VOLUME : 13 NUMBER : 2 YEAR :2025 ISSN: 2303-5188

NAUKA I TEHNOLOGIJA

SCIENTIFIC JOURNAL OF THE INTERNATIONAL UNIVERSITY OF TRAVNIK

Nauka i tehnologija

- ***Faculty of Traffic***
- ***Faculty of Economics***
- ***Faculty of Polytechnic Sciences***
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Publisher
International University Travnik in Travnik
Aleja Konzula-Meljanac bb
72270 Travnik
Tel: 00387 30 540 597
Fax: 00387 30 540 587

Aims and scope
Nauka i tehnologija / Science and technology is a scientific journal of the International University Travnik in Travnik, published twice a year, in which problems in the fields of social, artistic and technical sciences are dealt with in a scientific and professional manner, and readers are introduced to the ideas and goals from the above areas. In addition to scientific and professional papers, it also accepts review papers, as well as conference papers.

Journal „Nauka i tehnologija“ is indexed
The scientific journal of the International University of Travnik "Nauka i tehnologija" is indexed by the services: Google Scholar, Scilit, Dimensions, Semantic Scholar, Lens.Org, J-Gate, ErihPlus, Road, Open Alex, EconBiz, Ceeol, Miar, Index Copernicus.

Print
International University Travnik in Travnik
ISSN 2303-5188 (Print)
ISSN 2831-106X (Online)

Circulation
200

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Tel: + 387 30 540 597
Fax: + 387 30 540 587
www.iu-travnik.com
https://naukaitehnologija.iu-travnik.com/

UDK/UDC 62 ISSN 2303-5188

NAUKA I TEHNOLOGIJA

SCIENCE AND TECHNOLOGY

JOURNAL OF THE INTERNATIONAL UNIVERSITY TRAVNIK IN TRAVNIK

Vol. 13, No. 2, 2025.

Travnik, 2025.

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Words from the Editor

Welcome to the latest edition of *Nauka i tehnologija / Science and Technology*, the esteemed scientific journal of the International University Travnik in Travnik. Published biannually, our journal is dedicated to addressing pressing issues in the fields of social, artistic, and technical sciences with a blend of scientific rigor and professional insight.

Our mission is to engage our readers with groundbreaking ideas and goals from these diverse areas, fostering a deeper understanding and appreciation of the advancements shaping our world. Each issue of *Nauka i tehnologija* offers a platform for scholars and professionals to share their innovative research and thought-provoking perspectives. We take pride in featuring not only original scientific and professional papers but also comprehensive review papers and insightful conference proceedings.

As a testament to our commitment to excellence, *Nauka i tehnologija* is indexed by several prominent services, including Google Scholar, Scilit, Dimensions, Semantic Scholar, Lens.Org, J-Gate, ErihPlus, Road, Open Alex, EconBiz, Ceeol, Miar and Index Copernicus. This ensures that the valuable contributions of our authors are accessible to a wide audience, amplifying the impact of their work.

In this edition, Vol. 13, No. 2, 2025, we are proud to present a diverse array of papers that reflect the broad scope of our journal:

1. **Structures in Nature as an Inspiration for Contemporary Architecture and** Construction by Veis Serifi, Vesnera Serifi, and Senida Serifi write about how structures in nature inspire contemporary architectural and construction solutions, with an emphasis on efficiency, sustainability, and innovative structural design.
2. **Energy Management and Environmental Sustainability in Earthworks** by Alema Mašović, Berna Krbuzlić, and Nazim Manić write about how energy management and environmental sustainability are applied in earthworks, focusing on reducing environmental impact, improving energy efficiency, and promoting sustainable construction practices.

3. **Urban Transformations and Revitalization Strategies: Innovative Approaches for Sustainable City Development in Europe and Croatia** by Olgica Erceg writes about innovative strategies for sustainable urban development in Europe and Croatia, focusing on revitalizing cities and improving infrastructure.

4. **Avifauna of the Orjen Nature Park** by Aleksandar Vukanović and Krsto Mijanović writes about the bird species found in the Orjen Nature Park, focusing on their biodiversity, conservation status, and the importance of the park as a habitat for various bird species.
5. **Exhaust Gases from Internal Combustion Engines and Their Impact on the Environment** by Slavko Đurić, Mirjana Ćeranić, Enes Varupa, Milan Milotić, and Dragiša Đorđić writes about the harmful effects of exhaust gases from internal combustion engines on the environment, focusing on air pollution, health risks, and the need for sustainable solutions to reduce emissions.
6. **The Application of Artificial Intelligence in the Tax Systems of Bosnia and Herzegovina: Opportunities, Limitations, and Challenges** by Denis Šundrić writes about the use of AI in Bosnia and Herzegovina's tax systems, focusing on

its potential benefits, challenges, and limitations.

7. **Contemporary Structures in the Era of Digital and Sustainable Construction** by Emir Maslak, Timur Curić, Demir Vatić, and Ismail Nurković discuss the impact of digital technologies and sustainability principles on the development of contemporary building structures, with particular emphasis on design, materials, and building efficiency.

8. **Remote Employment in the Digital Era: An Analysis of Key Challenges in Cybersecurity and Information Technology (IT) Systems Management** by Sofiu Vehebi She writes about the challenges of remote work in the digital era, with a particular focus on cybersecurity and IT systems management.

Thank you for your support and interest in *Nauka i tehnologija*. We look forward to presenting you with the latest advancements and discussions in the upcoming issues.

Sincerely,

Editor-in-chief

Prof. dr. Rajko Kasagić

STRUCTURES IN NATURE AS AN INSPIRATION FOR CONTEMPORARY ARCHITECTURE AND CONSTRUCTION

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Professional paper
https://doi.org/10.58952/nit20251302001
UDC 72.01:59

Abstract

Biomimetic design represents an interdisciplinary framework that integrates principles of evolutionary biology, structural mechanics, materials science, and computational modeling to enhance the performance of architectural and structural systems. Natural structures exhibit hierarchical organization, optimized force distribution, and material-efficient geometries developed through evolutionary adaptation. This study presents a comparative analysis of ten representative biological systems and their engineering analogues, focusing on morphology, mechanical behavior, geometric efficiency, and structural functionality.

Key biological models—including trabecular bone, plant vascular networks, hexagonal cellular structures, spider silk tensile systems, and hydrodynamically optimized aquatic forms—demonstrate universal principles of minimum material usage, high strength-to-weight ratios, and efficient load transfer. Using parametric modeling, topology optimization, and numerical simulations, these principles are systematically translated into lightweight structural configurations, adaptive façade concepts, and material-efficient construction strategies.The results confirm that biomimetic design provides a robust and transferable framework for the development of sustainable, energy-efficient, and high-performance building systems. Natural systems, shaped by evolutionary selection, offer fundamental structural strategies that can significantly improve the reliability, efficiency, and optimization of contemporary engineering structures.

Keywords: *biomimetic design, natural structural systems, hierarchical materials, topological optimization, parametric modeling, adaptive facades, energy-efficient constructions, biologically inspired geometries, fractal and lattice structures, evolutionary morphology.*

1. INTRODUCTION

Biomimicry in modern engineering is profiled as a conceptual and methodological framework in which natural systems are viewed as highly optimized "reference constructions", whose principles of organization, material distribution and geometric rationality can be directly translated into architectural and construction solutions of new generations [25-27]. In contrast to the traditional approach, in which forms and systems are primarily the product of technological constraints and experiential engineering rules, biomimetic design starts from the assumption that evolution has already "performed" an enormous number of experiments over geologically long time scales, whereby the very structural concepts that simultaneously meet the requirements of minimal material consumption, energy efficiency, and adaptive resilience have survived.

Natural structures – from the trabecular architecture of bones, through the hexagonal alveolar matrices of honeycombs, to the fractal vascular networks of plants and the tension systems of spider silk – are characterized by an extremely sophisticated multiscale organization [29-31]. At the micro level, density gradients, fiber orientation and heterogeneous phase distributions are present; at the meso level, differentiation of load-bearing zones, dissipation and stabilization; and at the macro level, clearly recognizable geometries such as logarithmic spirals, geodesic schemes, fractal hierarchies, and minimal areas [32]. Such a hierarchical structure allows for the simultaneous fulfillment of multiple, often conflicting, requirements: local adaptation to stress, global stability, wear, shock and fatigue resistance, as well as economical use of available resources.

In architecture and construction, these natural models are becoming particularly relevant in the context of several contemporary challenges: the need to reduce mass and material consumption over large ranges, improving the energy efficiency of building envelopes, developing adaptive façade and roof systems, and introducing new biocomposite and functionally gradient materials. Trabecular bone is analyzed as a physical prototype of a topologically optimized support, where the density of the material is adjusted to the stress field [35]; plant vascular networks as a natural analogue of network systems of fluid and energy distribution across multiple hierarchical levels [36]; honeycomb as a paradigmatic example of minimal material consumption at maximum rigidity [37]; spider web as an extremely efficient tension system with the ability to localize damage Hydrodynamic forms of marine organisms as a model for minimizing fluid resistance and eddy effects. The geometry of the sea urchin, with its geodesic arrangement of tiles, indicates the principles of formation of double-curved scales and lattice domes of great stability [40].

The development of digital design techniques, especially parametric modeling, generative design, topological optimization, and numerical methods (FEM, CFD), is fundamentally changing the possibilities of applying these natural principles in technical practice [41, 42]. Instead of an intuitive or purely aesthetic "reference to nature", the engineer today has tools with which structural patterns observed in biological systems can be quantified, simulated and then precisely implemented in supports, trusses, shells, façade panels and spatial networks [43]. Additive technologies (3D printing of metals, polymers and composites) further open up the possibility of realizing complex, topologically optimized forms that until recently were constructively or economically unfeasible [44].

In this context, biomimetic architecture and civil engineering are not reduced to formally "biomorphic" objects, but introduce a deeper level of analogy: functional, material, structural, and performative. Natural systems are viewed not as a decorative model, but as an operating model, in which the concepts of morphological analogy (geometry and form), structural optimization (stress and stiffness distribution), material mimicry (biocomposites, gradient materials), and functional adaptation (reaction to changing external conditions, e.g., light, wind, humidity, temperature) are clearly distinguished.

Starting from this conceptual framework, this paper analyzes ten carefully selected biomimetic pairs – natural structures and their contemporary architectural-structural interpretations – through four key dimensions: (i) morphology and geometric logic, (ii) mechanical behavior and stress distribution, (iii) material organization and composite principles, and (iv) functional and energy efficiency of systems [47]. Particular emphasis is placed on structures that have already served as a basis for concrete engineering realizations (e.g., trabecular-inspired lattice systems, honeycomb facades, mesh and membrane structures, hydrophobic sheaths, and aerodynamically optimized towers), thus providing a direct link between biological analogues and measurable engineering performance.

The goal of the introductory theoretical framework is not only to affirm the inspiring value of nature, but to argue that biological systems contain clearly identifiable engineering strategies, which can be formalized, numerically modeled, and translated into sustainable, energy-efficient, and structurally rational building concepts. In this sense, nature is treated as a "large-scale experimental laboratory" and biomimicry as a bridge between evolutionary morphogenesis and contemporary architectural-engineering practice [50].

2. NATURAL STRUCTURES AS AN OPTIMIZATION MODEL

2.1. Natural Structures as a Model of Optimization: Theoretical Foundations and Biological Principles

Natural systems represent an extremely relevant model for the development of engineering structures thanks to their multiscale organization, adaptive mechanisms, and functional efficiency, resulting from long-term evolutionary processes. Understanding their internal structure, geometric structure, and functional logic makes it possible to formulate engineering models that combine minimal material consumption and high mechanical stability — a principle that modern architecture and construction seek to integrate through advanced digital and experimental methods [51].

This chapter discusses four fundamental groups of natural structures: (i) hierarchical biostructures, (ii) fractal and lattice systems, (iii) hexagonal and cellular organizations, and (iv) aerodynamic biofluidic forms, with particular emphasis on their direct engineering applicability [52].

2.1.1. Hierarchical Bio-Structures and Multi-Scalar Design

Hierarchical organization is one of the most common and evolutionarily efficient structural principles in nature. Structures such as bone, wood, and shells form complex composite systems in which material and geometric properties change through multiple levels of organization.

1. *At the nanoscale*, mineral phases (e.g., hydroxyapatite) and protein components (collagen) are arranged in crystallographically oriented matrices that determine local strength and fracture resistance.
2. *On the microscale*, lamellar and fibrous structures govern stress direction and deformation control.
3. *On the mesoscale*, the differentiation of zones of different densities allows for the formation of stiffness gradients and local adaptation to external forces.
4. *On a macro scale*, a global shape — such as the geometry of a femur or a vertical tree — is optimized according to the load

regime to which the structure is predominantly subject.

This multiscale principle has been directly applied in engineering through [54]:

1. Density gradient (FGM) materials.
2. Ultralake Sendvich structures,
3. topologically optimized carriers,
4. Variable inertia and modular lattice systems.

The application is particularly important in the design of tall buildings, slender structures, high-span bridges, and seismically resistant building systems, where hierarchical organization allows for improved weight-to-load ratios [55].

2.1.2. Fractal, dendritic and lattice structures

Fractal and lattice structures in nature represent a fundamental mechanism for optimizing transport, load distribution, and spatial organization.

1. Biological systems such as *lungs*, *circulatory networks*, *plant vessels,* and *root systems* use fractal logic to achieve maximum exchange surface area with a minimum amount of material.
2. Natural dendritic processes (e.g., the formation of river deltas or crystals) exhibit an efficient flow organization and branching that can be mathematically described by fractal principles.

In an engineering context, these models allow: [57]

1. design *of ultra-efficient lattice structures*,
2. development *of mesh façade and roof systems*,
3. optimization *of drainage and consolidation matrices* in geotechnics,
4. Analytical modeling of the redistribution of forces in minimal mass structures.

The most notable applications include the parametric design of load-bearing networks, the generative formation of structures according to mapped stress fields, as well as the additive factory realization of fractal-inspired elements.

2.1.3. Hexagonal, alveolar and cellular biostructures

Hexagonal and cellular geometries represent a universal principle of natural achievement of maximum rigidity with minimal material consumption. The most well-known examples include [59]:

1. *honeycomb bees (Apis mellifera)* – optimal hexagonal organization of cells for storage and load collection,
2. *trabecular bone* – a cellular network that locally adapts density according to strain,
3. *plant parenchymal tissues* – lightweight structures optimized for mechanical and fluid function,
4. *Coral and spongy skeletal forms* – biogenerated cellular composites with a high strength-porosity ratio.

These models have been used to develop [60]:

1. With the help of aluminum cores,
2. High Span Sandwich Panel,
3. two-layer façade systems,
4. biocomposite concrete with alveolar matrices,
5. Materials with improved thermal insulation and reduced weight.

Cellular logic has also shown significant potential in 3D printing of concrete and metal, where controlled porosity allows for mass optimization and improved thermomechanical functions [61].

2.1.4. Aerodynamic Forms and Biofluidic Optimization

Many organisms — fish, birds, insects, and marine mammals — have evolved in fluid environments that require optimal control of resistance, swirls, and stability. The body shape, surface texture, and stiffness distribution of these organisms are the result of multiple iterations of selection under turbulent and changing conditions.

For engineering, this made it possible to formulate a model for [63]:

1. design *of tall buildings in strong wind zones*,
2. development *of aerodynamic façade and roof profiles*,

3. optimization of *bridge bodies and girders with minimal resistance*,
4. Reduction of aeroelastic effects such as *flutter* and *galloping*.

Of particular importance are the so-called *"teardrop bodies"*, geometries with a minimum drag coefficient, used today in the design of bridge piers, canopies and special supports of high-performance structures [64].

2.2. Biomimetic transfer and systematization of the transfer of natural principles into engineering solutions

A biomimetic process is a methodological sequence of steps that enables the translation of natural phenomena — shaped by evolutionary, biomechanical, and biochemical processes — into usable engineering and architectural models. The key challenge of this approach is not only the identification of the relevant natural phenomenon, but its abstraction, mathematical formulation, and implementation into structural, material, and energy systems [65].

2.2.1. Stages of the biomimetic process

The methodological procedure of biomimetic transfer encompasses four interdependent phases: biological identification, theoretical abstraction, numerical modeling, and engineering implementation [66].

Biological identification **-** At this stage, analytical observation of the natural structure is performed, including its morphological structure, mechanical behavior, adaptive mechanisms, and multiscale organization. Reference models include trabecular bone tissue, streamlined fish forms, spider tensile webs, coral skeletons, and hexagonal honeycomb structures.

Abstraction is the stage in which principles that have engineering validity are extracted from a natural system: mass optimization, stress distribution according to the force field, gradient organization of materials, fractal branching logic, or geometry of minimal surfaces.

Mathematical and numerical modeling **-** Bio-principles are then formalized through various numerical models:

1. *FEM models*, especially in the analysis of stress transfer in trabecular bone and shells;
2. *CFD models*, in the analysis of the aerodynamic forms of birds, fish, marine mammals, and fluid flows around high-altitude objects;
3. *topological optimization*, which simulates the evolutionary processes of bone growth, distributing the material in proportion to local stresses;
4. *generative and stochastic algorithms*, which simulate the natural processes of branching, growth and adaptive morphogenesis.

This phase involves moving from a digital model to a real-world structural system, using advanced materials, parametric design, additive manufacturing, and system integration. Biomimetic patterns have been implemented in shell roofs, membrane structures, adaptive facades, mesh trusses, and energy-integrated cladding.

2.2.2. Bio-inspired materials

The development of bio-inspired materials today occupies a key place in construction and architectural science. These materials are not simple copies of natural substances, but rather engineered synthesized structures based on principles that occur in bones, plant tissues, insect chitinous shells, or protein fibers [67].

Composites with a gradient of stiffness and porosity **-** A martial analogue of trabecular bone tissue. The gradient allows for efficient stress dissipation and high load capacity with low weight.

Superhydrophobic Lotus Leaf-Inspired Nano-Coatings **-** Micro and nano-structural duality of the surface allows for extreme hydrophobicity and self-cleaning. This principle is applied in façade cladding and protective coatings.

Spider silk is one of the most resistant natural materials, with a specific tensile strength greater than steel. This structure is the basis for the development of high-resistance polymer fibers.

Lignin and cellulose-inspired biopolymers **-** Modified cellulose structures are used to develop flexible, lightweight and biodegradable composites.

Reactive and stimulus-responsive materials **-** Inspired by the hygroscopic movements of plants, these materials change shape or rigidity when exposed to moisture, heat, or light.

Each material is described through fundamental mechanical parameters (E, G, ν, σu, σy) and areas of application.

2.3. Application of biomimetic principles in contemporary architecture and construction

2.3.1. Structural systems

Biomimetic models increasingly determine the development of new constructions [68]:

1. *The tension structures*, based on interacting tension and compression components, are directly inspired by the tension webs of spiders.
2. *Arched, shell and dome systems* take optimization principles from sea urchin shells, corals and skeletons.
3. *Pneumatic and membrane structures* are based on the logic of minimum surface areas and uniform stress distribution, observed in biological membranes.
4. *Fractal lattices* replicate the dendritic branching logics of trees to achieve minimum mass and maximum range.
5. *Variable cross-section columns*, taken from the biomechanics of trees and bamboo, enable an optimized distribution of materials according to the stress field.

2.3.2. Energy Systems

Natural systems of energy distribution, storage and exchange have served as the basis for the development of high-efficiency building technologies [69]:

1. *Ventilation systems inspired by termite hills*, which maintain a stable microclimate through convection flows.
2. *Cold wraps inspired by the skin of an elephant*, whose multi-scale wrinkles and surface topology reduce thermal radiation.
3. *Solar systems inspired by heliotropism*, which follow the sun's path to maximize energy.
4. *Acoustic structures inspired by snail houses*, which optimize the absorption and propagation of sound.

2.4. Geometric systems

Biomimetic design also influences the development of new geometric paradigms [70]:

1. *Parametric design* allows the simulation of natural forms and their structural features.
2. *Generative algorithms*, imitate the processes of growth, fractal distribution and morphogenesis.
3. *Fractal architecture* uses multi-level geometries to create systems of exceptional spatial efficiency and visual complexity.

The biomimetic approach brings clear structural, energy and functional advantages: reduced weight of structures, increased energy efficiency, reduced operating costs, better aerodynamic and seismic response, and increased durability and adaptive resistance.

However, there are also significant limitations:

1. Lack of standardized design procedures and standards.
2. The complexity of multiscalar modeling of biological materials.
3. the need for interdisciplinary teams (architecture-biology-engineering),

4. The high cost of digital fabrication and biocomposite materials at an early stage of application.

The discussion shows that biomimetic design is in a phase of intensive development and that it represents one of the most promising directions of future engineering progress.

3. CONTEMPORARY BUILDINGS INSPIRED BY STRUCTURES IN NATURE

Contemporary architecture is marked by a growing tendency to view nature not only as an aesthetic benchmark, but as *a structural, energetic and biological model*. Numerous buildings around the world demonstrate how natural principles are successfully transformed into spectacular, technologically advanced buildings. The most important global examples that represent the highest reach of biomimetic architecture are systematized below.

3.1. Sea sponge *Euplectella aspergillum* → 30 St Mary Axe, The Gherkin (London)

*(**Architect:** Norman Foster, 2004)*

The biogenic skeleton of the deep-sea sponge *Euplectella aspergillum* (Venus' Flower Basket) represents one of the most sophisticated natural examples of hierarchical structural organization (Figure 1, right). Its architecture is based on a multilayered diagonal network of silicate spicules, arranged in regular rhomboid and hexagonal cells. This *diagrid structure* provides exceptional resistance to combined loads, high torsional stability, and minimal material consumption, making it one of the most widely studied natural models of structural efficiency [71-73].

The architectural-structural design of **30 St Mary Axe** (The Gherkin) directly builds on these bio-principles. The structure of the object is based on a steel-glass diagrid that geometrically reproduces the logic of stress distribution and sheath stabilization inherent in the *skeleton of Euplectelle* (Figure 1, left). The aerodynamic tapered profile reduces the intensity of vortex and lateral wind loads, while the diagonal mesh geometry allows for a significant reduction in torsional moments compared to conventional orthogonal frames [74-75].

Figure 1: *Sea sponge Euplectella aspergillum → The Gherkin (London)*

Biomimetic transfer in Gherkin includes the following key principles:

1. *structural hierarchy* and distribution of stiffness analogous to a multilayer network of sponges,
2. *diagonal grille*, which provides uniform voltage distribution and increased torsional resistance,
3. *aerodynamic form* that reduces vortex-shedding,
4. *increased energy efficiency* – hybrid ventilation system, inspired by passive fluid flow around the sponge skeleton, reduces the need for mechanical ventilation by up to 40%,
5. *constructive weight optimization* – application of a minimum amount of material while achieving maximum load capacity.

