable the creation of tailor-made components that take into account the specific requirements of the client or the building design.

Human and machine integration - While Industry 4.0 focuses on automation and digital technologies, Industry 5.0 seeks to improve the interaction between people and technology [17]. In construction, this means that robots or automated systems can work alongside workers, increasing productivity and safety while preserving the creative and decision-making potential of humans. For timber construction, this could mean using intelligent woodworking tools to assist workers in design and production.

Sustainability and green materials - Industry 5.0 places great emphasis on sustainability, which is also key in wood-based construction. With the increasing emphasis on green materials, energy efficiency and the circular economy, new technologies can enable more efficient wood processing and material recycling, thereby reducing the negative impact on the environment [18],[19].

Advanced manufacturing technologies - Industry 5.0 also includes the use of advanced manufacturing technologies, such as automated lines, robotic systems, or 3D printing of wooden components [20]. This allows for more precise and faster wood processing, reduces waste, and increases production efficiency.

Digital transformation and simulations - Digitalization and the use of digital twins, BIM (Building Information Modeling) and simulations enable better planning, design and optimization of timber structures [21],[22]. These tools can help to anticipate potential problems before construction begins, saving time and costs.

Robotic and automated systems on construction sites - Construction robots that can handle large pieces of wood or automated assembly systems can improve the speed and accuracy of timber construction [23],[24]. These technologies reduce the need for manual labor and can be less labor-intensive.

Industry 5.0 in construction thus brings innovation in the areas of efficiency, sustainability and safety while maintaining the important role of the human factor, which can use advanced technologies to achieve better results..

2.2. Industry 4.0 vs 5.0 in construction industry

Industry 4.0 focuses on digitalization, automation, and the interconnection of technologies to increase the efficiency and accuracy of construction processes [25]-[27]. Key elements include:

- **BIM** (Building Information Modeling) - digital modeling of buildings and infrastructure.
- **IoT** (Internet of Things) - sensors and devices for monitoring buildings in real time.
- **Robotization and automation** - the use of robots in construction work.
- **Data analytics and AI** - data-driven process optimization.
- **3D printing** - on-site production of building components.

The fundamental goal of Industry 4.0 is to reduce costs, minimize errors, and increase productivity through intelligent technologies.

Industry 5.0 builds mainly on the principles of Industry 4.0, but adds an emphasis on the humanization of technology, sustainability, and collaboration between people and machines. The main differences are:

- **Personalization and individualization of buildings** - adapting projects to the specific needs of users.
- **Human and machine collaboration** - robots work as assistants to construction workers, not their replacement.
- **Sustainability** - ecological materials, circular economy and reducing the carbon footprint.
- **Resilience and safety** - smart buildings that adapt to climate change and increase worker safety.
- **Social dimension** - better working conditions, increased safety on construction sites and support for worker skills.

Thus, Industry 4.0 is fundamentally focused on automation and efficiency, while Industry 5.0 is focused on harmonizing technology, humans, and nature. In construction, this means a transition from purely digital and robotic construction to sustainable, safe, and personalized construction with an emphasis on collaboration between humans and technology [28],[29].

3. Innovative Elements of Industrialization in the Field of Wood-based Construction

The industrialization of construction has accelerated significantly in recent years, thanks to automation, prefabrication, digitalization and sustainable solutions [30]-[32]. In the field of timber construction, these innovations translate into more efficient and environmentally friendly production and construction processes [33]-[35].

Prefabrication and modular construction

- **Panel and modular production** - wooden panels (CLT – Cross-Laminated Timber, GLT – Glued Laminated Timber) are produced in production halls and are delivered to the construction site as finished modules.
- **Hybrid systems** - a combination of wood with steel, concrete and glass to increase strength and design flexibility.
- **Automated production lines** - robotic CNC machines and 3D printing for precise shaping of wooden components without waste.

The above results in the following main benefits, in particular: reduction of construction time by up to 50%, higher quality and accuracy thanks to control in a factory environment, reduction of waste and more efficient use of materials.

Digitalization and BIM (Building Information Modeling)

- **Digital building modeling** - 3D models with accurate data on materials, statics and energy efficiency.
- **AI and data analytics** - optimization of designs based on simulations and environmental conditions.
- **Virtual and augmented reality (VR/AR)** - interactive planning and visualization of buildings before their implementation.