Due to the striking similarity of geometric and mechanical principles, the case *of Euplectella aspergillum* – Gherkin represents one of the most cited examples of biomimetic engineering analogy in the modern scientific literature, including studies from MIT, Harvard and the Max Planck Institute [71, 72, 75].

3.2. Beijing National Stadium (Bird's Nest), Peking – Inspired by birds' nests

*(**Architect**: Herzog and de Meuron, 2008)*

The biomimetic analogy between **the Beijing National Stadium** ("Bird's Nest") and *the natural bird's nest* is based on the transfer of the principle *of an irregular* but *mechanically optimized lattice network* (Figure 2). The stadium structure is built of a massive steel diagrid whose elements are arranged seemingly "chaotically", but in reality represent a topologically optimized system designed for combined gravitational, wind and seismic loads [77, 79].

Figure 2: *Bird's Nest – Beijing National Stadium „Bird's Nest" An example of biomimetic inspiration in contemporary architecture.*

The natural nest, composed of bent twigs of different lengths and stiffnesses, achieves stability through *local compaction at the places of greatest stress*, thus forming a multi-layered structure with a favorable mass-strength ratio [78]. The same principle was applied in the stage: *local reinforcement zones* were formed by increasing the density of steel elements at critical points, resulting in a monolithic spatial shell with high resistance to seismic excitations characteristic of the Beijing region [80].
Diagonal and interlocking steel profiles take on *horizontal and vertical forces*, while the global stadium geometry provides a *balanced ratio of rigidity and flexibility* – a feature inherent in biological lattice structures [76]. Although visually irregular, the mesh is the result *of FEM analysis and topological optimization*, ensuring a minimum amount of material with maximum structural efficiency.
This example clearly demonstrates that *natural irregular structures* are not the result of chance, but of an evolutionary optimum. It is this *principle of optimized irregularity* that is the essence of biomimetic transfer in the construction of Bird's Nest Stadium.

3.3. Sydney Opera House - seashells

*(**Architect**: Jørn Utzon, 1956)*

The left side of Figure 3 shows **the Sydney Opera House**, whose thin-walled concrete shells are formed from a series of spherical segments that morphologically and mechanically correspond to natural shells. The natural shells of mollusks, shown on the right side of Figure 3, possess radial ribs, double curvature, and lamellar microstructure, resulting in an optimal membrane stress distribution and a high load-to-weight ratio [82]. This biological principle is transferred to the construction of the wash through curved shells that minimize bending and allow for efficient load transfer in the plane of the surface [83].

Figure 3: *Sydney Opera House - seashells*

The layered structure of the shell, based on calcium carbonate-rich microlamellae, is analogous to the ceramic tiles that line the surface of the Opera House, creating a pearlescent reflection and optical homogeneity that is typical of biogenic mineral systems [84]. The modular organization of the shell – the repetition of segments around a central geometric axis – was reflected in Utzon's system of identical spherical slices, which allowed for standardization, structural rationalization, and the retention of a clear maritime character of the object [85]. The Sydney Opera House is one of the most accurate examples of biomorphic architecture, in which the natural logic of thin-walled protective structures is directly transposed into a large-scale engineering system [86].

3.4. Milwaukee Art Museum – Inspired by the wings of birds

*(**Architect:** Santiago Calatrava, 2001)*

On the left side of Figure 4 is the **Quadracci Pavilion** (Milwaukee Art Museum), one of Santiago Calatrava's most famous works, whose distinctive morphology is based on the dynamic interpretation of wings in flight. The movable brise-soleil, composed of over 70 lamellar elements, opens and closes depending on light and climatic conditions, producing the visual and structural effect of a "mechanical organism" that responds to external stimuli, which the authors rank among the pioneering applications of kinetic biomimetics in architecture [87, 91].

On the right, a great white heron is shown in the flight phase — with clearly defined primary and secondary feathers, radial curvature and aerodynamic profile. The morphological correspondence between the arrangement of the lamellae on the museum and the arrangement of the feathers on the wing of the bird indicates an extremely precise application of the principles of morphogenetic and biomechanical inspiration in the building structure [88].

Figure 4: *Milwaukee Art Museum – Inspired by the wings of birds*

The construction of the pavilion functions as an analogous aeroform: lamellar "wings" are arranged in a series of elements that behave like artificial feathers, and their curvature optimizes airflow, reduces local eddies, and allows for more favorable aerodynamic conditions — a principle that is well known in zoological aeromechanics [90, 91]. The wing movement mechanism is the technological equivalent of avian kinesiology: the cable system functions as biomechanical "tendons", while the massive central pillar takes on the role of the bird's sternum, ensuring stability and efficient voltage distribution under varying wind loads.

This pavilion can thus be interpreted as an extremely successful translation of *natural flight into an architectural and engineering system*, where the principle of adaptivity — crucial for the aerodynamics of birds — is transformed into a mechanical-kinetic façade with a real function of regulating light, heat and ventilation [89]. The form of the building thus remains a "frozen moment of flight", but fully functional, operational and structured through an engineering-rational biomimetic approach.

3.5. The Eden Project, Kornvol – Inspired by alveoli and honeycomb

*(**Architect**: Nicholas Grimshaw, 2001)*

On the left side of Figure 5 is the **Eden Project** in Cornwall, a complex of modular biospheres whose architectural logic is based on the geometry of geodesic spheres and alveolar panels made of ETFE membranes. The domes are formed by a three-dimensional steel lattice filled with hexagonal and pentagonal cells, creating a lightweight but mechanically extremely stable shell. The slightly reflective surface and spherical morphology allow for harmonious integration into the landscape, making the complex a paradigmatic example of biomimetic and ecological architecture [92].

On the right side of the image is a macro-representation of a honeycomb, the stability of which is based on hexagonal morphology – the most efficient geometry to achieve maximum volume with minimal material consumption [93]. The honeycomb functions as a thin-walled, repetitive structure that evenly distributes stresses and allows for a high load capacity despite its low weight; it is this geometric logic that underlies the domes of the Eden Project.

Figure 5: *The Eden Project, Kornvol – Inspired by alveoli and honeycomb*

In biomimetic terms, the architectural structure of the complex represents a direct interpretation of the natural optimization present in the honeycomb: hexagonal modules reduce the use of materials, increase the load-bearing capacity and form a high-energy efficiency shell. ETFE panels, weighing only 1% of the weight of glass, provide high thermal stability, diffused lighting and minimal energy consumption for air conditioning [94]. The panels act as "inserted membranes" within a rigid steel mesh, reproducing the relationship between wax and geometry in a natural honeycomb.

The structural analogy is reflected in the interaction of local membranes and the global carrier: while the steel lattice achieves primary spatial stability, ETFE cells function as secondary, adaptive elements that contribute to energy and structural efficiency – a principle identical to the way bees build honeycombs with minimal wax, relying primarily on topology [95, 96]. Thanks to the extremely low mass of the modules, the Eden Project domes achieve a range of up to 100 m, which was previously not possible with traditional materials.

The Eden Project thus becomes one of the clearest examples of the application of natural geometric intelligence in architecture: its morphology directly reflects the evolutionarily optimized honeycomb system, whereby the principles of minimum mass, maximum rigidity and energy efficiency are transferred to a modern engineering context.

3.6. The Lotus Temple, Nju Delhi – Inspired by the Lotus Flower

*(**Architect**: Fariborz Sahba, 1986)*

The left composition of Figure 6 shows **the Lotus Temple** in New Delhi, a monumental sacral edifice whose architectural articulation is based on the interpretation of the lotus flower as a geometric, symbolic and morphological source of form. The building is formed of 27 bent-flat, marble and concrete elements arranged in three concentric rings, which creates the impression of a spatial "opening" of the building towards the zenith. The visual purity of surfaces, emphasized radial symmetry and controlled curve transitions generate an extremely harmonious composition that is often cited in the literature as a paradigm of contemporary biomimetic sacral architecture [100, 101]. The reflective pools around the temple amplify the visual effect of floating, evoking the natural ambience in which the lotus grows.

The right-hand composition of Figure 6 shows a fully open lotus flower (Nelumbo nucifera), whose geometry is characterized by radially distributed petals, clearly defined central symmetry, and smooth three-dimensional transitions. The lotus is biologically specific for its highly hydrophobic epidermal structure — the so-called "lotus effect" — which allows for self-cleaning surface behavior and minimal particle retention [98]. This natural mechanism makes the lotus one of the most studied models in biomimetic design.

Figure 6: *The Lotus Temple, Nju Delhi – Inspired by the Lotus Flower*

The Lotus Temple represents an extremely consistent transposition of natural morphology into an architectural construct. The three concentric rings of "petals" almost directly reflect the organization of the flower, with each architectural "petal" functioning as a self-contained curved plate that optimizes stress distribution, contributes to spatial rigidity, and improves the seismic resistance of the building [102]. In this sense, the morphology of the flower is not only used as a visual motif but as a structural logic.

The material concept also carries a clear biomimetic analogy: white marble possesses the ability to reflect and disperse sunlight in a way that visually resembles the diffuse optical characteristics of a lotus petal. Experimental studies indicate that polished marble surfaces exhibit reduced dust and water retention, thus creating the partial equivalent of the lotus effect in an architectural context [99].

In a broader theoretical framework, the Lotus Temple can be understood as one of the most consistent examples of the application of biomimetic principles to the formative logic of an architectural object. It simultaneously replicates natural geometry (radial symmetry), material logic (hydrophobic effects and light reflection), functional configuration (opening space to the outside), and the symbolic semantics of the lotus — a universal sign of purity, unity, and spiritual elevation in numerous cultures [97]. In this way, architecture, construction and natural-biological morphology merge into an integrated system, which places Lotus Temple among the key reference examples of biomimetic architecture on a global scale.

3.7. Metropol Parasol, Sevilja – Inspired by the Mushroom Network *(fungal mycelium)*

*(**Architect**: Jürgen Mayer, 2011)*

The image on the left of Figure 7 includes the **Metropol Parasol structure** in Seville, known as the largest contemporary wooden urban canopy in the world, whose geometry derives from the complex interpolation of crossed slats that generate a three-dimensional, continuous lattice surface. The visual metaphor of this system – "Las Setas" – is not arbitrary, but directly refers to biological prototypes in the form of mushrooms, where massive "stems" turn into broadly curved canopy panels, creating the effect of organically developed crowns. The woody superstructure formed in this way shares characteristics with natural porous matrices, especially those occurring in fungal mycelial networks, which is recognized in the literature as one of the most efficient natural models of load distribution and adaptive growth [106, 109]. The right side of Figure 7 shows the micromorphology of the mycelium — networks of hyphae that achieve complex fractal organization. Hyphae branch into multiple hierarchical levels, allowing the system to be simultaneously lightweight, porous, and extremely resistant to spatial and mechanical perturbations. Micellial networks apply the principle of force distribution over a series of flexible connections, which is a paradigmatic example of natural optimization of structural efficiency, and which, according to modern research, is one of the key bioinspiration models for the development of highly adaptive structures [102].

Figure 7: *Metropol Parasol, Sevilja – Inspired by the Mushroom Network (fungal mycelium)*

The biological model — the mycelium — thus becomes the generator of the design logic of the Metropol Parasol. Congruences can be classified through five fundamental domains.

The first is geometric patterns. The mycelium exhibits fractal branching patterns and dense lattice organization, while the Metropol Parasol forms a three-dimensional matrix of crossed lamellae whose continuous flow functions as a macroscopic analogy of microscopic hyphal hierarchies. Such geometric correspondence confirms that the architectural concept arises from the logic of the distribution of materials by natural matrices [108].

The second is structural logic. The mycelium transmits loads over a network of interconnected strands, rather than through massive centralized supports. Metropol Parasol uses a similar principle — the laminated truss redistributes loads, allowing for minimal use of materials with maximum load-bearing capacity. Such a "distributed" load-bearing system, by analogy with biological networks, increases the robustness of the structure to load changes and external influences [103].

The third domain relates to morphology. The mycelium system and the above-ground fruiting part of the fungus — the stem and cap — realize the geometry of a vertical-horizontal organization, where the vertical element serves as a support, while the horizontal surface expands to protect the space below. Metropol Parasol constructs the same logic: the massive "stems" at the base turn into wide, curved canopies that create a continuous urban shelter.

The fourth is a material analogy. Mycelium is known for its ratio of low mass and high resistance. Metropol Parasol uses laminated timber (LVL), a material that possesses an extremely high strength-to-weight ratio, as well as the ability to achieve mechanical properties analogous to biological networks in a cross-sipe system [105].

The fifth domain is functional transposition. In natural mushroom systems, the cap regulates the microclimate underneath, provides shade, retains moisture, and moderates temperature extremes. The Metropol Parasol performs the same function in an urban context — it reduces the temperature of the space under the structure, creates an urban microclimate zone, and functions as the macro-equivalent of a biological "climate shield" [104].

Such a multi-layered correspondence between natural and architectural structure confirms that the Metropol Parasol represents one of the purest examples of bioinspired architecture of the 21st century, where natural models are used not only as a symbolic reference, but as integrated constructive, geometric and functional principles, in accordance with contemporary theories of biomimetic design.

3.8. ArtScience Museum, Singapur – Inspired by flowers and bio-lamellar structures *(**Architect**: Moshe Safdie, 2011)*

The ArtScience Museum in Singapore (Moshe Safdie, 2011) is one of the most developed examples of architectural biomimetics in the field of geometric and structural transposition of natural lamellar systems. The architectural composition is based on the motif of the lotus flower, whose geometric and functional characteristics have been widely documented in biomimetic literature (e.g., self-cleaning effect, radial symmetry, hydrophobic geometry) (Figure 8). The object is dominated by a system of ten large, ribbed "petals" that form a radial spatial structure, organized around a central core. This concept corresponds to the bio-lamellar morphologies present in flower petals and leaves, where lamellar panels conduct loads towards the stabilization zone at the root of the structure [112].

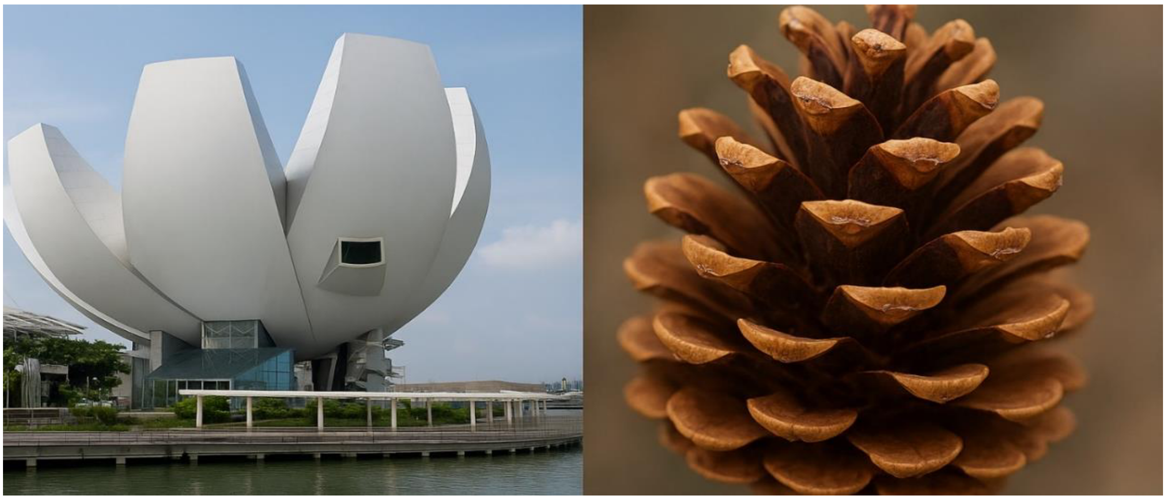

Figure 8: *ArtScience Museum, Singapur – Inspired by flowers and bio-lamellar structures*

The flowers, especially the lotus (Nelumbo nucifera), are characterized by clearly defined radial symmetry, curved lamellar elements, and integrated water guidance systems to the central part of the flower. Such structures have a high degree of geometric optimization and adaptation to environmental loads, making them a suitable model for architectural interpretations. Safdie's architecture takes these principles directly and transforms them into a complex spatial shell.

Each of the ten architectural petals is shaped as a separate lamellar volume, constructed using ribbed, curved panels. These solutions reflect the way in which biological lamellae transmit voltages [113]:

1. *The distribution of the load* takes place through curved surfaces towards the central nucleus, similar to biology where forces from the petal are transmitted to its base;
2. *continuous curvature* allows for increased rigidity with a minimum amount of material;
3. *Lamellar rib systems* mimic the living tissue structure of petals that possess an internal network of fibers for stability.

This approach fits into contemporary models of biomimetic optimization of structures, where biological patterns are used as algorithmic starting points for form-finding [112].

The object uses biomimetic principles not only in form, but also in function — a key criterion in contemporary SCI works on biomimetics.

The petals function as curved shells that transfer gravitational and external loads to a central concrete pillar. This logic is analogous to the way in which biological lamellae transfer mechanical stresses to their root [110].

Perforations are integrated in each "petal" that direct diffused daylight, imitating the filtration of light through flower structures. This reduces the need for artificial lighting and creates a dynamic light microclimate inside the museum.

The geometry of the arched petals allows rainwater to be gravitationally guided to a central point, from where the water is stored and filtered. This system is an architectural analogy of natural hydrophobic surfaces and capillary dynamics of flower petals [111].

The ArtScience Museum is a paradigmatic example of biomorphic architecture, where natural patterns are used not only as an aesthetic motif, but as a transdisciplinary generator of form, construction and sustainable performance. In combination with parameterized modeling, the object achieves a sophisticated synthesis of natural logic and modern technological infrastructure, thus becoming incorporated into the current course of SCI research on biomimetic architecture.

3.9. Heydar Aliyev Center (Baku, Azerbaijan) and biological membrane/cell structure

*(**Architect**: Zaha Haid, 2013)*

The architectural form shown on the left side of Figure 9 — **the Heydar Aliyev Center** in Baku — is a paradigmatic example of the application of biomorphic, continuous geometry based on the digital reinterpretation of biological membrane systems. The building, designed by Zaha Hadid, is based on a unique spatial logic in which the roof and façade cladding merge into a single continuous surface membrane with no clear boundary between functional elements. Such geometric continuity, which is aesthetically manifested through fluid transitions, smooth curvatures and the absence of right edges, is directly related to the principles of morphological optimization recognized in natural membrane tissues [115, 118, 122].

A microscopic representation of the biological membrane (right side of Figure 9) reveals a highly organized but nonlinear systematics: elliptical porous structures, variable lamella thicknesses, continuous pleated zones, and a topology adapted to the efficient distribution of mechanical stresses. These adaptive principles — controlled curvature, tension flow distribution, and multi-layered organization — are key patterns that contemporary architecture increasingly transposes into constructive systems of a high degree of performativity [117, 119, 123].

Figure 9: *Heydar Aliyev Center (Baku, Azerbaijan) and biological membrane/cell structure*

Biological membranes function as continuous sheaths whose curvature is not the result of formal aesthetics but rather optimization for stress distribution and minimization of strain energy. At the Heydar Aliyev Center, this principle is taken up through parametric models that allow the formation of a smooth three-dimensional "epidermis" of an object. The elimination of sharp transitions and the application of large continuous surfaces allow for the redistribution of loads through geometry — analogous to the way diaphragms carry stresses through tension flows [120].

In natural membranes, surface dynamics form ridges, depressions, and folded zones that occur in response to mechanical loads or pressure changes. A similar topological logic is recognizable in the architectural form of the center: the folds on the mantle act as "enlarged biological folds", while the overall form suggests a stretchy, elastic continuous material, like epithelial structures that change shape under the action of forces [118, 124].

Biological membranes carry loads through evenly distributed tension, relying on shape instead of material mass. The construction of the Heydar Aliyev Center realizes a similar principle: the supporting function is taken over by a system of curved shell surfaces that redirect forces through a network of voltage lines. In this way, the building functions as the architectural equivalent of a thin-walled biological membrane optimized by evolutionary processes [115, 121].

The macrostructural panels on the façade are organized in such a way as to reproduce the visual porosity and inhomogeneous texture typical of membrane microstructures. The interaction of light with curved surfaces produces effects reminiscent of the optical behavior of biological tissues — the surface appears to "breathe" depending on the intensity of the illumination. This object functions as an architectural interpretation of a living organism, where the building envelope becomes analogous to the skin that unifies and defines the interior and exterior space [122, 125].

The Heydar Aliyev Center can therefore be defined not only as an aestheticized imitation of nature, but as a performative system that operationalizes the principles of biological organization — continuity, elasticity, adaptive geometry, and the membrane logic of voltage distribution. This makes the building one of the most significant examples of the 21st century in which architecture demonstrates the ability to reconstruct natural processes and formal-structural principles in a high-tech, materially advanced context.

3.10. Al Bahr Towers, Abu Dhabi - pine cone *(**Architect**: Abdulmajid Karanouh, 2009)*

Figure 10 shows two complementary morphological patterns that demonstrate how contemporary architecture uses bioinspired principles to redefine the energetic, geometric and adaptive characteristics of façade systems. The visual parallel between the façade of the **Al Bahr Towers** system and the structural organization of the pine cone clearly confirms that modern engineering approaches increasingly rely on morphogenetic models from nature rather than just formal aesthetic analogy, a tendency widely affirmed by contemporary literature [128, 133].

On the left side, two cylindrical towers about 145 m high are shown, the entire envelope of which is enveloped by a dynamic system of geometric panels based on a modular diamond-rhombic matrix. These units, arranged according to an algorithmically generated pattern, open and close in real time depending on the intensity of solar radiation, thus achieving highly efficient solar gain regulation. Adaptive panel mechanics are based on mechatronic actuators that allow for modulation of transparency and shading, analogous to the way in which plant hygromorphic systems passively alter the geometry of tissues due to fluctuations in humidity [131, 134]. Visually and structurally, this behavior represents an architectural translation of an evolutionarily optimized natural mechanism.

The right side of the image shows a pine cone, the structure of which is one of the most famous natural examples of geometric organization in Fibonacci spiral sequences. The arrangement of the scales, formed through a diagonal and helical grid, is optimized for a combination of strength, minimal mass, and the ability to open and close adaptively as a result of hygromorphic changes in plant fibers [129]. These spiral patterns, supported by fundamental mathematical rules, simultaneously regulate mechanical stresses and stiffness distribution, making them particularly relevant for transfer to architectural façade systems.

Figure 10: *Al Bahr Towers - pine cone*

Bioinspired correlation between the Al Bahr Towers façade system (left) and the spiral-diagonal structure of the pine cone (right). Architectural mesh geometry and adaptive panels reinterpret Fibonacci-based arrangements and hygromorphic mechanisms of natural cones, demonstrating the application of biomimetics in energy optimization and structural logic of façade systems (Figure 10).

Compared to the pine cone, the façade of the Al Bahr Towers reinterprets the same logic of the spiral-diagonal grid, creating a porous-non-porous envelope whose permeability to solar radiation changes through the movement of more than 2,000 adaptive panels. This approach allows for a reduction in solar gain of up to 50%, which directly affects the reduction of energy consumption for air conditioning, confirming that biomimetic geometry can also have a high energy effect [126, 127].

The structural correlation between natural and architectural systems is manifested in their shared network topology, where the helical-diagonal distribution of elements allows for an optimal combination of rigidity, elasticity, and adaptability. In nature, this geometry allows the cone to control the opening of the shells depending on humidity, while in architecture it provides stability to the façade structure under changing wind loads and dynamic solar conditions. Thus, the Al Bahr Towers represent one of the most relevant examples of architectural biomimetics in high-performance façade systems of the 21st century, in which the natural model is not only an aesthetic but primarily a functional, structural, and energetic prototype [130, 132].

CONCLUSION

Nature is the most complex system optimized through millions of years of evolution and therefore an inexhaustible source of inspiration for contemporary architecture and construction. The analysis of natural structures, principles of formation and behavior under load enables the development of advanced structures, efficient materials and sustainable energy systems. The integration of biomimetic principles into engineering practice represents the future of design and construction — a future that combines science, technology, and biological wisdom.
An analysis of ten representative examples of biomimetic architecture clearly shows that natural structures are not just aesthetic inspiration, but extremely sophisticated models of structural efficiency, resilience, intelligence, and optimization. Each natural system analyzed — from microscopic fibers to macroscopic biological organisms — possesses clearly recognizable optimization principles: hierarchical organization, topological rationality, minimal material consumption, optimal voltage distribution, adaptive functions, and integrated sensor networks.
Architectural and building structures inspired by nature demonstrate significant advantages:

1. reduced material consumption
2. Greater energy efficiency
3. Greater resistance to wind, snow and seismic
4. Increased spans and free geometry
5. Possibility of adaptive and reactive facades
6. Integration of intelligent sensors modeled on biological systems

Biomimicry has already proven itself as a key direction of progress, and its role will only grow with the development of digital tools (FEM, CFD, topological optimization, robotic fiber winding, parametric design).
We conclude that the future of architecture and construction lies in:

1. integration of evolutionary principles into design,
2. the development of new biocomposites,
3. energy-intelligent façades,
4. minimum mass structures,
5. A digital factory based on nature.

The common denominator is the *optimization of mass, energy, form, and performance* according to a logic that nature has developed over millions of years.

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ENERGY MANAGEMENT AND ENVIRONMENTAL SUSTAINABILITY IN EARTHWORKS

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Scientific article
https://doi.org/10.58952/nit20251302024
UDC 502.131.1:624

Abstract
The modern construction sector faces the challenge of high energy consumption and emissions of harmful gases, with earthworks occupying a particularly important place due to the intensive use of heavy machinery. This paper analyzes strategies for increasing energy efficiency through process optimization, proper machine management and the application of new technologies. Special emphasis is placed on hybrid and electric machines, telematics systems and software solutions that enable real-time monitoring and planning of work. Experimental studies have shown that changing operating parameters, such as engine speed and depth of engagement, can lead to significant fuel savings, reduced emissions and increased productivity. The results confirm that energy management in earthworks does not only contribute to cost reduction, but is a key step towards sustainable construction and reduction of negative environmental impact.

Keywords: *earthworks, energy efficiency, sustainable construction, emissions of harmful gases, construction machinery.*

JEL classification: **Q01, Q40**

1. INTRODUCTION

Energy efficiency in the construction sector is one of the key issues in modern engineering today. The reasons for this lie in increasingly stringent environmental requirements, rising energy prices and global efforts to reduce the negative impact on the environment. Construction consumes between 30 and 40% of total energy globally, and a significant part is accounted for by earthworks, which are among the most energy-intensive segments of construction due to the intensive use of heavy machinery. A particular challenge is the fact that these works are an unavoidable initial phase of most infrastructure and construction projects, and that the ways in which they are carried out largely determine the subsequent energy efficiency of the entire project.

Earthworks include various procedures such as excavation, filling, leveling, compaction, drainage and slope stabilization. Their implementation requires the use of powerful machines with diesel engines, whose fuel consumption directly affects the cost of construction, but also the emission of CO2 and other harmful gases. On a global level, the burning of fossil fuels in the construction industry is one of the main sources of CO_2 emissions, which further emphasizes the importance of energy responsible management in this sector.

Energy management in earthworks implies an integrated approach on several levels: planning and organization of the workplace, proper selection and optimal use of machines, as well as technical improvements of the equipment itself. A particularly important role is played by modern technologies, such as telematics systems for monitoring consumption in real time,

software solutions for optimizing planning, and hybrid and electric machines that significantly reduce the consumption of fossil fuels and emissions. In addition to technical solutions, equally important factors are operator training and proper equipment maintenance, which can contribute to fuel savings of up to 20%.

In this paper, the focus is placed on the analysis of energy aspects of earthworks and the possibilities of their optimization. Special emphasis is placed on examining the relationship between the operating parameters of machines and their productivity, fuel consumption and emissions. Experimental research conducted in real conditions of a construction site aims to confirm the importance of proper energy management and show that even small changes in the performance of work tasks can lead to measurable savings and productivity improvements.

Based on these facts, the aim of this paper is to show the possibilities of improving energy efficiency in earthworks through the optimization of organization and application of modern technologies, with the ultimate goal of reducing costs, increasing productivity and minimizing the negative impact on the environment.

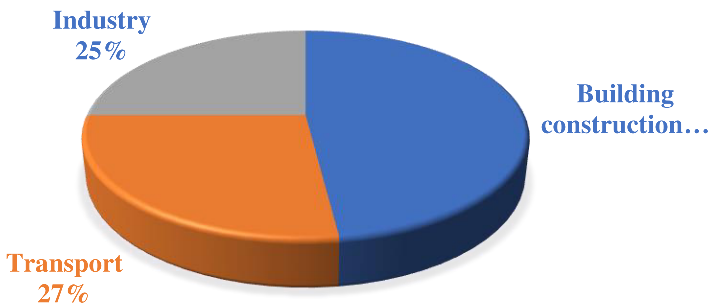
2. ENERGY EFFICIENCY AND ENVIRONMENTAL ASPECTS OF ENERGY SOURCES IN CONSTRUCTION

The increase in the consumption of non-renewable energy sources and the increase in environmental pollution condition the need for more rational use of energy in all industries. Construction, accounting for 30–40% of total energy consumption and about 12% of global water use, has a particular responsibility in the energy transition process [1].

The concept of green building encompasses all phases of the life cycle of a building, from site selection, design, construction and use, to maintenance and removal. The basic principles of green building include the efficient use of resources, the protection of the health of users, the increase in employee productivity and the reduction of harmful gas emissions.

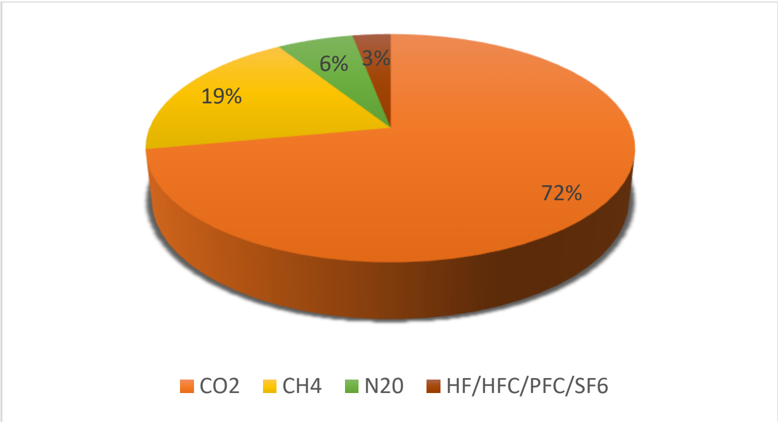
According to the Intergovernmental Panel on Climate Change (IPCC), the construction industry is the largest emitter of greenhouse gases, with the potential to emit 15.6 billion tonnes of CO_2 by 2030, which is about 30% of global emissions. However, by using existing technologies and renewable sources, it is possible to reduce emissions and achieve energy savings of up to one third. However, researchers warn of the so-called rebound effect (Khazzoom-Brookes postulate), where increasing energy efficiency can lead to an increase in overall consumption if energy prices remain stable [3].

The Republic of Serbia still has an unfavorable energy structure, predominantly based on non-renewable resources [5]. The needs of the construction industry include oil and derivatives for machinery, electricity for equipment and lighting, and natural gas for the production of building materials. Domestic reserves cover a small part of the needs, so dependence on imports remains pronounced [6]. This situation points to the necessity of strategic planning and implementation of energy efficiency measures in accordance with national and European decarbonization goals [6].



Picture 1: Percentage of global carbon dioxide production

Burning fossil fuels produces about 98% of the total amount of carbon dioxide, which is the most significant greenhouse gas. Its concentration in the atmosphere has been steadily increasing and has exceeded 396 ppm, further fueling global warming. In 2013, CO_2 concentrations were as much as 40% higher than in the mid-19th century, with an average increase of 2 ppmV/year in the last decade. This trend is accompanied by an increase in the concentration of other greenhouse gases: methane (CH_4), nitrogen oxide (N_2O) and hydrofluorocarbons ($HF/HFC/PFC/SF_6$). After the Industrial Revolution, CO_2 emissions rose to 32 Gt in 2012.



Picture 2: Percentage of greenhouse gases [7]

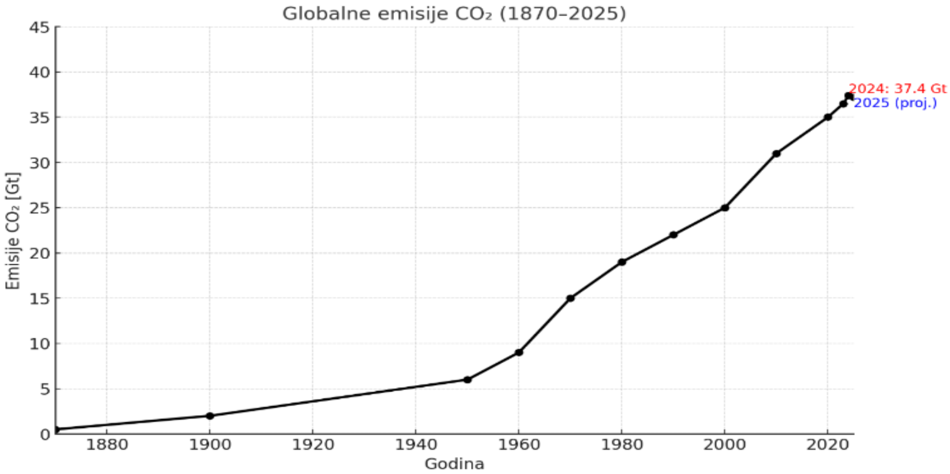


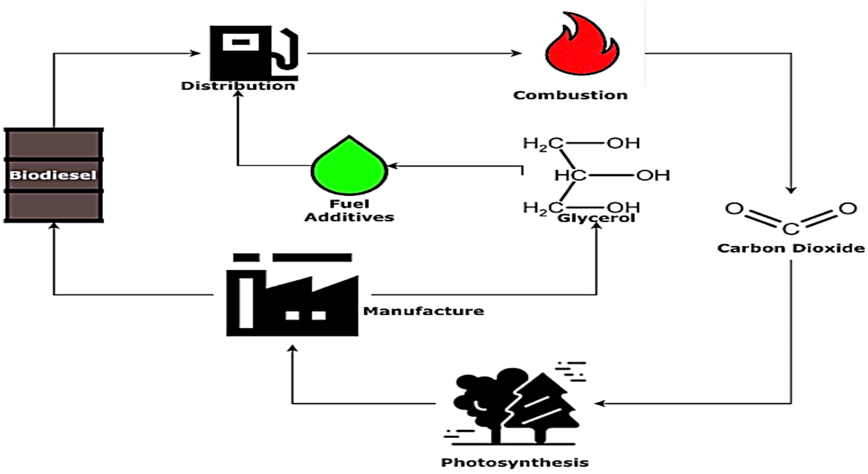
Diagram 1: Increasing CO2 emissions from the combustion of fossil fuels

Table 1: Coefficient of carbon dioxide emissions of different fuels [8]

Fuel	***Show kgCO2/GJ***
Coal (all kinds)	95,99
Lignite	98,27
Heavy fuel	75,09
Diesel	74,14
Kerosene	73,19
Gas	76,11
Natural gas	52,91
Unusable oil	74,00

These data confirm that switching from coal to gas or biofuels can significantly reduce emissions. A particularly important alternative energy source is biodiesel**,** obtained by transforming biomass into liquid fuels. Its application makes it possible to reduce dependence on oil and its derivatives, while emissions of sulfur compounds remain minimal. Although its cost is higher than fossil diesel, using waste edible oil as a feedstock is more economically viable. The life cycle of biodiesel includes the cultivation of raw materials, their pre-treatment, biochemical transformation and end use in internal combustion engines, thus confirming it as a renewable and practically applicable energy source.

In addition to biodiesel, the construction sector is increasingly using natural gas as a transition fuel, while the use of electrical machinery and renewable energy (solar and wind farms, geothermal energy) is expected in the future. The use of these energy sources has the potential to significantly contribute to reducing emissions and costs in the life cycle of buildings.



Picture 3: Life cycle of biodiesel production and use [9]

The life cycle of biodiesel includes the cultivation of raw materials, their pre-treatment, biochemical transformation and end-use in internal combustion engines. This confirms that biodiesel is a renewable, environmentally friendly and practically applicable energy source.

The construction industry makes extensive use of non-renewable energy sources, predominantly oil, its derivatives and natural gas. Their combustion emits a variety of harmful gases. When biofuels are burned, carbon dioxide emissions are generally neutral, as plants absorb an amount of CO2 approximately equal to that released during combustion. Also, sulfur emissions are minimal, which significantly reduces the risk of acid rain. Depending on the chemical composition of the fuel, there are different levels of CO2 emissions. The mass of CO2 emitted per unit of energy released is the CO2 emission coefficient:

$$KCO_2 = 3{,}67\,\frac{g_c}{H}$$

where: 3.67→ stoichiometric coefficient,
GC → the mass fraction of the fuel carbon in the fuel.
H→ the heat output of the fuel [MJ/kg].

Diagram 2: Evolution of the oil price per barrel (159 l) from 2002 to 2022

Reducing air pollution when using non-renewable energy sources can be implemented through a number of environmental protection measures:

- **catalytic processes** – combustion of unburned fuel residues until complete decomposition,
- **absorption** – removal of harmful gases using solutions or solid absorbents,

- **adsorption** – the binding of gases to solid materials such as activated carbon or silica gel,
- **increasing green areas** – one hectare of forest annually binds about 15t of CO_2 and releases approximately 14.2t of oxygen [7].

The construction industry makes extensive use of non-renewable energy sources, predominantly oil, its derivatives and natural gas. Their combustion emits significant amounts of CO_2, with earthmoving machinery being one of the largest sources of fuel consumption and emissions.

Therefore, switching to biodiesel, natural gas or the use of hybrid and electric machines can have a direct impact on

reducing pollution and costs in this area. That is why the analysis of energy and environmental aspects of energy sources in construction is of particular importance for the optimization of earthworks.

3. EARTHWORKS OPTIMIZATION

The energy impact of earthworks depends on several parameters: the type of soil, the type and number of machines, the mode of operation, as well as the organization of the construction site. Heavy and more powerful machines have more powerful engines that consume significantly more fuel, but allow for more work in less time. On the other hand, lighter machines consume less fuel but are less efficient with large amounts of material. An increase in the number of machines does not necessarily mean greater efficiency, as each heavy machine consumes an average of 10 to 40 liters of diesel per hour of operation, depending on the load and operating regime [12].

Energy management in the process of earthworks can be achieved on three levels:

- Optimization of the construction site – proper planning and arrangement of machines, reduction of unnecessary movement and waiting.
- Optimization of machine use – selection of the appropriate type of machine for a specific task and organization of work that reduces idling and overloads.
- Optimization of the machine itself – technical adjustments and innovations that reduce losses and increase energy efficiency.

Regular maintenance and coordination of work contribute to a reduction in the number of operating hours of machinery and fuel consumption, while the type of soil (hard or loose) significantly affects productivity and energy consumption [12].

Table 2: Potential fuel savings for loaders

Optimization	Potential savings
Optimization of the construction site	up to 30%
Optimization of the use of the machine	-40% to +40%
Optimization of the machine itself: - Reduction of losses - Optimization of mutual cooperation - Separation of the system	up to 50%

Table 2 shows that optimizing the interoperability of the system brings the greatest potential for savings (up to 50%).

The development of construction machinery has enabled the application of new technologies that contribute to the reduction of energy consumption and emissions:

- Telematics systems monitor the parameters of machine operation in real time (speed, fuel consumption, idle time, location), which makes it possible to optimize operation and reduce fuel consumption by 10–15% [7].
- Software solutions (BIM and project management systems) are used to simulate and plan work processes,

thus increasing the efficiency of construction site organization.

- Hybrid and electric machines are becoming more and more common. Hybrids combine a diesel engine with an electric drive and provide fuel savings of up to 30% without compromising productivity. Electric machines do not emit CO_2 and are suitable for working in urban areas and enclosed spaces.

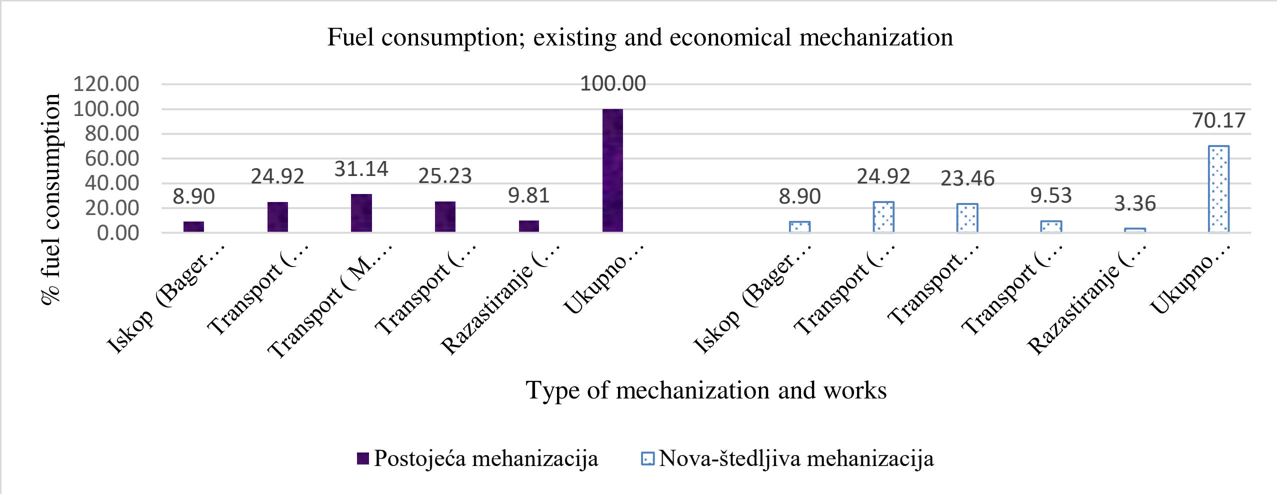


Diagram 3: Display of fuel consumption with existing and new-economical earthmoving machines according to the USACE standard

In addition to technical innovation, the human factor plays a crucial role in energy efficiency.
Regular maintenance of machines (filters, lubrication, replacement of worn parts) can reduce fuel consumption by 10–20%.
Operator training is one of the most cost-effective ways to increase efficiency, since the correct use of the operating mode and the avoidance of idling significantly affects consumption. The differences between operators on the same tasks and the same machine can be as high as 40% [10].
Advanced operator support systems, including the development of autonomous driving, further increase efficiency and reduce emissions.
Fuel Efficiency (FE) is defined as the relationship between productivity and fuel consumption.

$$FE\ [t/L] = \frac{\text{productivity}\ [t/h]}{FC\ [L/h]}$$

where:
FC – fuel consumption (L).
We can convert fuel consumption in liters to kg.

$$m_{fuel}\ (kg) = FC \cdot \rho$$

where is:
ρ- Fuel density (kg/l; typically ~0,832 kg/l for diesel).
Fuel efficiency can be increased either by increasing productivity at the same consumption, or by reducing consumption while maintaining productivity.
Experiments with hydraulic excavators have shown that combinations of different engine speeds and cutting depths can increase productivity by up to 30%, reduce greenhouse gas emissions by 24%, and move 62% more material per week for every liter of fuel consumed.

$$CO_{2emission} = E_{CO_2} * \left(3600 * n_{th} * \frac{E_{con}}{P} * LHV\right)$$

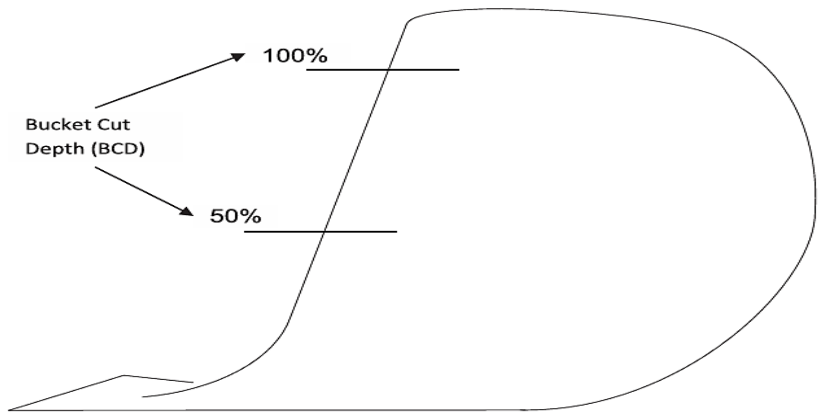
E_{CO_2}- CO2 emission factor for diesel combustion (kg CO_2/kg fuel), (approx. 3.16 kg CO_2 / kg diesel or ~2.64 kg CO_2 / l diesel).