The above results in the following main benefits, in particular: elimination of errors and collisions already in the design phase, more effective coordination between architects, engineers and suppliers, lower costs thanks to optimization of materials and processes.

Smart building materials and sustainability

- **CLT and LVL (Laminated Veneer Lumber)** - structural materials with high strength and low weight.
- **Ecological insulation** - wood fiber boards, hemp or cellulose insulation instead of synthetic materials.

- **Facade systems with active protection** - self-regulating wooden facades that react to changes in temperature and humidity.

The above results in the following main benefits, in particular: longer lifespan and higher fire resistance of wooden buildings, lower carbon footprint compared to traditional materials, better energy efficiency and living comfort.

Automation and robotization in construction

- **Robotic assembly systems** - automated assembly of wooden structures on the construction site.
- **Drones and sensors for monitoring construction sites** - real-time quality and safety control.
- **3D printing of wooden elements** - use of innovative technologies for the production of curved and non-traditional structural parts.

The above results in the following main benefits, in particular: increased productivity and reduced need for manual labor, minimized construction errors, and increased safety in the workplace.

Intelligent wooden buildings and IoT technologies

- **Sensors for measuring humidity and stability** - early detection of damage or degradation of wooden structures.
- **Smart home solutions** - integration of energy-saving systems into wooden buildings.
- **Dynamic regulation of ventilation and lighting** - wooden buildings that adapt to external conditions.

The above results in the following main benefits, in particular: lower energy consumption and greater living comfort, reduced building maintenance costs, and increased durability of wooden structures.

3.1. Application of industry 5.0 elements in the field of production and construction of wooden buildings

Industry 5.0 takes the digitalization and automation of Industry 4.0 to a new level by emphasizing the humanization of technology, sustainability, and collaboration between people and machines [36],[37]. In the field of timber construction and manufacturing [38],[39], this is reflected in several key areas:

Human-Robot Collaboration (Human-Centric Approach)

- Robots and CNC machines work in close cooperation with craftsmen, increasing precision while preserving the uniqueness of artisanal production.
- Exoskeletons and assisting robots make physically demanding work easier in wood handling and assembly processes.
- Augmented reality (AR) allows for visualization of the project directly on site, reducing the risk of errors.

Sustainability and ecological approach

- Circular economy - maximizing the use of wood waste (recycling sawdust, using offcuts for new products).
- Wood as a carbon-neutral material - focusing on certified wood from sustainable forests (e.g. FSC, PEFC).
- Green technologies - combining wooden buildings with solar panels, heat recovery systems and green roofs to increase energy efficiency.
- Biocomposite materials - using a combination of wood and ecological binders instead of synthetic adhesives.

Digital technologies for production optimization

- BIM (Building Information Modeling) - digital modeling enables detailed planning and waste minimization.
- AI and machine learning - optimization of wooden building designs based on data analysis (energy efficiency, statics, material moisture).
- Sensors and IoT in wooden buildings - smart wooden houses with automatic control of humidity, temperature and air quality.

Personalization and customer-centric approach

- Custom-made modular timber buildings - the possibility of adjusting the design to the customer's needs thanks to digital production and prefabrication.
- Mass personalization - thanks to robotic production, individualized elements can be produced without increasing costs.
- Virtual reality (VR) - customers can "walk through" their future home in advance and adjust design details.

Durability and safety of buildings

- Sensors in structures - real-time monitoring of the structural integrity of wooden buildings.
- Advanced fire technologies - use of flame retardants to increase the durability of wooden structures.
- Automated assembly systems - reducing the risk of work-related accidents in construction using robotic manipulators.

4. Conclusion

Industrialization in the construction industry, and more specifically in the field of timber construction, represents a significant step towards a more efficient, ecological and technologically advanced construction industry. Innovative elements such as prefabrication, digitalization, automation and the use of smart materials not only enable the acceleration and improvement of construction, but also significantly reduce the environmental impact. Timber construction, supported by Industry 4.0 and 5.0 technologies, is becoming a sustainable alternative to traditional construction solutions. CLT and LVL panels, 3D printing, robotic assembly, BIM modeling and smart sensors contribute to higher efficiency and durability of timber construction. In addition, increasing emphasis is placed on the circular economy, recyclability of materials and reducing the carbon footprint. The future of construction lies in the synergy between innovation and natural resources. Wood as a renewable material, combined with advanced technologies, offers a solution for modern, energy-efficient and sustainable buildings.

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