NTH - Thermal Efficiency of the Machine
Econ – energy consumed during a given operation (kWh)

P – density of diesel fuel (kg/m3)
LHV (Lower heating value of diesel fuel) – lower heat value of diesel fuel (kJ/kg)
Operator training, which improves the choice of engine speed and bucket gripping depth, is a cost-effective way to reduce fuel consumption and emissions, while extending the life of the machines.
The CO2 emissions formula can be simplified and calculated solely on the basis of fuel consumption:

$$CO_2\left(\frac{kg}{h}\right) \approx 2{,}63 * FC\ \left(\frac{l}{h}\right) * t(h)$$

- Cycle time is a key indicator of productivity.
- The Bucket Cut Depth – BCD parameter introduces a more accurate measurement of the impact of the depth of the grip.



Picture 4: Side view of the construction bucket [14]

BCD is expressed as a percentage (BCD50 = 50% of the procedure, BCD100 = complete penetration). Operating at the BCD50 allows for greater productivity stability and 25% lower fuel consumption than the BCD100 [14].

Filling the bucket increases productivity by up to 80% [14]. Spinelli et al. (2009) show that productivity increases to the optimal piece size and then decreases due to machine overload.

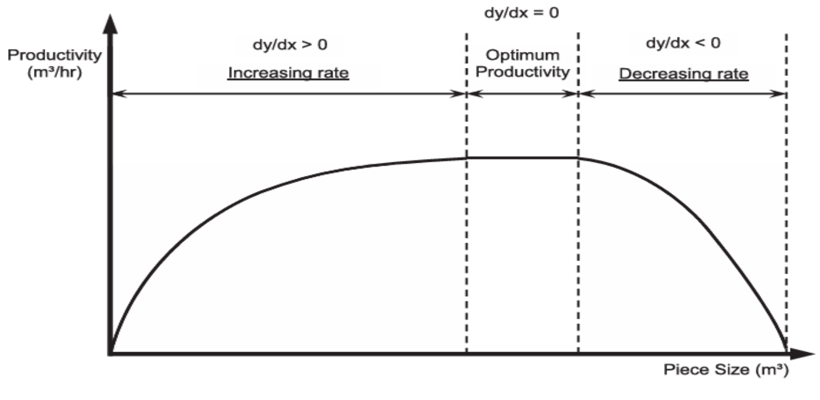


Diagram 4: The Law of Piece Size [14]

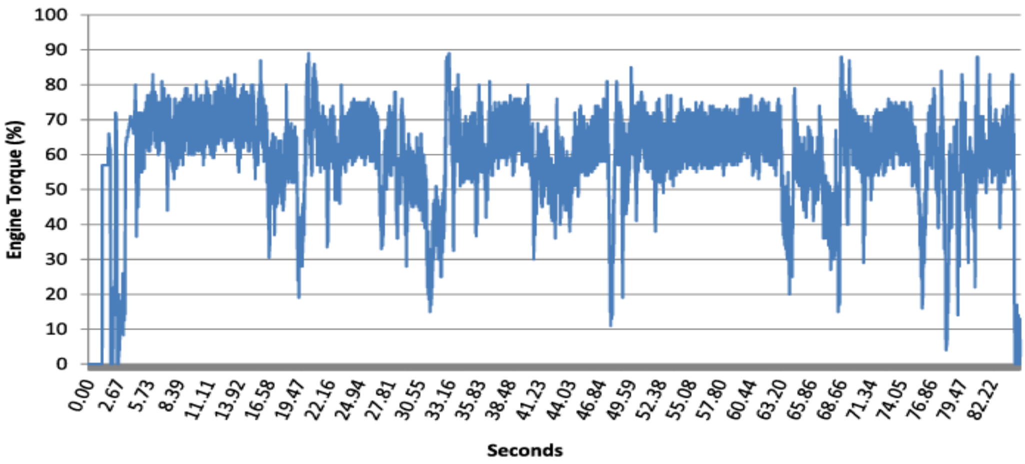


Diagram 5: Torque behavior when digging trenches [14]

Overloading the engine shortens service life and increases emissions.

Optimization of earthworks includes technical innovation, proper organization and the human factor. The greatest potential for savings lies in:

- reduction of idling,
- Use telematics and software solutions.
- The introduction of hybrid and electric machines.
- Continuous training of the operator.

Experiments confirm that relatively small changes in parameters (rpm, depth of stroke) lead to significant fuel savings and increased productivity. This makes earthworks optimization a key element of sustainable construction and reducing the environmental footprint of construction.

By analyzing the different depths of the bucket, it was found that the BCD50 provides greater productivity stability and lower fuel consumption than the BCD100. In particular, at 1600 RPM, up to 23.5% lower fuel consumption per kilogram of material moved was achieved, with the ability to move 30% more material and achieve about 25% fuel savings compared to the BCD100 [14].

Similar research shows that the correct positioning of excavators and trucks, as well as optimal digging technique, significantly reduce emissions and costs. Volvo Construction Equipment Division states that proper machine management can reduce fuel consumption by 5–25%, while Komatsu points out that a 25% reduction in engine power delivers 23% fuel savings with a smaller drop in productivity.

4. EXPERIMENTAL RESEARCH

The aim of the study was to quantify the impact of different operating parameters of earthmoving machinery on fuel consumption and CO_2 emissions. The focus is on hydraulic excavators, as they are one of the most widely used machines in the construction industry.

- Machine: hydraulic excavator (typical engine power 120–150 kW, bucket volume 1 m^3).
- Operating parameters: bucket grip depth (BCD50 and BCD100), engine speed (1600 and 2000 RPM).
- Data: taken from [14], adjusted for own calculations.
- Calculation of CO_2 emissions: the formula used:

  $$CO_2\left(\frac{kg}{h}\right) \approx 2{,}63 * FC\left(\frac{l}{h}\right) * t(h)$$

  where:

  FC - fuel consumption.
- Scenarios are formed for combinations:
  - BCD50, 1600 RPM
  - BCD50, 2000 RPM
  - BCD100, 1600 RPM
  - BCD100, 2000 RPM

Table 3: Fuel consumption and CO_2 emissions depending on operating parameters

Script	Fuel consumption (l/h)	CO_2 emissions (kg/h)	Productivity (t/h)	Fuel Efficiency (t/L)
BCD50 – 1600 RPM	18,5	48,6	520	28,1
BCD50 – 2000 RPM	23,0	60,5	600	26,1
BCD100 – 1600 RPM	24,0	63,1	570	23,8
BCD100 – 2000 RPM	29,0	76,3	640	22,0

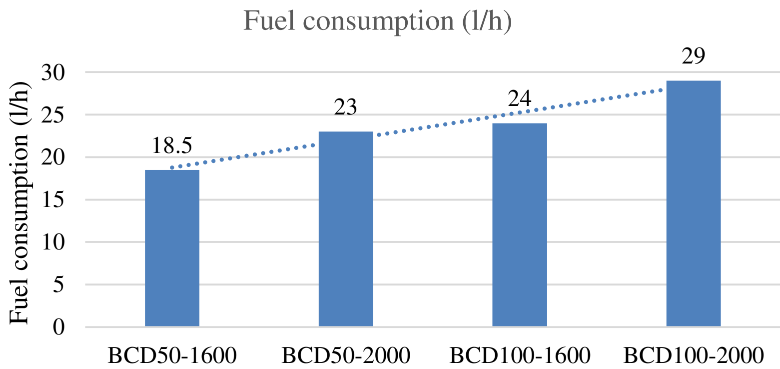


Diagram 6: Display of the dependence of fuel consumption on the depth of engagement and engine speed

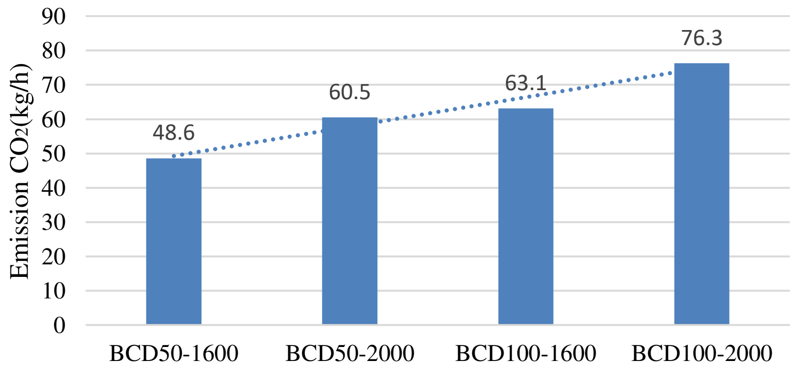


Diagram 7: Display of the dependence of CO2 emissions on the depth of engagement and engine speed

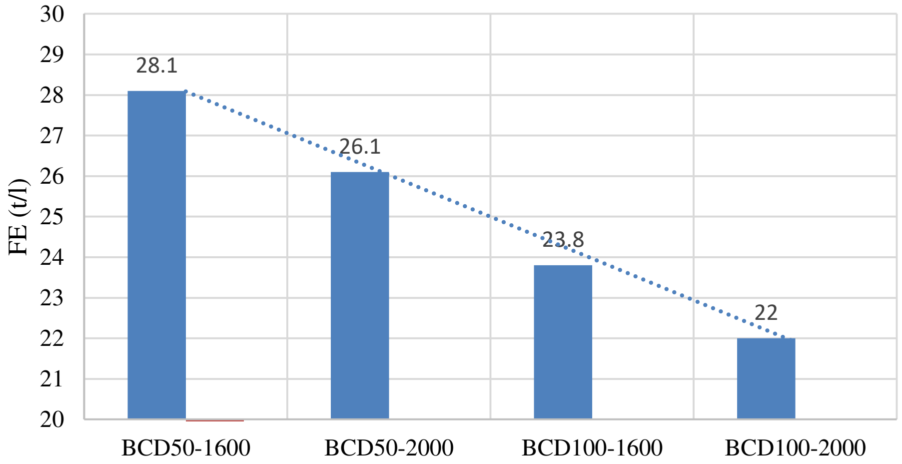


Diagram 8: Display of the dependence of emissions, fuel efficiency (FE) on the depth of engagement and engine speed

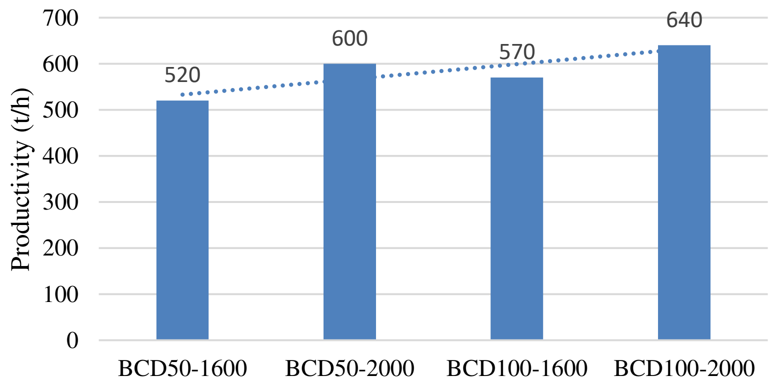


Diagram 9: Display of productivity from depth of engagement and engine speed

- The lowest fuel consumption and CO_2 emissions are obtained at BCD50 – 1600 RPM.
- The highest productivity was achieved at BCD100 – 2000 RPM, but with significantly higher fuel consumption.
- The optimal compromise is achieved at BCD50 – 2000 RPM, where productivity is increased (600 t/h), with a moderate increase in emissions.
- The results are in line with data from Volvo CE and Komatsu, which state that a reduction in revs can result in up to 25% fuel savings, but also slightly lower productivity [14].

Fuel efficiency can be increased by optimizing the operating parameters (BCD, revs).
Switching from a maximum grip (BCD100) to a semi-grip (BCD50) brings savings of 20–25% with a relatively small drop in productivity.
Operator training and the application of telematics are key to choosing the optimal operating mode.

CONCLUSION

Earthworks represent one of the most energy-intensive segments of construction, but at the same time they offer great potential for improving energy efficiency and reducing the negative impact on the environment. Their complexity stems from the use of heavy machinery with powerful engines, which consume large amounts of fuel and emit significant amounts of harmful gases. That is why the application of modern energy management methods and technologies is essential for the development of sustainable construction.
By analyzing all factors – from the type and number of machines, work organization, planning of operations and soil type, to the human factor – it has been shown that a high degree of energy efficiency can be achieved. Experimental studies have confirmed that even the smallest changes in operating parameters, such as engine speed or bucket grip depth, can bring fuel savings of 20–25% with an increase in productivity. Further advances are being achieved through the application of telematics systems, scheduling software solutions, hybrid and electric machines, as well as continuous operator training.
Energy efficiency in earthworks should not only be seen as an economic benefit, but also as a social obligation in the context of global efforts to achieve climate neutrality. Energy management at this level is not only a way to reduce costs, but also a way to a more responsible attitude towards natural resources and the environment. Sustainable construction starts from the first phase, i.e. earthworks, so knowledge, planning and the use of innovative technologies are key elements in the transformation of the construction industry into an energy-efficient and environmentally friendly system. Contractors are encouraged to standardize operator training, introduce telematics systems, and plan to switch to hybrid machines in larger projects.

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URBAN TRANSFORMATIONS AND REVITALIZATION STRATEGIES: INNOVATIVE APPROACHES FOR SUSTAINABLE CITY DEVELOPMENT IN EUROPE AND CROATIA

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Scientific article
https://doi.org/10.58952/nit20251302037
***UDC* 711.4(4+497.5):502.131.1**

Abstract

Urban transformations and revitalization processes have become essential components of sustainable development strategies in contemporary cities. This paper explores the theoretical and practical dimensions of urban transformation, emphasizing the balance between economic development, environmental sustainability, and social inclusion. Through an interdisciplinary framework, the research examines the evolution of European urban policies, particularly the shift from industrial urbanism toward post-industrial, knowledge-based development models. Special attention is given to revitalization as a strategic approach for reusing degraded or obsolete urban spaces and transforming them into vibrant, multifunctional environments.

Drawing on examples from major European cities—including Hamburg, Barcelona, Ljubljana, Copenhagen, and Vienna—the paper identifies key factors for successful sustainable regeneration. The case study of Split, Croatia, with emphasis on the areas of Kopilica and Dračevac, is used to evaluate the applicability of European urban transformation models in a local context. The analysis is guided by the zero hypothesis that:

"The application of integrated European revitalization models has no significant impact on sustainable development outcomes in Split's urban zones of Kopilica and Dračevac."

Based on comparative analysis, planning documentation, qualitative spatial assessment, and policy review, the hypothesis is rejected. The study concludes with recommendations for developing resilient and inclusive urban environments in Croatia and outlines directions for future research.

Keywords*: urban transformation, revitalization, sustainable development, Split, European models, regeneration*

JEL classification: R11, Q01

1. INTRODUCTION

Urban areas across the world are undergoing profound transformation driven by globalization, technological innovation, demographic shifts, and climate-related pressures (1). Cities have evolved from industrial production centers into complex socioeconomic ecosystems that must simultaneously ensure competitiveness, sustainability, and social well-being (2). Modern urban planning increasingly emphasizes adaptability, digitalization, public participation, and human-centered design.
Yet, in Croatia—particularly in Split—urban development remains constrained by governance fragmentation, insufficient infrastructural investment, and the overwhelming influence of tourism-driven growth (7, 8). These challenges hinder the development of comprehensive, integrated frameworks for urban transformation.

1.1 Problem Statement
Given these constraints, this study examines:To what extent can integrated European urban transformation models be applied to the redevelopment of Split, particularly in the urban zones of Kopilica and Dračevac?
The literature shows that European cities have adopted increasingly sophisticated regeneration frameworks that combine sustainability, innovation, participation, heritage protection, and economic diversification (4, 5, 12, 17). The question remains whether such models can be effectively adapted to a Mediterranean, mid-sized, tourism-dependent city such as Split.

1.2 Zero Hypothesis

In line with scientific methodology and reviewer recommendations, the following zero hypothesis is introduced:
H_0: Integrated European revitalization models have no significant applicability or impact on sustainable redevelopment in the urban zones of Kopilica and Dračevac in Split.
The goal of the study is to examine, test, and ultimately reject this hypothesis through comparative evidence, planning documentation, and qualitative assessment.
1.3 Importance of the Study
Split's historical structure, constrained geography, obsolete industrial zones, and rising pressure from mass tourism make it an exemplary case for exploring the transformative potential of integrated revitalization approaches. By analyzing European best practices and comparing them with Split's strategic planning context, this study provides a scientifically grounded foundation for the development of a long-term urban regeneration model.

2. THEORETICAL BACKGROUND: CONCEPTS OF URBAN TRANSFORMATION AND REVITALIZATION

Urban transformation represents a set of multidimensional processes that reshape the physical, functional, economic, and social characteristics of contemporary cities (9). These processes are driven by global economic restructuring, technological innovation, cultural shifts, climate change adaptation pressures, and evolving governance models (10). Scholars emphasize that today's urbanization far exceeds traditional city boundaries and increasingly reflects regional and planetary scales of development (11).
In European planning discourse, urban transformation is commonly examined through paradigms such as the smart city, sustainable city, and resilient city. These paradigms highlight the need to embed digital infrastructure, environmental responsibility, inclusive decision-making,

and long-term urban adaptability into policy frameworks (12, 13).

2.1 Defining Urban Transformation

Urban transformation involves the reconfiguration of spatial patterns and social relations within cities to meet changing human, economic, and environmental needs (14). Harvey (15) further argues that urban transformation is inseparable from economic and political dynamics that continually reshape urban form, producing both inequalities and opportunities for innovation.
The contemporary shift toward systemic and integrated urbanism aligns with the European Green Deal and the New European Bauhaus (4, 17), both of which promote a holistic understanding of cities as interconnected socio-ecological systems.

2.2 The Role of Revitalization

Within the broader framework of urban transformation, revitalization plays a critical role in regenerating obsolete, degraded, or underused urban areas. It includes several interconnected dimensions:

- Physical revitalization: upgrading infrastructure, buildings, and public spaces; adaptive reuse of existing structures (18)
- Economic revitalization: stimulating new business activity, supporting innovation, and diversifying the economy (19)
- Social revitalization: promoting equity, inclusion, and improved quality of life for local communities (20)
- Environmental revitalization: enhancing green networks, climate resilience, and ecological sustainability (23)

  Revitalization is most effective when based on collaborative governance models and meaningful citizen participation (20).

2.3 The Creative and Green City Paradigm

Post-industrial cities increasingly adopt creative and green development trajectories. Florida (21) argues that thriving cities rely on creativity, technology, and talent, while Gehl (22) emphasizes the importance of human-scale design and socially vibrant public spaces.
Green city models advance climate adaptation, renewable energy, circular economy strategies, and low-carbon mobility systems (23). Cities such as Freiburg, Copenhagen, and Ljubljana exemplify how environmental sustainability can be embedded within major urban transformations (24).

2.4 Methodology (expanded and revised)

This study applies a qualitative, multi-method research design to examine how European urban transformation models can inform the redevelopment of Split—specifically the zones of Kopilica and Dračevac.

2.4.1 Analysis of Planning and Policy Documents

The research examined core strategic frameworks of the City of Split, including:

- Spatial Plan of Split (PPU) (62)
- General Urban Plan (GUP) (63)
- Development Strategy 2020–2030 (64)
- Split Smart City Strategy (65)
- Kopilica Intermodal Hub Study (66)
- Dračevac Innovation District Masterplan (67)

These documents served as the empirical foundation for understanding existing conditions, constraints, future development vectors, and policy intentions.

2.4.2 Comparative Analysis with European Cases

The European cities selected—Hamburg, Barcelona, Ljubljana, Copenhagen, and Vienna—were analyzed using explicit criteria:

- Governance structures
- Stakeholder participation
- Environmental and climate adaptation frameworks
- Heritage and cultural policy
- Economic diversification
- Brownfield and waterfront redevelopment models.

The comparative approach clarifies how these cities inform Split's transformation potential.

2.4.3 Spatial Assessment (Qualitative GIS-Based Review)

Orthophoto maps, cadastral layers, and land-use patterns were reviewed to assess:

- Existing built form
- Connectivity and mobility systems
- Availability of redevelopment parcels
- Environmental vulnerabilities
- Opportunities for greening and public space upgrades.

While not a quantitative GIS analysis, this step provided spatial diagnostics necessary for identifying realistic redevelopment options.

2.4.4 SWOT Analysis

Separate SWOT analyses for Kopilica and Dračevac helped structure:

- Strengths (strategic position, land availability)
- Weaknesses (infrastructure gaps, fragmentation)
- Opportunities (innovation, EU funds, transit integration)
- Threats (tourism pressure, climate risks)

2.4.5 Theoretical Triangulation

Key frameworks—sustainable urbanism, creative city theory, and resilience planning—were synthesized to create the conceptual foundation for the Integrated Urban Regeneration Model developed later in the paper.

3. EUROPEAN URBAN TRANSFORMATIONS: MODELS AND COMPARATIVE RELEVANCE

European cities provide a rich landscape for analyzing how large-scale urban transformations can be implemented through integrated planning that combines sustainability, innovation, heritage preservation, and citizen participation. The five selected cases—Hamburg, Barcelona, Ljubljana, Copenhagen, and Vienna—were chosen because they reflect urban challenges and opportunities directly relevant to Split, particularly in relation to brownfield redevelopment, waterfront transformation, sustainable mobility, cultural identity, and governance capacity (25).

The following sections offer an expanded comparative analysis, illustrating the structural parallels that justify the transferability of European models to the Croatian context.

3.1 Hamburg – HafenCity and Adaptive Waterfront Redevelopment

Hamburg's HafenCity represents one of Europe's largest, most comprehensive brownfield redevelopment projects, transforming former port and industrial land into a mixed-use district integrating residential areas, commercial zones, cultural institutions, and redesigned waterfront spaces (26). The project covers approximately 157 hectares and stands as a model of climate-resilient design, with elevated building platforms, improved flood protection strategies, and innovative architectural solutions (27).

Central to HafenCity's success is its governance structure—HafenCity Hamburg GmbH, a dedicated public company responsible for strategic coordination, implementation, and stakeholder engagement (28). This single-agency model ensures continuity, transparency, and long-term planning efficiency.

Relevance to Split

Both Split and Hamburg face challenges of underused or obsolete waterfront and industrial areas situated near the historical core. Kopilica in Split shares functional similarities with Hamburg's pre-redevelopment port zone. HafenCity's governance model is highly applicable to Split, where fragmented institutional structures hinder coordinated development. The establishment of a unified regeneration body could accelerate the transformation of Kopilica and the Eastern Waterfront in Split.

3.2 Barcelona – From Industrial Decline to Creative and Inclusive Transformation

Barcelona's urban transformation, initiated in the 1980s, illustrates how cultural infrastructure, public space redesign, and human-centered planning can revitalize formerly degraded neighborhoods. The renewal of El Raval, once considered one of the most marginalized districts, demonstrates the power of integrating cultural investment (such as the Barcelona Museum of Contemporary Art), social housing, and public space improvements (29).

While Barcelona's regeneration successfully enhanced urban quality and attractiveness, studies note rising risks of gentrification and social displacement (30). The city has since embraced new urban strategies—such as the Urban Innovation Plan 2019–2025—that emphasize digital equity, sustainability, and participatory governance (31).

Relevance to Split

Split's historic core faces pressures similar to those experienced in Barcelona, including over-tourism, loss of residential function, and commercialization. Barcelona's experience highlights the importance of balancing cultural-led regeneration with social protection measures. Furthermore, Barcelona's creative industries model offers a valuable framework for planning the Dračevac Innovation District.

3.3 Ljubljana – Sustainable Urban Infrastructure and Human-Centered Mobility

Ljubljana's transformation has been widely recognized as a leading example of sustainable urban mobility and pedestrian-focused planning (32). The closure of the city center to private vehicles, introduction of cycling routes, greening of public spaces, and revitalization of the riverfront have contributed to Ljubljana being named the European Green Capital.

Ljubljana's approach demonstrates how environmental improvements can simultaneously enhance urban identity, reduce emissions, and improve quality of life (33).

Relevance to Split

Many of Ljubljana's interventions—including pedestrianization, riverfront redesign, and ecological corridors—are directly transferable to Split's Eastern Waterfront. Split's mobility challenges, exacerbated by seasonal tourism, make Ljubljana's model particularly relevant for structuring sustainable transport solutions in Kopilica.

3.4 Copenhagen – Climate Adaptation and Blue–Green Infrastructure

Copenhagen aims to become the world's first carbon-neutral capital by 2025. Its Climate Adaptation Plan (34) integrates water-sensitive design, rainwater management, coastal defense, and expansive networks of cycling and public transport infrastructure. The city employs multifunctional blue–green public spaces that provide stormwater retention, cooling, recreation, and biodiversity benefits (35).

Public participation is embedded within Copenhagen's planning process, with digital platforms facilitating transparent, citizen-led decision-making (36).

Relevance to Split

Split's coastal location makes it vulnerable to heatwaves, flooding, and sea-level rise. Copenhagen's adaptation-led urbanism provides essential guidance for designing climate-resilient redevelopment strategies, particularly for Kopilica and Dračevac, which require integrated mobility and environmental solutions.

3.5 Vienna – Inclusive Housing, Governance Stability, and Smart Development

Vienna is often cited as one of the world's most livable cities, largely due to its strong institutional capacity, long-term governance stability, and robust social housing system (37). Over 60% of residents live in subsidized housing, ensuring social stability and affordability (38). Vienna's Smart City Strategy integrates sustainability targets, digitalization, energy efficiency, and participatory governance frameworks (39).
Relevance to Split
Split faces rising housing costs and increasing displacement of residents due to tourism-driven market pressures. Vienna's example shows how coordinated policy frameworks and social housing models can preserve affordability while pursuing urban transformation. These insights support Split's need for a regulated, socially inclusive approach to redevelopment.

3.6 Comparative Lessons for Split

A cross-case comparison reveals several recurring principles that underpin European success in urban transformation:

1. Unified and long-term governance
2. Adaptive reuse of industrial and waterfront areas
3. Sustainable mobility and climate adaptation
4. Cultural identity as a driver of regeneration
5. Strong citizen participation and co-creation
6. Economic diversification grounded in innovation ecosystems

Direct Link to Split

European City	Key Feature	Comparable Challenge in Split	Application to Kopilica & Dračevac
Hamburg	Unified governance & brownfield redevelopment	Fragmented institutions	Kopilica redevelopment & Eastern Waterfront
Barcelona	Cultural-led regeneration; gentrification risk	Over-tourism in Split's old town	Heritage-sensitive planning for Dračevac
Ljubljana	Sustainable mobility & public space	Overloaded transport system	Kopilica multimodal hub
Copenhagen	Climate adaptation & blue–green systems	Coastal vulnerability	Integrated climate-resilient design
Vienna	Social housing & inclusive governance	Rising housing costs	Socially inclusive redevelopment models

The analysis demonstrates that European models are not only relevant, but structurally aligned with Split's urban context—forming the basis for rejecting the zero hypothesis.

4. CASE STUDY: URBAN TRANSFORMATION AND REVITALIZATION IN SPLIT

Split, the second largest city in Croatia, represents a complex Mediterranean urban

system shaped by its Roman heritage, constrained coastal morphology, limited land availability, and an economy heavily dependent on tourism. These characteristics amplify the need for integrated and adaptive urban transformation strategies. The city's redevelopment potential is particularly concentrated in two large underutilized zones: Kopilica and Dračevac. Both areas align conceptually and spatially with European regeneration models analyzed in earlier sections.

4.1 Rationale for Selecting Kopilica and Dračevac

The selection of these two locations is grounded in methodological criteria established in this study and supported by the City of Split's strategic documents (62–67):

4.1.1 Strategic Position in City Planning

Both sites are explicitly identified as priority redevelopment zones in:

- Development Strategy of Split 2020–2030 (64),
- Split Smart City Strategy (65),
- Kopilica Intermodal Hub Study (66),
- Dračevac Innovation District Masterplan (67).

4.1.2 Brownfield or Underutilized Character

- Kopilica: A fragmented transport–industrial zone with obsolete facilities, poorly integrated into the urban fabric.
- Dračevac: A former military area with significant land reserves suitable for conversion to innovation and technology activities.

4.1.3 High Potential for Integrated Regeneration

Both zones require interventions linking mobility, economy, environment, digital infrastructure, and public space design—matching European best practices.

4.1.4 Comparability to European Cases

Kopilica ↔ Hamburg (brownfield), Copenhagen (mobility), Ljubljana (space integration)

Dračevac ↔ Barcelona (cultural/creative renewal), Vienna (innovation, governance)

Thus, both sites provide an ideal testing ground for evaluating the zero hypothesis.

4.2 Existing Conditions and Challenges

4.2.1 Kopilica

Kopilica is currently characterized by:

- The central railway and intercity bus terminus
- Low-density industrial and storage buildings
- extensive paved surfaces and minimal greenery
- traffic congestion
- insufficient cycling and pedestrian infrastructure
- Weak spatial integration with Split's historic center

The Kopilica Intermodal Hub Study (66) identifies Kopilica as a future multimodal mobility core capable of connecting rail, bus, cycling, and ferry traffic. However, without coordinated planning, the area remains underused despite its exceptional location.

4.2.2 Dračevac

Dračevac contains:

- Obsolete military structures
- Large unused parcels of land
- Poor accessibility and few public services
- Limited economic activity

- Strong potential for redevelopment into innovation-oriented functions

The 2023 Innovation District Masterplan (67) envisions a research–technology district focusing on green energy, entrepreneurship, and higher education.

4.3 Transformation Potentials Identified Through Methodology

The combined methodological approach—including document analysis, comparative study, spatial assessment, and SWOT—highlights clear transformation potentials.

4.3.1 Kopilica: A Multimodal Transport and Innovation Hub

Drawing on models from Hamburg and Copenhagen, Kopilica can be developed as:

- A major multimodal hub, integrating railway, buses, cycling, micromobility, and pedestrian flows
- A gateway district, with redesigned public spaces, mixed-use development, cultural and commercial anchors
- An innovation corridor, linking the University of Split with Dračevac and the city center
- A sustainable mobility zone, incorporating renewable energy systems, intelligent transport management, and low-emission mobility

Spatial analysis (66) confirms that the area offers sufficient land availability, strategic location, and transport potential to support such transformation.

4.3.2 Dračevac: Innovation and Green Technology District

Inspired by Barcelona's creative regeneration and Vienna's innovation frameworks, Dračevac can evolve into:

- a regional innovation hub with start-up incubators, research facilities, and training centers;
- a green technology district, implementing renewable energy systems, circular economy principles, and climate-adaptive infrastructure;
- a cultural and creative cluster, using adaptive reuse of military heritage;
- a campus-like urban environment, integrating greenery, promenades, and collaborative workspaces.

This vision is consistent with the City of Split's medium-term development strategies (64, 65, 67).

4.4 Evaluation of the Zero Hypothesis

The zero hypothesis stated:

H_0: Integrated European revitalization models have no significant impact on sustainable redevelopment in Kopilica and Dračevac.

However, the case study demonstrates clear applicability:

- Hamburg shows how a unified agency can manage large-scale regeneration → applicable to Split's fragmented governance.
- Barcelona provides strategies for creative, socially balanced renewal → relevant for Dračevac.
- Ljubljana illustrates successful mobility and public space redesign → relevant for Kopilica and Eastern Waterfront.
- Copenhagen showcases climate-resilient planning → directly relevant to Split's coastal risks.
- Vienna demonstrates institutional stability and inclusive housing → critical for addressing Split's affordability pressures.

Conclusion:

The zero hypothesis is rejected.

European models significantly inform feasible redevelopment pathways for both zones.

4.5 Integration with Split's Strategic Plans

To ensure contextual relevance, the proposed regeneration strategies were aligned with:

- PPU – Spatial Plan (62): land-use, zoning, infrastructure guidelines

- GUP (63): development rules, density standards, mobility networks
- Development Strategy 2020–2030 (64): pillars of innovation, sustainability, quality of life
- Smart City Strategy (65): digital services, data-driven planning
- Kopilica Intermodal Hub Study (66): transport integration
- Dračevac Masterplan (67): innovation ecosystems

These documents confirm that the proposed regeneration model is feasible, coherent, and strategically aligned with the city's long-term objectives.

4.6 Summary of Case Study Findings

The analysis shows that:

1. Kopilica and Dračevac are strategic assets for Split's future development.
2. European models offer highly relevant frameworks for redevelopment.
3. Integrated planning is essential for managing tourism pressure, climate risks, and housing affordability.
4. Split's urban transformation requires coordinated governance, innovation, sustainability, and heritage protection.
5. The methodological evaluation provides a strong empirical basis for rejecting the zero hypothesis.

These findings form the foundation for the Integrated Urban Regeneration Model elaborated in the Discussion section.

5. DISCUSSION

The findings of this research highlight that Split's urban transformation challenges—in Kopilica and Dračevac—are structurally comparable to those encountered in many European cities at earlier stages in their development. The comparative analysis revealed significant alignment between Split's strategic goals and established European regeneration practices (48). This indicates that integrated, sustainable, and innovation-driven models can be effectively adapted to the local context.
However, the successful application of such models requires strong governance capacity, strategic coordination, and institutional continuity—areas where Croatian coastal cities, including Split, traditionally face difficulties due to administrative fragmentation, political instability, and inconsistent long-term planning (49).

To address these issues, this Discussion section synthesizes insights from the European case studies, the spatial and strategic analysis of Split, the methodological findings, and the implications for the zero hypothesis. It also outlines key recommendations for future transformation processes.

5.1 Governance and Institutional Capacity: A Precondition for Transformation

European examples, particularly Hamburg, Vienna, and Copenhagen, demonstrate that large-scale urban regeneration requires stable and unified governance structures (50). HafenCity Hamburg GmbH, for instance, integrates planning, financing, implementation, and public coordination within a single body, facilitating long-term development and protecting projects from political fluctuations (51).

In contrast, Split's current institutional landscape is fragmented, with multiple departments and agencies responsible for land-use planning, mobility, infrastructure, culture, heritage protection, and economic development. Such fragmentation slows decision-making and prevents integrated planning.

Key Recommendation:

Establish a Split Urban Regeneration Agency responsible for coordinating all major redevelopment processes (Kopilica, Dračevac, Eastern Waterfront). This agency would serve as a central governance platform ensuring long-term continuity.

5.2 Community Participation and Social Inclusion

Sustainable urban transformation in Europe is characterized by strong citizen

participation and community engagement (52). Barcelona's neighborhood governance mechanisms and Copenhagen's digital participation tools show how community involvement contributes to project acceptance, social cohesion, and equitable development (53).
In Split, participatory mechanisms remain relatively weak and often symbolic. Residents are generally informed rather than actively engaged in shaping redevelopment strategies.
Recommendations:

- Establish neighborhood participation councils for Kopilica and Dračevac.
- Use digital tools for public consultations (maps, surveys, simulations).
- Implement participatory budgeting for certain phases of redevelopment (54).

Meaningful participation fosters public trust and supports socially balanced transformation.

5.3 Economic Diversification and Innovation Ecosystems

Split suffers from substantial economic dependency on tourism, making the city vulnerable to market fluctuations, global crises, and high seasonality (55). For long-term resilience, the redevelopment of Kopilica and Dračevac must be designed to diversify the economy.

Kopilica can evolve into a transport, mobility, and innovation hub, providing:

- Offices for creative and digital industries
- Co-working spaces
- Research facilities
- Mobility innovation labs connected to the University of Split

Dračevac can develop into a regional innovation district, hosting:

- Renewable energy labs
- Green technology start-ups
- Educational institutions
- Incubation and acceleration programs (56, 57)

Examples from Vienna and Barcelona show how innovation-oriented environments stimulate long-term economic growth while reinforcing sustainable development.

5.4 Environmental Sustainability and Climate Adaptation

Mediterranean coastal cities face severe climate risks, including heatwaves, flash flooding, drought, and sea-level rise (58). Copenhagen's and Ljubljana's climate adaptation strategies illustrate the importance of integrating blue–green infrastructure, water-sensitive urban design, and sustainable mobility systems into transformation projects.

Recommendations for Split:

- Introduce blue–green corridors connecting Kopilica, Dračevac, and Eastern Waterfront.
- Implement permeable surfaces and advanced stormwater retention systems.
- Expand shaded pedestrian routes and bicycle infrastructure.
- Integrate renewable energy systems (solar, microgrids) into new developments.

Environmental adaptation is not optional—it is essential for long-term resilience.

5.5 Heritage and Identity as Drivers of Regeneration

Split's unique historical identity—shaped by Diocletian's Palace and its layered Mediterranean urban fabric—is one of its greatest assets. European examples such as Vienna's MuseumsQuartier and London's Tate Modern highlight how heritage can be leveraged as a catalyst for cultural and economic revitalization (59, 60).

Implications:

- Heritage must be embedded into the design logic of Kopilica and Dračevac.
- Public spaces should reflect local cultural narratives.

- Adaptive reuse of buildings (especially in Dračevac) can create authentic, place-based identity.

Heritage is not a constraint; it is a development resource.

5.6 Foundation for the Integrated Urban Regeneration Model

On the basis of the comparative analysis, spatial assessment, and strategic review, the study identifies the following foundational principles of a future Integrated Urban Regeneration Model for Split:

1. Unified governance and long-term institutional stability
2. Participatory and transparent planning processes
3. Climate adaptation and blue–green infrastructure
4. Transit-oriented development and sustainable mobility
5. Economic diversification through innovation ecosystems
6. Heritage-led public space design
7. Digital and data-driven planning frameworks
8. Alignment with existing Split strategic documents (62–67)

Relation to the Zero Hypothesis

These findings clearly demonstrate that European models are highly applicable to Split's urban context. Thus, the zero hypothesis is rejected. European revitalization frameworks significantly influence, guide, and enhance sustainable redevelopment opportunities in Kopilica and Dračevac.

5.7 Recommendations for Urban Policy and Practice

Based on the discussion, the following recommendations are proposed:

- Create a Split Urban Regeneration Agency.
- Integrate planning with PPU, GUP and Smart City Strategy
- Establish participatory platforms for citizens and stakeholders
- Redevelop Kopilica as a multimodal transit-oriented development hub
- Implement Dračevac as a green innovation and creative district
- Integrate climate adaptation in all phases of redevelopment
- Prioritize heritage-led design principles
- Develop measurable sustainability metrics to monitor progress

CONCLUSION

Urban transformation has become a defining challenge for contemporary cities facing pressures related to climate change, demographic shifts, economic restructuring, spatial constraints, and social inequality (61). For Mediterranean coastal cities such as Split, these pressures are amplified by tourism dependency, limited land availability, and fragmented governance structures. This study explored the relevance and applicability of integrated European urban revitalization models to the redevelopment of Split, with emphasis on the strategic areas of Kopilica and Dračevac. Using a comprehensive qualitative methodology—including comparative analysis, policy and planning document review, spatial assessment, and SWOT analysis—the paper tested the zero hypothesis:

H_0: Integrated European revitalization models have no significant impact on sustainable redevelopment opportunities in Split's key urban zones of Kopilica and Dračevac.

Based on the evidence, the zero hypothesis is clearly rejected.

Key Findings

1. European models are structurally relevant to Split.

Strategies from Hamburg, Barcelona, Ljubljana, Copenhagen, and Vienna align closely with the challenges of Kopilica and Dračevac, particularly regarding governance, mobility, innovation, sustainability, and heritage.

2. Split's existing planning documents support integrated regeneration.

The PPU, GUP, Development Strategy, Smart City Strategy, and masterplans for Kopilica and Dračevac (62–67) collectively provide a strong foundation for sustainable transformation.

3. Kopilica and Dračevac have significant redevelopment potential.
   Kopilica can become a multimodal mobility hub and innovation corridor; Dračevac can evolve into a regional innovation and green technology district.
4. Integrated urban regeneration is essential.
   Fragmented or sectoral planning approaches cannot address the scale of challenges facing Split. A unified model is required.
5. Governance is the critical success factor.
   A dedicated urban regeneration agency would significantly improve coordination, reduce political fragmentation, and enable long-term implementation.

Contribution of the Study

This research contributes:

- A structured comparison of European transformation models
- A methodology for evaluating their applicability
- A detailed assessment of Split's urban conditions,
- And a conceptual Integrated Urban Regeneration Model tailored for Split
  Future Research
  Future studies should focus on:
- Quantitative modelling of mobility and climate adaptation scenarios
- Economic feasibility testing for the innovation district and mobility hub
- Social impact and housing affordability research
- Advanced GIS simulations and climate risk mapping
- And participatory planning evaluations.

Closing Remark

With strategic coordination, innovative governance, and a clear long-term vision, Split has the potential to transition from fragmented development to a resilient, inclusive, and future-oriented Mediterranean city—one that harmonizes its unique heritage with European standards of sustainable urban transformation.

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AVIFAUNA OF THE ORJEN NATURE PARK

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Scientific article
https://doi.org/10.58952/nit20251302051
***UDC*598.2(497.16):502.4**

Abstract

The bird fauna along the Orjen Mountain massif and the border area of the park along the Trebišnjica River was studied. The analysis covered habitats and migrations during the period from the summer of 2021 to the autumn of 2023, with the aim of long-term monitoring, forecasting, and protection of species.
The methods used for monitoring, marking, recording, and data processing included: the kilometer transect method, point census, movement along freely chosen routes, and the "playback" method. Previous studies of bird fauna in this park were also analyzed to synthesize results.
The main outcomes obtained after field research are as follows: a systematic list of bird species was compiled, supported by a photographic album, and maps were created showing the most important nesting habitats.
The proposal was presented to the nature park management and the stakeholders interested in this area, with the aim of protecting species and ensuring their sustainability within the habitat.
Keywords: *ornithofauna, nature park, bird habitat, bird movement, migration monitoring, survival forecasting, species protection.*

1. INTRODUCTION

The Orjen mountain massif is located in the far south of Bosnia and Herzegovina, at the tri-border area between Bosnia and Herzegovina, Montenegro, and Croatia. This region represents an important natural complex of exceptional geological, landscape, and biological value, known for its high habitat diversity and rich fauna, particularly birds. Despite this, the ornithofauna of Orjen has not yet been systematically studied, which highlights the need for a more detailed and long-term scientific approach aimed at better understanding its structure and ecological significance.

Orjen has been identified as one of three potential pilot Natura 2000 sites in Bosnia and Herzegovina, selected by domestic and international experts within the project *"Support for the Implementation of the Birds Directive and Habitats Directive in Bosnia and Herzegovina."* The Orjen area encompasses more than twenty different habitat types, making it one of the most diverse regions in the southeastern part of the country. Such habitat heterogeneity requires systematic field research to collect reliable and representative data on the presence, abundance, and spatial distribution of bird species.

The main goal of this research is to assess the importance of the Orjen Nature Park area as a bird habitat, in the context of its possible nomination as a future protected area of a higher category. At the same time, this area has been recognized as a potential IBA (Important Bird Area) site in Bosnia and Herzegovina (Kotrošan et al., 2012), which further confirms its ornithological and ecological value.

Available data on the ornithofauna of Orjen remain fragmentary. The earliest records come from the works of Grubač and Gašić (2004), who documented the presence of certain species in the vicinity of the village of Orahovac. A significant contribution to the knowledge of the local ornithofauna was made by Jovica Sjenčić (2013) in his study *"Data on Ornithological Research of Bijela Gora near Trebinje."* Additional studies have been presented and published by Aleksandar Vukanović, focusing on the ornithofauna of the Orjen–Bijela Gora area (2017–2018), as well as *"The Winter Census of Waterbirds of Trebinje Lake in 2017."*

In comparison with neighboring countries such as Montenegro and Croatia, where numerous monitoring programs have been conducted and detailed species lists published for areas with similar orographic characteristics (e.g. Lovćen, Sniježnica, Biokovo), research in Bosnia and Herzegovina is still in its early stages and mostly consists of individual field observations. This discrepancy further emphasizes the need for continuous study of ornithofauna in the mountain ecosystems of the country's southern region.

The subject of this study is the ornithofauna of the Orjen area, with a special focus on identifying bird species and their relationships with specific habitat types. The significance of the topic lies in the fact that systematic ornithological research contributes to a better understanding of ecological processes, the planning of natural resource management, and the advancement of nature conservation in Bosnia and Herzegovina.

This paper presents the results of field research, an overview of bird species and their abundance across different habitat types, as well as an analysis of their spatial distribution and ecological roles. The contribution of this study lies in supplementing existing knowledge about the ornithofauna of southern Herzegovina, identifying key areas for bird conservation, and providing a scientific basis for future management and protection plans for the Orjen area as a valuable natural complex.

2. MATERIALS AND METHODS

The research was conducted across several sites characteristic of the Mediterranean biogeographical region, an area distinguished by its specific combination of climatic conditions and vegetation types. The following section presents the habitat categories included in the study, together with the codes assigned to each surveyed locality.

Although the division of habitats does not strictly follow established phytosociological classification frameworks, the selected categorization provides a clearer overview of the key features of each habitat type, particularly in relation to their relevance for the structure and diversity of the local avifauna. In this way, the habitats are arranged so as to emphasize their differences, ecological functions, and their role in supporting and preserving bird communities within the studied area.

Overview of the habitat types defined for the study:

- predominantly beech forests – Štirovnik, Begova Korita, slopes of Mala Jastrebica
- pine forests – Borova glava, Prijevor
- Bosnian pine (*Pinus heldreichii*) forests – Boljovska greda and Mala Jastrebica
- mixed forests and scrublands – Koritska Grede, Ubla
- rocky terrains – Milanov Osijek, Buganja greda, Vučji zub,
- cliffs – Koritska Grede, Velika and Mala Jastrebica
- mountain pastures and meadows – Carevo polje, Dobri Do, Konjsko polje, Begova Korita, Ubla, Pirina Poljana
- riverine and lacustrine ecosystems – Trebišnjica River and its reservoir Gorica Lake, Sušica River
- settlements – Jazina, Orovac, Konjsko

Time frame of research
Fieldwork was carried out over several seasons during a three-year period (2021–2023).
Winter surveys were conducted in January 2021, 2022, and 2023, focusing on the Trebišnjica River basin during the period when birds occupy their wintering grounds. Additional research was conducted in May and August 2021, May 2022, and May–June 2023.
In total, 15 field research days were carried out during the mentioned period.

Methods used
Standard ornithological methods were applied, including:

- kilometer transect method
- point census
- free field movement
- playback method (Gregory et al., 2004).

Among the methods used, transect surveys were the most commonly implemented. Observers conducted these surveys by walking along defined routes to collect data on species presence and distribution, covering the following routes: Lastva – Orovac – Donji Orahovac, Koritske Grede – Begova Korita, Ubla –Mala Jastrebica – Pririna Poljana - Dobri Do, Dobri Do-Buganje Grede- Vučji Zub, Tuli – Carevo polje – Konjsko, as well as in the areas surrounding Lake Goričko and along the course of the Trebišnjica River.

Free-range field surveys were carried out across the habitats of Ubla, Pirina Poljana, Dobri Do, Carevo Polje, and Zubačko Polje. This method enabled detailed monitoring of reproductive behavior, detection of breeding pairs, and the identification of currently active nests, while allowing observers to adapt their movements to local habitat conditions and species activity.

The point census method was used during stationary observation or prolonged stays at the following localities: Koritske Grede, Begova Korita, Milanov Osijek, Goričko Lake, and the peaks of Vučji Zub.

The playback technique was used for species known to react to broadcasted vocalizations, whether songs or calls, played through speakers, as shown in Figure 1.

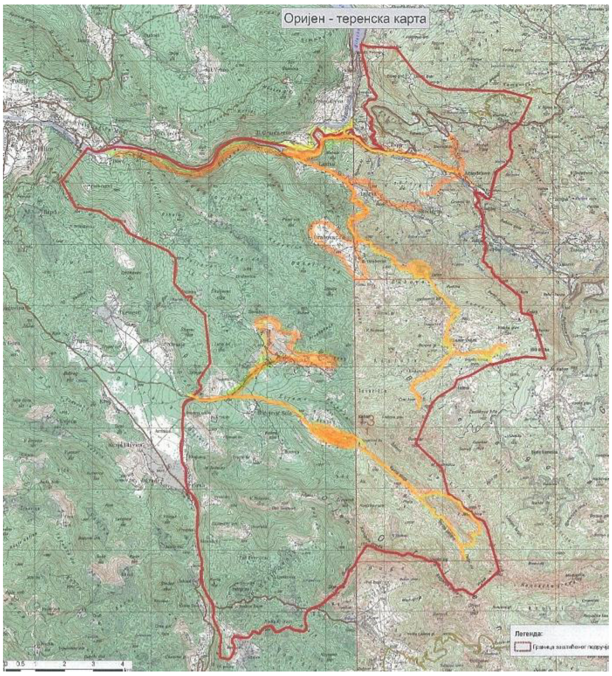

Figure 1. Studied ornithofauna of the Orjen area in relation to the boundaries (red line) of the Nature Park – the orange line represents transects (surveyed on foot), while the orange-shaded areas indicate zones investigated through field searches and free movement. (Source: ZZKIPN, processed by J. Sjeničić, A. Vukanović)

Most bird species were also photo-documented using a Nikon P900 camera. Identification was carried out using the illustrated field guides *"Birds of Europe with North Africa and the Middle East"* (Heinzel et al., 1996) and the *"Collins Bird Guide, 2nd Edition"* (Svensson et al., 2010). The scientific names of species, taxonomic order, and breeding status in Bosnia and Herzegovina follow del Hoyo et al. (2014, 2016). An assessment of the breeding status for the Bijela Gora area is also provided, although the research period was relatively short to confirm breeding for most species. The Serbian bird nomenclature used follows Vasić et al. (2004; 2005).

3. ANALYSIS OF RESULTS AND CONCLUSIONS

During field research on the Orjen Mountain area, a total of 68 bird species were recorded, belonging to 15 orders and 33 families. All species whose identification was uncertain or doubtful were excluded from the final list.

Endangered species, which should be the main focus in defining protection zones and conservation measures, are marked in red. These species meet the criteria of threat according to the EU Directives system, the Red List, as well as criteria related to habitat loss, rarity, and low population density at the level of Bosnia and Herzegovina.

The results of the research conducted in the area planned for protection, Orjen – Bijela Gora, indicate the existence of two distinctly different types of bird habitats. The first comprises the riverine and riparian system of the Trebišnjica basin the second encompasses the hilly–mountainous areas of the Orjen massif,

1 List of Bird Species Recorded in the Study Area in Trebišnjica basin:

1. **Anas platyrhynchos** – *Mallard* – Breeding species, present along the Trebišnjica River almost the year.
2. **Anas crecca** – *Eurasian Teal* – Breeding species, present along the Trebišnjica River almost throughout the year.
3. **Anas querquedula** – *Garganey* – Wintering species along the Trebišnjica River.

4. **Aythya ferina** – *Common Pochard* – Wintering species along the river.
5. **Aythya nyroca** – *Ferruginous Duck* – Wintering species along the river.
6. **Aythya fuligula** – *Tufted Duck* – Wintering species along the Trebišnjica River.
7. **Tachybaptus ruficollis** – *Little Grebe* – Present along the Trebišnjica River almost throughout the year.
8. **Podiceps nigricollis** – *Black-necked Grebe* – Wintering species along the Trebišnjica River.
9. **Podiceps cristatus** – *Great Crested Grebe* – Wintering species along the Trebišnjica River.
10. **Ardea cinerea** – *Grey Heron* – Present year-round; wintering in larger numbers along the Trebišnjica River.
11. **Mergus merganser** – Goosander – Confirmed breeder in the Trebišnjica River section within the study area.
12. **Columba livia** – *Rock Dove / Feral Pigeon* – Breeder near settlements and observed in flight across the area.
13. **Tachymarptis melba** – *Alpine Swift* – Probable breeder; a small colony recorded within the area.
14. **Cuculus canorus** – *Common Cuckoo* – Common breeder in forest habitats.
15. **Phalacrocorax carbo** – *Great Cormorant* – Present year-round and wintering along the Trebišnjica River.
16. **Larus michahellis** – *Yellow-legged Gull* – Migrant and breeder in nearby regions (e.g., Bilećko Lake, Adriatic islands, etc.).
17. **Chroicocephalus ridibundus** – *Black-headed Gull* – Migrant and breeder in nearby regions (e.g., Bilećko Lake).
18. **Fulica atra** – *Eurasian Coot* – Migrant and wintering species along the Trebišnjica River.
19. **Merops apiaster** – *European Bee-eater* – Recorded calling and in flight; possible breeder in suitable microhabitats (earth banks, excavations).
20. **Falco tinnunculus** – *Common Kestrel* – Breeder of open areas with suitable nesting sites.
21. **Oriolus oriolus** – *Eurasian Golden Oriole* – Breeder near settlements and along the Trebišnjica River.
22. **Garrulus glandarius** – *Eurasian Jay* – Common breeder.
23. **Corvus cornix** – *Hooded Crow* – Breeder in lower zones and near settlements.
24. **Pica pica** – *Eurasian Magpie* – Possible breeder.
25. **Poecile palustris** – *Marsh Tit* – Sporadically recorded; probable breeder.
26. **Delichon urbicum** – *Common House Martin* – Breeder on cliffs and rocky terrain; scarce.
27. **Cinclus cinclus** – *White-throated Dipper* – Common along the Trebišnjica River, present year-round.
28. **Turdus merula** – *Common Blackbird* – Most abundant thrush species in the study area, found in all habitats
29. **Phoenicurus ochruros** – *Black Redstart* – Naturally occurring but less numerous; inhabits rocky areas
30. **Erithacus rubecula** – *European Robin* – Breeding species, recorded in many habitats.
31. **Oenanthe oenanthe** – *Northern Wheatear* – One potential territory recorded at Milanov Osijek.
32. **Passer domesticus** – *House Sparrow* – Synanthropic species, recorded near settlements.
33. **Passer montanus** – Eurasian Tree Sparrow – Breeding species near settlements.
34. **Motacilla alba** – White Wagtail – Probable breeder, present near aquatic and humid habitats.
35. **Motacilla flava** – Yellow Wagtail – Probable breeder, recorded throughout the year.
36. **Fringilla coelebs** – Common Chaffinch – Very abundant species recorded in all transects and surveyed areas

List of Bird Species Recorded in the Study Area Orjen and Bijela Gora

1. **Cuculus canorus** – Common Cuckoo – Common breeder in forest habitats.
2. **Pernis apivorus** – European Honey Buzzard – Possible breeder
3. **Aquila chrysaetos** – Golden Eagle – Frequently observed hunting within the area; may occur outside the breeding period.
4. **Accipiter gentilis** – Northern Goshawk – Possible breeder.
5. **Accipiter nisus** – Eurasian Sparrowhawk – Possible breeder.
6. **Buteo buteo** – Common Buzzard – Widespread raptor, less numerous than in northern parts of the country.
7. **Upupa epops** – Eurasian Hoopoe – Confirmed breeder; common in lowland and hilly semi-open habitats.
8. **Merops apiaster** – European Bee-eater – Recorded calling and in flight; possible breeder in suitable microhabitats (earth banks, excavations).
9. **Alcedo atthis** – Common Kingfisher – Recorded along the Trebišnjica River throughout the year.
10. **Dryocopus medius** – Middle Spotted Woodpecker – Breeder in beech forests.
11. **Dendrocopos major** – Great Spotted Woodpecker – Breeder in forested areas.
12. **Falco tinnunculus** – Common Kestrel – Breeder of open areas with suitable nesting sites
13. **Lanius collurio** – Red-backed Shrike – Common passerine breeder in open shrubland habitats.
14. **Lanius minor** – Red-backed Shrike – Common passerine breeder in open shrubland habitats.
15. **Garrulus glandarius** – Eurasian Jay – Common breeder.
16. **Corvus corax** – Common Raven – Breeding species of the area.
17. **Corvus cornix** – Hooded Crow – Breeder in lower zones and near settlements.
18. **Lophophanes cristatus** – Crested Tit – Breeder in high-altitude forest habitats.
19. **Parus major** – Great Tit – Common species inhabiting various habitats.
20. **Lullula arborea** – Woodlark – Common and abundant breeder in semi-open mountain habitats.
21. **Hirundo rustica** – Barn Swallow – Breeding species near rivers and settlements.
22. **Phylloscopus collybita** – Common Chiffchaff – One of the most numerous breeders, especially on Jastrebica and in Bosnian pine forests.
23. **Aegithalos caudatus** – Long-tailed Tit – Occasionally recorded in small family groups within forest habitats.
24. **Sylvia atricapilla** – Eurasian Blackcap – Relatively numerous in suitable, mostly mosaic and shrubby habitats.
25. **Sitta europaea** – Eurasian Nuthatch – Numerous in suitable beech and mixed forests.
26. **Troglodytes troglodytes** – Eurasian Wren – Recorded only in cooler beech forests beneath Jastrebica.
27. **Monticola solitarius** – Blue Rock Thrush – Several territories recorded in lower altitudes.
28. **Turdus merula** – Common Blackbird – Most abundant thrush species in the study area, found in all habitats
29. **Turdus philomelos** – Song Thrush – Several territories recorded in suitable forest and shrub habitats.
30. **Ficedula albicollis** – Collared Flycatcher – Territory recorded on Bijela Gora, at the edge of beech forests.
31. **Phoenicurus ochruros** – Black Redstart – Naturally occurring but less numerous; inhabits rocky areas
32. **Erithacus rubecula** – European Robin – Breeding species, recorded in many habitats.
33. **Luscinia megarhynchos** – Common Nightingale – Several territories

recorded in lowland forest and shrubby habitats

34. **Oenanthe oenanthe** – Northern Wheatear – One potential territory recorded at Milanov Osijek.
35. **Passer domesticus** – House Sparrow – Synanthropic species, recorded near settlements.
36. **Passer montanus** – Eurasian Tree Sparrow – Breeding species near settlements.
37. **Motacilla cinerea** – Grey Wagtail – Probable breeder, recorded throughout the year.
38. **Fringilla coelebs** – Common Chaffinch – Very abundant species recorded in all transects and surveyed areas
39. **Chloris chloris** – European Greenfinch – Common breeder of various habitats.
40. **Carduelis carduelis** – European Goldfinch – Recorded in Ubla; confirmed breeder.
41. **Serinus serinus** – European Serin – Present in mosaic habitats and near settlements.
42. **Emberiza citrinella** – Yellowhammer – Common bunting,
43. **Emberiza cia** – Rock Bunting – Probable breeder in mountainous and rocky shrub habitats within the study area.

Photo Album of Selected Bird Specimens from the Field
Figures 2–9. Photographic documentation of several bird species recorded during field research.

Figure 2. Lanius collurio (Red-backed Shrike) -Carevo pilje (Photo: Aleksandar Vukanović)

Figure 3. Erithacus rubecula (European Robin) - Jazina (Photo: Aleksandar Vukanović)

Figure 4. *Oriolus oriolus (Eurasian Golden Oriole) – Aranđelovo (Photo: Aleksandar Vukanović)*

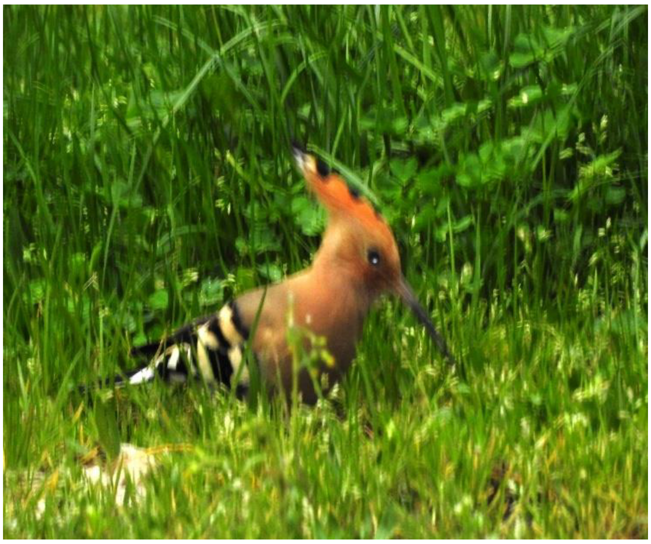

Figure 7. Upupa epops (Eurasian Hoopoe) – Ubla (Photo: Aleksandar Vukanović)

Figure 5. *Emberiza cia (Rock Bunting) – Begova Korita (Photo: Aleksandar Vukanović)*

Figure 8. *Troglodytes troglodytes (Eurasian Wren) – Lastva (Photo: Aleksandar Vukanović)*

Figure 6. *Oenanthe oenanthe (Northern Wheatear) – Milanov Osijek (Photo: Aleksandar Vukanović)*

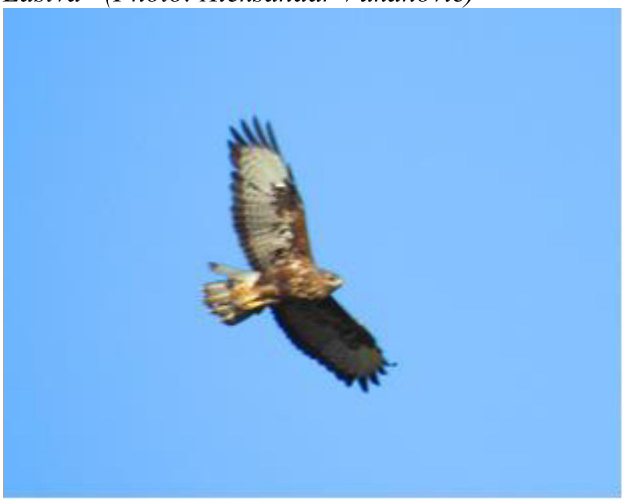

Figure 9. *Buteo buteo (Common Buzzard) – Pirina Poljana (Photo: Aleksandar Vukanović)*

Riverine and Riparian Habitats

The area along the Trebišnjica River holds exceptional ornithological value, particularly during the winter months. Over the three-year period of monitoring and recording birds in aquatic habitats, it was established that a large number of birds regularly inhabit the surroundings of Trebinjsko Lake, ranging from several hundred to several thousand individuals. During cold winters, when most inland water bodies in Bosnia and Herzegovina freeze over, the open waters of the Trebišnjica become a crucial refuge for numerous species.

The most frequently recorded species were *Tachybaptus ruficollis*, *Podiceps cristatus*, *Phalacrocorax carbo*, *Ardea cinerea*, *Anas crecca*, *Anas querquedula*, *Anas platyrhynchos*, *Larus michahellis*, *Chroicocephalus ridibundus*, *Fulica atra*, and *Gallinula chloropus*. A direct relationship was observed between the severity of winter conditions and bird abundance — the lower the winter temperatures, the higher the number of individuals present.

Out of the total of 68 species recorded across the entire study area, species associated with aquatic habitats showed the highest representation, which aligns with their ecological requirements and the local hydrological conditions.

Mountainous Part of the Orjen Massif

In the higher areas of Mount Orjen, songbirds (Passeriformes) are predominant, with particular emphasis on representatives of the families Paridae, Sylviidae, Muscicapidae, and Fringillidae. During field surveys, the most frequently recorded species were Fringilla coelebs (chaffinch), Turdus merula (common blackbird), Sylvia atricapilla (blackcap), Phylloscopus collybita (common chiffchaff), and Lanius collurio (red-backed shrike).

Of these species, only Lanius collurio is listed in Annex II of the European Union Birds Directive, indicating that it requires special protection and habitat conservation. The other species, although commonly present, belong to the group of widely distributed and ecologically stable birds that adapt well to various Mediterranean-type habitats.

The structure of bird communities at higher altitudes shows a clear dominance of songbirds, reflecting the richness of forest and semi-forest habitats that provide a variety of resources for nesting, feeding, and protection from predators. These areas represent an important ecological space for the conservation of Orjen's avifauna, as they allow for the maintenance of stable populations of both protected and common species.

Significance of the Studied Area

The results obtained indicate the significant conservation value of the Orjen area, which, based on the richness and diversity of its avifauna, could be considered for formal protection. Given that previous ornithological data for this area are very limited, comparative analyses are constrained. However, the results can be interpreted in the context of similar ecosystems in southern Herzegovina and the neighboring Montenegrin part of Orjen.

Although the recorded diversity does not fully reflect the actual state of populations, the findings confirm that the Orjen massif lies on an important Adriatic migratory route. The combination of specific geomorphological, climatic, and floristic conditions has created a variety of ecosystems — from fir-beech forests, through mountain meadows and rocky areas, to the riverine ecosystems of the Trebišnjica — all of which collectively contribute to the high biological diversity of the region.

Rare and Conservation-Significant Species

Special attention of the researchers was focused on the presence of rare and threatened species of particular conservation importance: Circaetus gallicus (Short-toed Snake Eagle), Aquila chrysaetos (Golden Eagle), and Pernis apivorus (European Honey Buzzard). Confirmation of the presence of Aquila fasciata (Bonelli's Eagle) would be of exceptional significance, as this species is considered potentially extinct in Bosnia and Herzegovina, highlighting the international importance of this area for avian conservation.

In addition to these key species, other notable birds were recorded during the field surveys, including Alectoris graeca (Rock Partridge), Bubo bubo (Eurasian Eagle-Owl), Tachymarptis melba (Alpine Swift), Upupa epops (Eurasian Hoopoe), Mergus merganser (Common Merganser), Monticola solitarius (Blue Rock Thrush), and Hippolais olivetorum (Olive-tree Warbler). The presence of these species further emphasizes the richness and diversity of habitats on Bijela Gora, ranging from forested complexes and rocky areas to water bodies and edge habitats.

According to the Regulation on the Red Lists of the Republic of Srpska (Official Gazette RS, 124/12), 52 of the 53 species recorded on Bijela Gora are classified as protected. This confirms the high ecological value of the area and highlights its important role in the conservation of both local and migratory bird populations. Moreover, the varied habitat structure and presence of species with different ecological requirements make Bijela Gora a key site for future conservation strategies and monitoring of threatened species.

Research Limitations and Recommendations

The study was conducted during a favorable period (May–June), but certain limitations affected the scope of the results. Adverse weather conditions (rain, wind), a short time frame, and seasonal restrictions (spring–summer focus) meant that some habitats, particularly rocky areas, screes, and higher mountain zones, remained insufficiently surveyed.

In these locations, species typical of mountain and Mediterranean ecosystems can be expected, such as *Buteo rufinus*, *Falco naumanni*, *Falco biarmicus*, *Eremophila alpestris*, *Anthus spinoletta*, *Prunella collaris*, *Monticola saxatilis*, *Sylvia cantillans*, *Sitta neumayeri*, and *Emberiza hortulana*.

It is recommended that the management of the Hunting Association incorporate activities for the protection of all fauna species into their plans. The mountaineering association *Vučiji zub*, as well as the organization *Center for Sustainable Development and Ecology (CORIE)*, should also include the protection of particularly rare species in their annual and long-term activities. Local ministries of ecology and tourism are tasked with developing and monitoring instruments for the protection of rare species and overall biodiversity.

For a comprehensive assessment of the avifauna of Orjen, systematic research throughout all seasons is necessary, with particular emphasis on migratory and winter periods. Forest habitats and the presence of diurnal and nocturnal raptors are of special importance, as they, together with large mammals such as wolves, lynxes, and bears, represent so-called "umbrella species" that are crucial for the conservation of overall biodiversity.

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EXHAUST GASES FROM INTERNAL COMBUSTION ENGINES AND THEIR IMPACT ON THE ENVIRONMENT

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Professional paper
https://doi.org/10.58952/nit20251302062
***UDC* 621.43:504.5**

Abstract

This paper presents the basic characteristics of gaseous combustion products (CO_2, CO, NOx, SOx, NH_3, etc.) in internal combustion engines (ICE) and their harmful impact on the environment, i.e., the ecological context. Special attention is given to the formation of $CO_2$and CO, specifically the reaction kinetics $CO_2=CO+0.5\cdot O_2$ as the dominant gases in the exhaust gases of ICE. At an ambient temperature of 298K, the considered reaction ΔH=282990 kJ is endothermic and the equilibrium constant at normal pressure (1.013·105Pa) is much less than one $Kp'=1.40\cdot 10^{-45}$, which means that the equilibrium of the reaction is shifted to the left, towards the reactant CO_2. This practically means that the formed CO_2 in the exhaust gases remains stable and, as a greenhouse gas, has an impact on the 'greenhouse effect.' Only at significantly high temperatures, above 2000K, does a slight formation of CO and reduction of CO_2 occur.

Keywords*:* *exhaust gases, carbon-dioxide, thermodynamic functions, equilibrium constant*

JEL classification: Q53, Q42

1. INTRODUCTION

Internal combustion engines represent one of the most widespread sources of energy in transportation, industry, and agriculture. However, the combustion process of fuel in these engines is far from ideal, leading to the formation of various gaseous and solid combustion products. Among the most significant pollutants are carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NOx), sulfur dioxide (SO_2), and hydrocarbons (HC).
In addition to gases, engines, particularly diesel engines, also emit soot resulting from incomplete combustion of hydrocarbon fuel.

Carbon monoxide is a colorless and toxic gas. It is produced by the incomplete combustion of fossil fuels such as coal and gasoline or oil. When inhaled, CO blocks the transport of oxygen to the brain and other organs.

Carbon dioxide is a greenhouse gas and contributes to global warming. In direct contact, CO_2 is not harmful.Large amounts of CO_2 are emitted from diesel engines, but due to incomplete combustion of fuel in the engines, CO is formed while CO_2 is reduced according to the formula $CO_2+0.5\cdot O_2=CO$.

Nitrogen oxides (NOx) are formed at high temperatures, which is common in diesel engines, and concentrations are usually high.

Large amounts of CO_2 are emitted from diesel engines, but due to incomplete combustion of fuel in the engines, CO is formed while CO_2 is reduced according to the formula. Nitrogen oxides (NOx) are formed at high temperatures, which is common in diesel engines, and concentrations are usually high. NOx emissions contribute to acid rain and the formation of photochemical smog. Sulfur oxides, particularly SO_2, are produced from sulfur present in diesel fuel. Today's low-sulfur fuels significantly reduce SO_2 emissions, but in lower quality fuels (heavy fuel oil, crude oil) they are still significant [1,2,3] .
Ammonia (NH_3) is not a primary combustion product but mainly appears as a byproduct in exhaust gas after-treatment systems [4,5].

The emission of gaseous pollutants and soot directly depends on the type of fuel, the operating mode of the engine, the design of the combustion system, as well as the applied emission control systems (catalysts, particulate filters, SCR systems). In the context of tightening environmental regulations, especially those defined in EU standards (e.g., Euro 6/VI), reducing gas and soot emissions becomes a key challenge in the development of new engines and the improvement of existing technologies.

2. REGULATIONS AND LEGAL PROVISIONS ON THE EMISSION OF EXHAUST GASES INTO THE ATMOSPHERE

The air we breathe must have certain characteristics, i.e. components that do not negatively affect humans and other living beings; there must not be any other components exceeding the limit that negatively affect living beings, especially humans. Figures 1, 2 and 3 show CO emissions in Bosnia and Herzegovina for the years 2016 and 2022. It can be observed that the highest CO emissions are in the Tuzla Canton (TK). It can also be noted that there is a reduction in CO emissions from internal combustion engines (ICE) in 2022 compared to CO emissions in 2016.

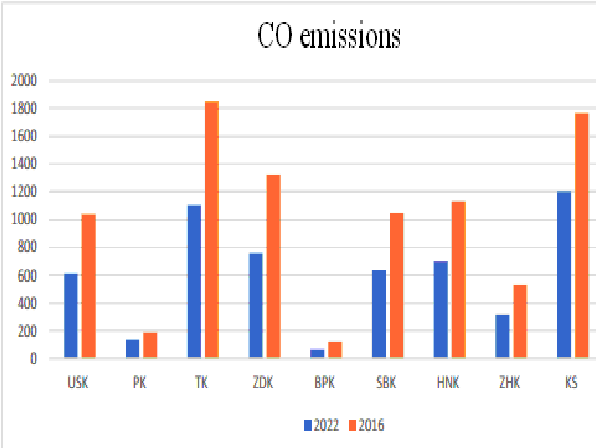

Figure 1. *CO emissions in tons by canton in theof Bosnia and Herzegovinafor the years 2016 and 2022 [6]*

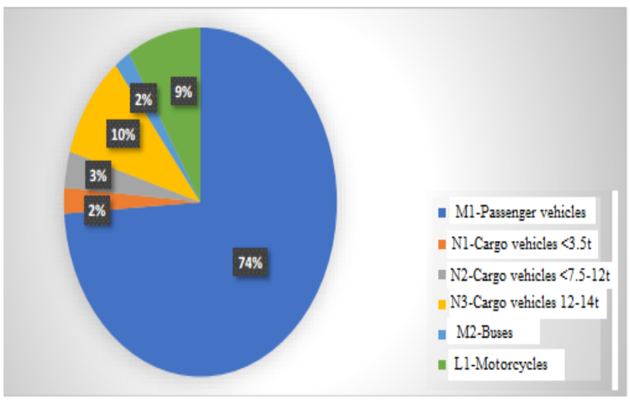

Figure 2. *Percentage share of individual categories of vehicles in carbon monoxide (CO) emissions in the of Bosniaand Herzegovina in 2022. [6]*

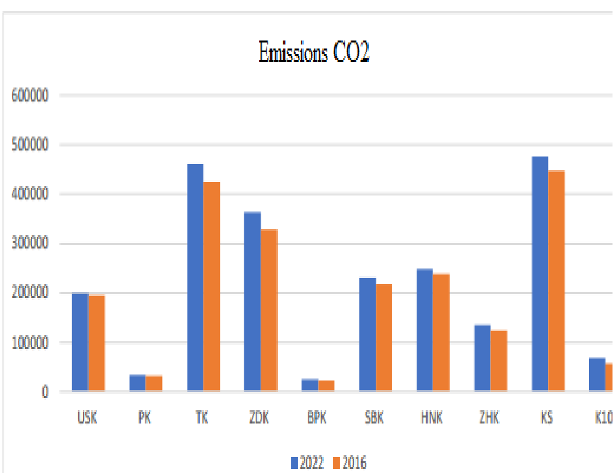

Figure 3*. CO_2 emissions in tons by cantons in the of Bosnia and Hezegovina for the years 2026 and 2022 [6]*

The participation of individual vehicle categories in carbon dioxide (CO_2) emissions in Bosnia and Herzegovina in 2022 refers to passenger vehicles, which account for 74% (Figure 4).

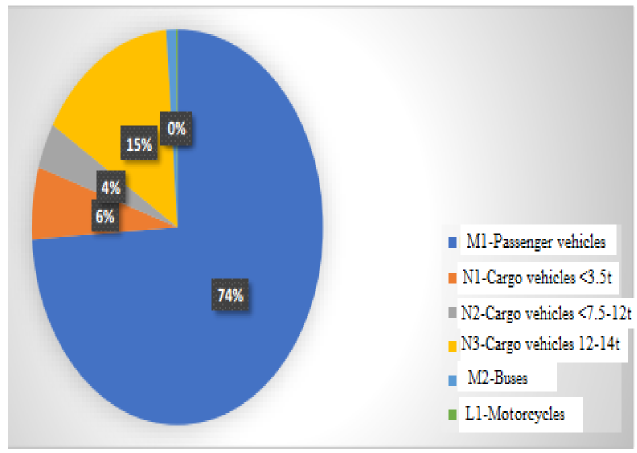

Figure 4. *Percentage share of individual categories of vehicles in carbon dioxide (CO2) emissions in the of Bosnia and Herzegovina in 2022 [6].*

The limit that determines the maximum allowable amount of a harmful substance in a unit of observed volume is called the Emission Limit Value (ELV). It is evident that the ELV is a Quality Standard, a tolerance limit. Table 1 shows the ELVs of individual harmful substances emitted by a gasoline engine. From Table 1, it can be observed that the goal of Euro 5 and 6 requirements is a further reduction in NOx emissions.

Table 1. *Limit values (maximum allowed quantities (g/km)) of certain harmful substances from internal combustion engines [7]*

	Year	CO	HC	HC+NOx	NOx	PM
Diesel engines		(g/km)				
Euro 1	1992/07	3.16	-	1.13	-	0.18
Euro 2	1996/01	1.00	-	0.70	-	0.08
Euro 3	2000/01	0.64	-	0.56	0.50	0.05
Euro 4	2005/01	0.50	-	0.30	0.25	0.025
Euro 5	2009/09	0.50	-	0.23	0.18	0.005
Euro 6	2014/09	0.50	-	0.17	0.08	0.005
Otto engines		(g/km)				
Euro 1	1992/07	3.16	-	1.13	-	-
Euro 2	1996/01	2.20	-	0.50	-	-
Euro 3	2000/01	2.30	0.20	-	0.15	-
Euro 4	2005/01	1.00	0.10	-	0.08	-
Euro 5	2009/09	1.00	0.10	-	0.06	0.005
Euro 6	2014/09	1.00	0.10	-	0.06	0.005

3. MATHEMATICAL MODEL

3.1 Thermodynamic functions

For the chemical reaction [3]:

$$a_1A_1 + a_2A_2 + a_3A_3 + \cdots = b_1B_1b_2B_2 + b_3B_3 + \cdots \quad (1)$$

where:
A_i , B_j - symbols for chemical substance
a_i - stoichiometric coefficients for reactants
b_j - stoichiometric coefficients for products.

Thermodynamic functions $\Delta H, \Delta S, \Delta G$ at 298K and $1.013 \cdot 10^5$Pathey are defined using the expression [8]:

$$\Delta H = \sum_j b_j \cdot \Delta h_j - \sum_i a_i \cdot \Delta h_i \quad (2)$$

$$\Delta S = \sum_j b_j \cdot s_j - \sum_i a_i \cdot s_i \quad (3)$$

$$\Delta G = \sum_j b_j \cdot \Delta g_j - \sum_i a_i \cdot \Delta g_i \quad (4)$$

where:
a_i - the number of kilomolesof the i-th reactant components
b_j - the number of kilomoles of the j-th component for products
Δh_i - bond enthalpy of the i-th component
Δh_j - bond enthalpy of the j-th component
s_i - specificentropies and connections of the i-th component
s_j -specific entropies and connections of the j-th component
Δg_i -specific free enthalpies of the i-th component
Δg_j -specific free enthalpies of the j-th component.

The dependence of enthalpy, entropy and free enthalpy of reaction (1) on temperature are defined by the expression:

$$\Delta H_T = \Delta H_{298} + \int_{298}^{T} \Delta c_{mp}(T) dT \quad (5)$$

$$\Delta S_T = \Delta S_{298} + \int_{298}^{T} \frac{\Delta c_{mp}(T)}{T} dT \quad (6)$$

$$\Delta G = \Delta H - T \cdot \Delta S \quad (7)$$

where are:

$\Delta c_{mp} = \sum_j b_j \cdot c_{mp_j} - \sum_i b_i \cdot c_{mp_i}$ - specific molar heat capacities (8)

If it is $\Delta G > 0$ the reaction proceeds from right to left, i.e. In the direction of formation of reaction reactants. If it is $\Delta G < 0$ the reaction proceeds from left to right, i.e. Towards the formation of reaction products. Values of enthalpy, entropy and free enthalpy of reaction components $CO_2 = CO + 0.5 \cdot O_2$ at $298K$ and $1.013 \cdot 10^5$Pa are shown in Table 2.

Table 2. Thermodynamic data of the reaction components $CO_2 = CO + 0.5 \cdot O_2$ at $298K$ and $1.013 \cdot 10^5$Pa [9]

	Δh **J/mol**	Δg **J/mol**	s **J/(molK)**
CO	-110520	-137150	197.56
O_2	0	0	205.03
CO_2	-393510	-394360	213.64

Heat capacities of individual components of the reaction $CO_2 = CO + 0.5 \cdot O_2$depending on the temperature, they are determined using the expression [10]:

$$C_{mpCO} = 29.556 - 6.5807 \cdot 10^{-3} \cdot T + 2.0130 \cdot 10^{-5} \cdot T^2, \text{kJ/(kmol} \cdot K) \quad (9)$$

$$C_{mpO_2} = 29.526 - 8.8999 \cdot 10^{-3} \cdot T + 3.8083 \cdot 10^{-5} \cdot T^2, \text{kJ/(kmol} \cdot K) \quad (10)$$

$C_{mpCO_2} = 27.437 + 4.2315 \cdot 10^{-2} \cdot T - 1.9555 \cdot 10^{-5} \cdot T^2$,kJ/(kmol $\cdot K$) (11)

For a chemical reaction:

$$\sum_i a_i \cdot A_i = \sum_j b_j \cdot B_j \tag{12}$$

the chemical equilibrium constant expressed in terms of partial pressures is: $K_p = \frac{\prod_j (p_{B_j})^{b_j}}{\prod_i (p_{A_i})^{a_i}}$

(13)

The value of the chemical equilibrium constant K'_p reduced to pressure $p_0 = 1.013 \cdot 10^5\,\text{Pa}$ is determined by the expression:

$$K_p{}' = e^{-\frac{\Delta G}{R_u \cdot T}} = K_p \cdot p_0{}^{-(\sum_j b_j - \sum_i a_i)} \tag{14}$$

where is:

$R_u = 8.314 kJ/(kmol \cdot K)$ – universal gas constant.

3.2 Results of calculation of thermodynamic reaction functions $\boldsymbol{CO_2 = CO + 0.5 \cdot O_2}$

Using numerical thermodynamic data for the pure components involved in the reaction $CO_2 = CO + 0.5 \cdot O_2$ at 298K and $1.013 \cdot 10^5\,\text{Pa}$ (Table 2) and using expressions (2) to (4) and expressions (13) and (14) the values of the thermodynamic functions can be calculated $\Delta H, \Delta S, \Delta G, Kp'$ considered reactions depending on the reaction temperature (Table 3).

In the temperature interval 298K to 2000K thermodynamic functions ΔH and ΔS are positive, so the sign is ΔG determined by the relative ratio of the enthalpy and entropy terms (equation (7)) (Figure 5). It can be seen that in the considered temperature interval (Table 3, Figure 5). This means that the reaction temperature is a crucial factor for the thermodynamic equilibrium of the considered reaction. In the temperature interval 298K to 2000K the free enthalpy of the reaction is greater than zero $\Delta G > 0$ and the equilibrium constant of the reaction under consideration is very small $K_p{}' << 1$, which means that the reaction is shifted towards the reactants of the reaction.

This practically means that the CO2 emitted in the exhaust gases of SUS engines is very stable and affects the greenhouse effect, i.e. in larger quantities it affects the warming of the earth or the earth's atmosphere. Only above 2000K does a slight reduction of CO2 occur and the formation of CO.

Table 3. Thermodynamic reaction functions as a function of temperature.

T (K)	ΔH (kJ)	ΔS (kJ/K)	$T \cdot \Delta S$ (kJ)	ΔG (kJ)	Kp' $(-)$	Kp $(Pa^{1/2})$
298	282990	86.44	25759	257232	$1.40 \cdot 10^{-45}$	$4.46 \cdot 10^{-43}$
400	283546	88.05	35220	248324	$3.72 \cdot 10^{-33}$	$1.18 \cdot 10^{-30}$
600	284558	90.09	54054	230503	$8.55 \cdot 10^{-21}$	$2.72 \cdot 10^{-18}$
800	286254	92.49	73992	212260	$1.38 \cdot 10^{-14}$	$4.40 \cdot 10^{-12}$
1000	289572	96.15	96150	193421	$7.88 \cdot 10^{-11}$	$2.51 \cdot 10^{-8}$
1200	295492	101.47	121740	173689	$2.75 \cdot 10^{-8}$	$8.75 \cdot 10^{-6}$
1400	304835	108.66	152124	152708	$2.00 \cdot 10^{-6}$	$6.38 \cdot 10^{-4}$
1600	318658	117.85	188560	130090	$5.66 \cdot 10^{-5}$	$1.80 \cdot 10^{-2}$
1800	337864	129.13	232434	105428	$8.72 \cdot 10^{-4}$	0.28
2000	363390	142.55	285100	78296	$9.02 \cdot 10^{-3}$	2.87
2273	410136	164.38	373636	36493	0.14	46.15

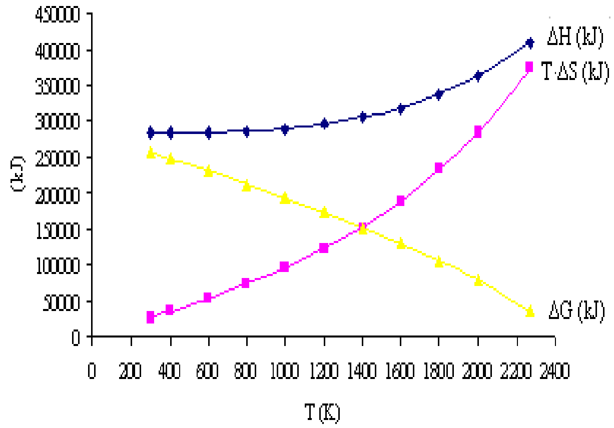

Figure 5. *Thermodynamic reaction functions* $CO_2 = CO + 0.5 \cdot O_2$ *from the temperature*

4. CONCLISION

The paper presents the basic properties of gaseous combustion products (CO_2, CO, NOx, SOx, NH_3, etc.) in internal combustion engines (SUS engines) and their harmful impact on the environment.

The ELVs of individual harmful substances emitted by each SUS engine are presented.

It was noted that additional reduction of NOx emissions requires the introduction of Euro 5 and Euro 6 fuels. Introducing this fuel as a quality standard also has a positive effect on the reduction of CO emissions in the exhaust gases of SUS engines.

Special attention is paid to the formation of CO_2 and CO, i.e. the kinetics of the reaction as dominant gases in the exhaust gases of SUS engines.

At an ambient temperature of 298K, the considered reaction is endothermic and the equilibrium constant at normal pressure (1.013·105Pa) is much less than one, which means that the reaction equilibrium is shifted to the left, i.e. in the direction of the reactant CO2.

This practically means that the CO_2 formed in the exhaust gases remains stable and as a greenhouse gas has an impact on the "greenhouse" effect. Only at significantly high temperatures, higher than 2000K, does a slow formation of CO and reduction of CO_2 occur.

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THE APPLICATION OF ARTIFICIAL INTELLIGENCE IN THE TAX SYSTEMS OF BOSNIA AND HERZEGOVINA: OPPORTUNITIES, LIMITATIONS, AND CHALLENGES

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Professional paper
https://doi.org/10.58952/nit20251302071
***UDC* 336.2:004.8(497.6)**

Abstract

This paper examines the opportunities and limitations of applying artificial intelligence (AI) within the tax administrations of Bosnia and Herzegovina through an analytical framework that integrates the normative, institutional, and technological preconditions of the system. The objective of the research is to provide a comprehensive understanding of how AI can enhance risk management processes, supervision, regulatory interpretation, and the relationship between tax authorities and taxpayers, while simultaneously identifying obstacles arising from a fragmented fiscal structure, uneven administrative practices, and the lack of standardized data.

Methodologically, the paper relies on a qualitative analysis of the existing legislative framework, comparative international practices, and principles of public revenue management, complemented by a theoretical perspective on the transformative effects of digital technologies in public administration. The findings indicate that AI has the potential to serve as an instrument of institutional modernization; however, its effective application depends on the level of technical readiness, data quality, and institutional willingness to adopt an analytical, evidence-based approach.

The conclusion emphasizes that artificial intelligence does not represent a substitute for existing institutions, but rather a mechanism capable of strengthening their efficiency and transparency, provided that modernization is implemented gradually and within a clearly defined strategy for the development of tax administrations.

Keywords: *artificial intelligence, tax administration, risk management, digital transformation, public administration, fiscal policy, data analytics*

JEL Classification: *H21, H26, H83, O33*

1. INTRODUCTION

Tax administrations worldwide are facing a rapid increase in data volumes and increasingly complex forms of economic transactions. Traditional operational models, based on manual processing and experience-based judgment, are becoming insufficient in an environment where financial flows occur almost in real time. Bosnia and Herzegovina faces similar challenges, but within a more complex institutional framework characterized by inconsistent records, fragmented jurisdictions, and varying levels of digital maturity.

For this reason, digital transformation in Bosnia and Herzegovina is not merely a technical issue, but a process requiring stable registries, standardized procedures, and coordination across different levels of government. The experience of OECD member states confirms that technological progress yields results only when grounded in reliable data and clearly defined administrative responsibilities (OECD, 2023). In Bosnia and Herzegovina, these preconditions are still evolving, raising the question of the extent to which AI can be effectively applied under existing conditions.

Within this context, the development of the "AI Poreznik" model provides valuable insight into the potential application of artificial intelligence even in systems that are not fully standardized. The model demonstrates that AI can improve regulatory interpretation, increase consistency, and reduce subjectivity, even when administrative infrastructure is suboptimal. This confirms that the core potential of AI in tax administrations lies in its ability to process large volumes of data and identify patterns that remain invisible to traditional methods (Davenport, 2018).

2. METHODOLOGICAL FRAMEWORK

The methodological framework of this study is based on a combination of theoretical sources, institutional analysis, and insights into contemporary public revenue management practices. The research proceeds from the assumption that the application of artificial intelligence in tax administrations is inseparable from the institutional context of the tax system of Bosnia and Herzegovina.

At the core of the research is a comparative analysis of international practices, used as a basis for assessing domestic institutional capacities. Relevant models developed within the OECD, the European Union, Australia, and the United States were analyzed in order to identify key prerequisites for the successful application of AI in tax administrations, particularly with regard to data standardization, unified registries, and clearly defined institutional responsibilities.

The second component of the methodological approach consists of a documentary analysis of legal and technical sources governing the operation of tax authorities in Bosnia and Herzegovina. This analysis includes laws, by-laws, technical guidelines, and publicly available reports, with a focus on data recording, exchange, and interpretation in practice. Special attention is given to the relationship between normative solutions and their implementation, as inconsistent records and partial enforcement of regulations directly affect the development of reliable analytical models.

The third methodological element includes qualitative insights derived from the professional practice of tax experts, based on the analysis of concrete cases and standard administrative procedures. This approach enables the identification of differences in regulatory interpretation and risk assessment that are not visible through normative sources alone, yet significantly affect the functioning of the tax system and its readiness for advanced technologies.

The methodological framework is further complemented by a case study of the domestic “AI Poreznik” model, which serves as a practical test of AI application in an administratively fragmented environment. The analysis provides insight into algorithmic behavior under conditions of inconsistent regulations, diverse reporting formats, and limited data centralization, thereby illustrating the realistic scope and limitations of AI implementation.

Despite certain methodological limitations such as the lack of access to internal tax authority databases, reliance on publicly available sources, uneven data updates, and the inability to conduct quantitative analysis, the combined use of comparative analysis, documentary research, qualitative insights, and a case study provides a sufficiently reliable basis for drawing conclusions regarding the real opportunities and constraints of AI application in the tax system of Bosnia and Herzegovina.

3. OVERVIEW OF THE TAX SYSTEM OF BOSNIA AND HERZEGOVINA

The tax system of Bosnia and Herzegovina represents a unique example of fiscal architecture that is simultaneously functional and restrictive, stable yet fragmented, legally defined yet operationally inconsistent. Its specificity stems from the constitutional structure of the state, as well as from a prolonged administrative development that has not followed a uniform trajectory across all levels of government. Consequently, this system cannot be analyzed through a conventional framework of a unified tax administration; instead, it requires a holistic approach, as each of its components exists at a different stage of institutional and digital maturity.

In international contexts, tax systems over recent decades have evolved into highly centralized, data-intensive mechanisms. In Bosnia and Herzegovina, however, taxpayer interaction with the state is divided among multiple administrative units that do not share a unified logic of record-keeping. This creates a paradox: although jurisdictions are formally well defined, the fiscal reality cannot be observed from a single point; it is dispersed, fragmented, and layered.

From this fragmentation arises the necessity to view the tax system of Bosnia and Herzegovina as a dynamic network of parallel structures rather than a unified whole. Each structure operates autonomously, yet their functions are deeply interdependent, creating an institutional environment in which even minor procedural differences can have multiplied effects on data quality, analytics, and oversight

3.1. The Indirect Taxation Authority of Bosnia and Herzegovina as a Pillar of Fiscal Stability

The Indirect Taxation Authority of Bosnia and Herzegovina (ITA BiH) represents the most centralized and technically developed component of the fiscal system. Its database functions as a unified information system, enabling the monitoring, recording, and analysis of value added tax, excise duties, and customs revenues in a manner that is not achievable within the remainder of the tax structure.

The ITA demonstrates that it is possible to establish a high-quality, standardized system in Bosnia and Herzegovina, while simultaneously revealing its inherent limitation: its jurisdiction is confined exclusively to indirect taxes. Key fiscal information that should ideally be available within a single fiscal center such as income tax, corporate profit tax, social security contributions, real estate transfer taxes, and records of sole proprietors remains outside its competence.

As a consequence, the state level provides a clear and comprehensive overview of indirect tax flows, but not of the taxpayer's overall fiscal position. From the perspective of advanced AI applications, this implies that constructing a complete risk profile is not feasible, as a taxpayer may appear fully compliant within the VAT system while simultaneously exhibiting significant irregularities in income tax or contribution obligations in segments that fall under the jurisdiction of entity-level tax administrations.

3.2. Entity and District Tax Administrations: Institutional Diversity within the Fiscal System

The Tax Administration of the Federation of Bosnia and Herzegovina, the Tax Administration of Republika Srpska, and the Tax Administration of the Brčko District constitute the second, substantially more complex layer of the tax system. Each authority administers direct taxes, but does so based on its own software solutions, by-laws, reporting formats, and operational protocols.

Although all three administrations formally apply the same fundamental principles of taxation, differences in data collection procedures, coding structures, and internal processing are so pronounced that the same taxpayer may effectively appear as a “different fiscal entity” depending on which administration maintains the records. For example:

- In one administration, a change of address is automatically linked to the taxpayer identification number;
- In another, the change is recorded only at the level of the tax card;
- In a third, it is entered manually and may remain inconsistent for years.

Due to such discrepancies, the data are not merely incompatible; they cannot be systematically compared or merged without prior cleansing, transformation, and standardization. In practice, this means that no domestic institution possesses a unified historical record of taxpayer behavior, which represents a fundamental prerequisite for the development of machine learning models.

3.3. The Taxpayer as "Four Administrative Entities"

From a systemic perspective, a single taxpayer in Bosnia and Herzegovina simultaneously exists within:

- The ITA BiH – for indirect taxes;
- the Tax Administration of the Federation of BiH – for direct taxes within the Federation;
- The Tax Administration of Republika Srpska – for direct taxes within Republika Srpska;
- The Tax Administration of the Brčko District – for direct taxes within the Brčko District.

Each of these institutions maintains separate records, characterized by different data depths, fields, validation rules, and storage methods. When this is combined with the fact that:

- Portions of records are still maintained manually;
- Many corrections are entered retroactively;
- There is no automated exchange of information between levels of government;

the result is a tax system that is not fragmented by accident, but is institutionally multilayered and operationally divergent.

For AI model development, this represents one of the most significant obstacles: an algorithm cannot be reliable if the foundation on which it operates is not consistent, continuous, and standardized.

3.4. Digital Asymmetry as a Source of Systemic Constraints

The level of digital maturity among tax administrations in Bosnia and Herzegovina ranges from relatively modernized segments (such as the ITA) to systems that continue to operate on semi-digital foundations. Documents that are automatically retrieved from registries in advanced administrations are often, in Bosnia and Herzegovina:

- Manually transcribed;
- Scanned as PDF files;
- Transmitted via e-mail as unstructured data;
- Entered through web forms lacking validation mechanisms.

Such operational practices generate three direct consequences:

- Data cannot be automatically analyzed;
- Stable data lineage cannot be established;
- Risk analyses exhibit a high error rate due to unclean inputs.

AI systems are highly sensitive to data quality. While they can handle large volumes of information, they cannot compensate for a high degree of inconsistency.

3.5. The Human Factor and Procedural Variability

Despite frequent references to digitalization, the essence of tax practice in Bosnia and Herzegovina continues to rest on the tax officer as the central interpreter of regulations. The human factor represents both the strength and the weakness of the system:

- A strength, because an experienced officer can identify anomalies that systems may overlook;
- A weakness, because subjective judgment produces inconsistent outcomes.

In practice, four officers may reach four different interpretations of the same legal provision, depending on experience, prior cases, or even internal guidelines applicable only to a specific organizational unit.

For artificial intelligence, this means that the algorithm does not inherit a “rule,” but rather a “variation of the rule.” Without a unified standard of procedure, AI cannot construct a predictable decision-making model.

3.6. Why These Factors Define the Scope of Artificial Intelligence

The weaknesses described above do not represent barriers to digitalization; they constitute the reality from which digitalization must begin. The application of AI is not a question of technological capability, but of institutional readiness. AI can:

- Analyze data;
- Identify patterns;
- Detect irregularities;
- Enhance transparency.

However, AI cannot:

- Replace fragmented data foundations;
- Create standards where institutions have not established them;
- Compensate for inconsistent practices;
- Build inter-institutional connections that are not provided for by law.

Bosnia and Herzegovina therefore stands between two points: the technical possibility of implementing AI and the institutional constraints that define its effective reach.

This leads to the central thesis of this chapter:

AI will not improve the tax system of Bosnia and Herzegovina on its own but it can become the most reliable diagnostic tool for understanding its weaknesses and a guide for future modernization.

4. CASE STUDY: AI POREZNIK AS A DOMESTIC RESPONSE TO GLOBAL CHALLENGES

The third methodological component of this study is a case study based on a detailed analysis of the domestic model **"AI Poreznik."** In this section, the focus is not on the promotion of a technological solution, but on understanding its architecture and its capacity to function under the real conditions of the tax system of Bosnia and Herzegovina.

The analysis covers the following elements:

- The structural design of the model and the manner in which tax regulations are processed;
- The types of queries the system is capable of analyzing;
- The accuracy of responses in relation to applicable laws and administrative practice;
- Limitations arising from fragmented institutional jurisdictions;
- The potential application of the model as an assistive tool for tax officers and tax professionals.

This case study serves as a practical illustration of how intelligent systems may operate within the Bosnian and Herzegovinian context, while simultaneously demonstrating that domestically developed solutions possess the capacity to address highly specific regulatory challenges.

Beyond its technical characteristics, the case study enables an assessment of the actual feasibility of implementing algorithmic solutions within an administratively complex system such as that of Bosnia and Herzegovina. In this sense, the model is not viewed merely as a technological demonstration, but as an analytical instrument for identifying barriers, opportunities, and the conditions under which similar systems could be integrated into the institutional framework of tax administrations.

5. APPLICATION OF ARTIFICIAL INTELLIGENCE IN THE TAX ADMINISTRATIONS OF EU AND OECD COUNTRIES

The digital transformation of tax administrations in European Union and OECD countries represents one of the central processes of contemporary public governance. This transformation does not involve the mere introduction of new technologies, but a fundamental change in the way fiscal institutions collect, integrate, and analyze data, as well as in how administrative and supervisory decisions are made. Within this context, the development of artificial intelligence constitutes a logical continuation of reforms initiated when traditional oversight models —based on partial inspections and ex post controls— proved insufficient in relation to the dynamics of modern economic activity.

Experience from OECD tax administrations shows that the application of artificial intelligence is built upon two core prerequisites: standardized and reliable data, and advanced analytical capacities. In such systems, tax returns no longer represent the primary source of information, but rather one element within a broader fiscal ecosystem. Data are automatically linked, analytics assume a central role in risk identification, and the human factor intervenes primarily at the stage of expert assessment and decision-making. Oversight is no longer based on isolated actions, but on continuous monitoring of behavioral patterns. The OECD emphasizes that successful AI implementation in tax administrations is contingent upon institutional clarity and a high level of data standardization (OECD, 2023).

In contrast, the tax administration of Bosnia and Herzegovina faces constraints arising from a fragmented institutional structure and uneven levels of digital maturity. While administrations such as those in Estonia or the Netherlands apply highly automated analytics based on unified registries, Bosnia and Herzegovina continues to rely on parallel records, heterogeneous data formats, and limited interoperability among institutions. These differences are not merely technical challenges, but reflect deeper institutional preconditions without which the full application of AI models is not feasible.

It is important to emphasize that artificial intelligence in tax administrations does not function as a substitute for administrative reform, but rather as its catalyst. AI systems cannot compensate for inconsistent regulations or misaligned registries; however, they can clearly indicate where the system loses coherence and where structural interventions are required. This constitutes their comparative value, particularly in administrations that remain at an earlier stage of digital transformation.

Institutional capacity to absorb artificial intelligence defines the boundary of its effectiveness. In advanced tax systems, this capacity includes standardized registries, clear identifiers, interoperable databases, a stable normative framework, and trained personnel capable of understanding data-driven logic. In the context of Bosnia and Herzegovina, the absence of some of these prerequisites does not preclude the application of AI, but necessitates a gradual and controlled approach, adapted to existing institutional capabilities.

Under current conditions, artificial intelligence can be effectively applied in regulatory analysis and case law review, preliminary legal interpretation, document classification, compliance verification, and the identification of anomalies in taxpayer behavior. More complex applications such as systemic risk assessment or automated decision-making remain constrained until a unified fiscal infrastructure is established.

The experience of EU and OECD countries confirms that digital transformation of tax administrations is fundamentally an institutional rather than a technological process. Artificial intelligence can accelerate and deepen reform efforts, but their sustainability depends on the system's ability to develop reliable data foundations and cultivate a culture of analysis-based decision-making. In this sense, AI does not represent the final objective of reform, but rather an instrument of its gradual and measurable advancement.

6. MODEL FOR IMPLEMENTING ARTIFICIAL INTELLIGENCE IN THE TAX SYSTEMS OF BOSNIA AND HERZEGOVINA

The development of artificial intelligence in tax administrations raises the question of institutional readiness to adopt a technology that fundamentally alters the processing and interpretation of data. In advanced tax systems, AI is built upon stable digital infrastructures, whereas in Bosnia and Herzegovina it is introduced under conditions of fragmented records, inconsistent procedures, and varying levels of technological maturity. Within this context, artificial intelligence represents not only a technological innovation, but also a mechanism that exposes structural weaknesses within the system and highlights the need for their gradual resolution.

The value of artificial intelligence lies in its capacity to identify patterns, irregularities, and deviations that remain invisible in traditional administrative procedures. In doing so, AI assists institutions in gaining insight into their own processes, particularly in areas where the absence of standards is compensated by individual judgment. However, compared to systems equipped with unified fiscal registries, the tax administration of Bosnia and Herzegovina faces a fundamental limitation: data instability and inconsistency. AI can analyze large volumes of information, but it cannot compensate for outdated records or divergent administrative approaches, making standardization an institutional rather than a technical obligation.

The application of AI also alters the role of tax officers, whose work gradually shifts from operational tasks toward analytical interpretation of data and decision-making based on a combination of professional expertise and algorithmic findings. At the same time, AI can improve the relationship between tax administrations and taxpayers, as earlier identification of irregularities reduces oversight costs and contributes to greater predictability and trust in the system.

Ultimately, the scope of AI implementation in Bosnia and Herzegovina depends not on algorithmic complexity, but on the willingness of institutions to develop standardized, interoperable, and reliable data foundations. Only with strengthened institutional capacities can artificial intelligence become an integral component of tax administration, serving as a foundation for a more modern and transparent decision-making system.

7. ANALYTICAL INTERPRETATION OF THE CASE STUDY AND INSTITUTIONAL IMPLICATIONS

The application of artificial intelligence within the tax system of Bosnia and Herzegovina enables a renewed understanding of how institutions operate within a fragmented fiscal reality. Unlike traditional administrative models, AI introduces an analytical logic based on data integration and pattern recognition across structures that are, in practice, separated by levels of authority and procedural boundaries. In this sense, artificial intelligence does not represent a technical add-on, but rather a new approach to understanding the existing system.

AI functions as an analytical layer that enhances the visibility and consistency of institutional information flows. In a system that relies heavily on human judgment and informal knowledge, such an approach enables the identification of irregularities arising from misaligned records, divergent interpretations of regulations, and procedural limitations—rather than from intentional non-compliance.

The use of AI also reshapes how tax administrations perceive risk and compliance. Algorithmic analysis of a large number of variables enables the detection of patterns that remain invisible in manual processing, clearly distinguishing between consistent procedures and those based on improvisation. In this respect, AI does not replace institutions; instead, it provides them with a tool for systematically identifying internal weaknesses and governance challenges.

The application of artificial intelligence is particularly significant for improving the relationship between tax administrations and taxpayers. Earlier detection of irregularities reduces the scope for subjective interpretation, enhances procedural transparency, and contributes to increased trust in fiscal institutions. At the same time, clearer interpretation of tax regulations narrows the gap between the normative framework and administrative practice—an especially important factor in systems characterized by legal uncertainty.

In a broader context, AI facilitates a gradual transition from a model based on documents and experiential knowledge to one grounded in structured data. In Bosnia and Herzegovina, this process is only beginning and requires the standardization of registries, clearer information flows, and institutional readiness to accept data-driven analysis as the foundation for decision-making. The key conclusion is that artificial intelligence within the tax administration of Bosnia and Herzegovina does not represent a sudden transformation, but rather an instrument of gradual change that strengthens the system's capacity to deliver more consistent, fair, and efficient decisions.

8. DISCUSSION

An examination of the application of artificial intelligence in the tax system of Bosnia and Herzegovina indicates that the primary limitations of this technology stem from the institutional and normative framework rather than from its technical capabilities. Under current conditions, the central challenge lies in data quality and consistency, as a significant portion of administrative records continues to rely on practices developed in an analog environment. Inconsistent formats, partial databases, and the absence of interoperability across levels of government directly constrain the development of reliable analytical models.

An additional source of limitation is found in the normative structure of the tax system. Regulations have evolved incrementally and without a unified digital concept, resulting in ambiguous provisions and divergent interpretations in practice. In such an environment, artificial intelligence cannot overcome normative indeterminacy; it can only reproduce existing interpretative patterns. This confirms that technological solutions cannot substitute for the need for regulatory harmonization and legal clarity.

Cultural and organizational factors further influence the scope of AI implementation. Administrative practice in Bosnia and Herzegovina relies heavily on the experience of tax officers and flexible, often informal procedural rules. By contrast, algorithmic systems require standardization, consistency, and verifiability. This disparity generates resistance to full analytical integration and demonstrates that digital transformation entails a change in institutional culture, not merely the adoption of new technologies.

A particularly significant limitation is the shortage of specialized personnel who simultaneously understand tax regulations, administrative processes, and analytical methodologies. While technical solutions may be available, their effective application remains partial without an adequate professional framework.

Nevertheless, these limitations should not be viewed solely as obstacles. They provide an analytical basis for understanding the system's actual capacities and indicate areas where standardization and institutional strengthening are essential. In this context, artificial intelligence currently delivers its greatest value as a diagnostic and analytical tool, rather than as a mechanism for automated decision-making.

The discussion confirms that successful AI implementation in the tax administrations of Bosnia and Herzegovina depends on the parallel development of data infrastructure, normative clarity, and professional competencies. Only within such a framework can artificial intelligence evolve from a supportive analytical instrument into a genuine driver of institutional modernization.

CONCLUSION

The application of artificial intelligence in tax administrations demonstrates that this process extends beyond technological innovation into the realm of institutional design. The analysis confirms that the effectiveness of AI solutions depends on data quality, regulatory clarity, and administrative coordination. In Bosnia and Herzegovina, where the tax system is fragmented and digital infrastructure unevenly developed, AI can currently deliver its greatest contribution through data analysis, deviation detection, and improved consistency in regulatory interpretation.

The case study of the “AI Poreznik” model shows that it is possible to enhance the standardization of tax regulation interpretation even within an institutionally complex system such as Bosnia and Herzegovina. This creates a foundation for a more predictable tax environment and greater transparency in public revenues. Nevertheless, the scope of AI application remains constrained by existing records and the normative framework, as algorithms cannot achieve their full potential without accurate and harmonized registries.

The research findings indicate that the digital transformation of tax administrations in Bosnia and Herzegovina must simultaneously be a technological and an institutional process. Artificial intelligence does not replace the professional judgment of tax officers, but complements it, requiring clearly defined procedures for the use of analytical recommendations and continuous development of professional capacities. Only through changes in work practices, information flows, and risk management approaches can artificial intelligence become a foundation for a modern and efficient tax administration.

- Based on the conducted research, three priorities for the sustainable integration of artificial intelligence into the tax administrations of Bosnia and Herzegovina have been identified:
- Standardization and consolidation of tax registries;
- Introduction of unified identifiers and interoperable information systems
- Strengthening analytical and digital competencies within tax administrations.

These priorities constitute an institutional roadmap for the gradual and measurable modernization of the tax system in alignment with international best practices.

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CONTEMPORARY STRUCTURES IN THE ERA OF DIGITAL AND SUSTAINABLE CONSTRUCTION

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Review article
https://doi.org/10.58952/nit20251302081
***UDC* 624.042.7:624.04:69.04**

Abstract

Digitalization of design, growing sustainability requirements and the growing need for functional resilience of buildings after earthquakes are changing the paradigm of modern construction. This paper provides a critical overview of modern seismically resistant structural systems (frame systems, wall/core systems, dual systems, additional energy dissipation systems and basic seismic isolation), with a mathematical foundation of basic principles (spectral calculation, control of interfloor displacements, energy dissipation and effective attenuation). The analysis is complemented by five representative case studies from recent practice: (i) Başakşehir Çam & Sakura City Hospital (Istanbul) – large-scale base isolation, (ii) Apple Park (Cupertino) – base isolation of a large corporate campus, (iii) SFO International Terminal (San Francisco) – an early example of a friction pendulum, (iv) Tokyo Skytree (Tokyo) – a central pillared vibration control system inspired by the concept of "shinbashir", and (v) Wilshire Grand Center (Los Angeles) – a high-rise building with Stiffening System and Dissipative Elements (BRB). A comparative table of performance, key technologies and project frameworks is provided, as well as a critical discussion in the context of Eurocode 8 and ASCE 7/41. In conclusion, an integrated framework for performance-based design with BIM/digital twin and LCA metrics is proposed, with a focus on preserving the functionality of buildings and reducing overall lifecycle losses.

Keywords: *seismically resistant structure, ram constructive systems, basic seismic isolation, energy dissipation, performance design, BIM; digital twin, Eurocode 8, ASCE 7, sustainability.*

JEL classification: P01, P56, O33, L74, R33

1. INTRODUCTION

Modern construction is at a turning point in its development, conditioned by the simultaneous action of accelerated urbanization, climate change, increasingly stringent requirements in terms of sustainability and intensive digital transformation of engineering practice [10, 21]. In this context, the design and implementation of seismically resistant structures occupy a central place, especially in regions with pronounced seismic activity, because earthquakes dominate the risk of sudden collapse and large indirect losses. A modern approach to seismic safety goes beyond minimal collapse prevention and includes damage control, preservation of functionality (e.g., hospitals, airports, management centers), reduction of economic losses, and accelerated community recovery [5, 12].

The concept of performance-based design (PBSD) relies on nonlinear analysis and clearly defined objectives (drift, plastic rotations, damage to non-load-bearing elements), applying the principles of capacitive design and detailing for ductile behavior [7, 17, 18]. At the same time, the development of numerical methods (FEM) and nonlinear dynamics algorithms has allowed for more realistic modeling of stiffness and strength degradation, cyclic behavior, and cumulative damage [3, 9]. The connection of BIM, digital twins and SHM systems enables the closing of the loop between the project, the as-built state and the exploitation, which is especially important for critical infrastructure facilities [4, 10].

The aim of this paper is to systematize modern seismically resistant constructive systems, mathematical and engineering foundation of basic response parameters, processing of five case studies from recent practice and critical linking with Eurocode 8 and ASCE 7/41 for the transferability of conclusions.

The paper is based on an analytical-synthetic review of literature and project practice. For case studies, publicly available technical descriptions and expert reviews of investors, designers and relevant professional publications (e.g. ENR, SOM), as well as expert reviews on specific systems (e.g. base insulation, BRB, vibration control) were used. The comparison was made through: system type, performance targets, dominant energy dissipation mechanisms, expected drift/acceleration reduction, execution complexity, and compatibility with Eurocode 8 and ASCE frameworks.

2. MODERN SEISMIC RESISTANT STRUCTURAL SYSTEMS

The design of seismically resistant structures in modern engineering practice is based on a clearly defined hierarchy of load-bearing capacity, control of fracture mechanisms and rational management of seismic energy (Figure 1). Unlike traditional approaches, which mainly relied on increasing rigidity and strength, modern systems tend to optimize ductility, energy dissipation, and controlled damage to load-bearing elements [7, 17, 18].

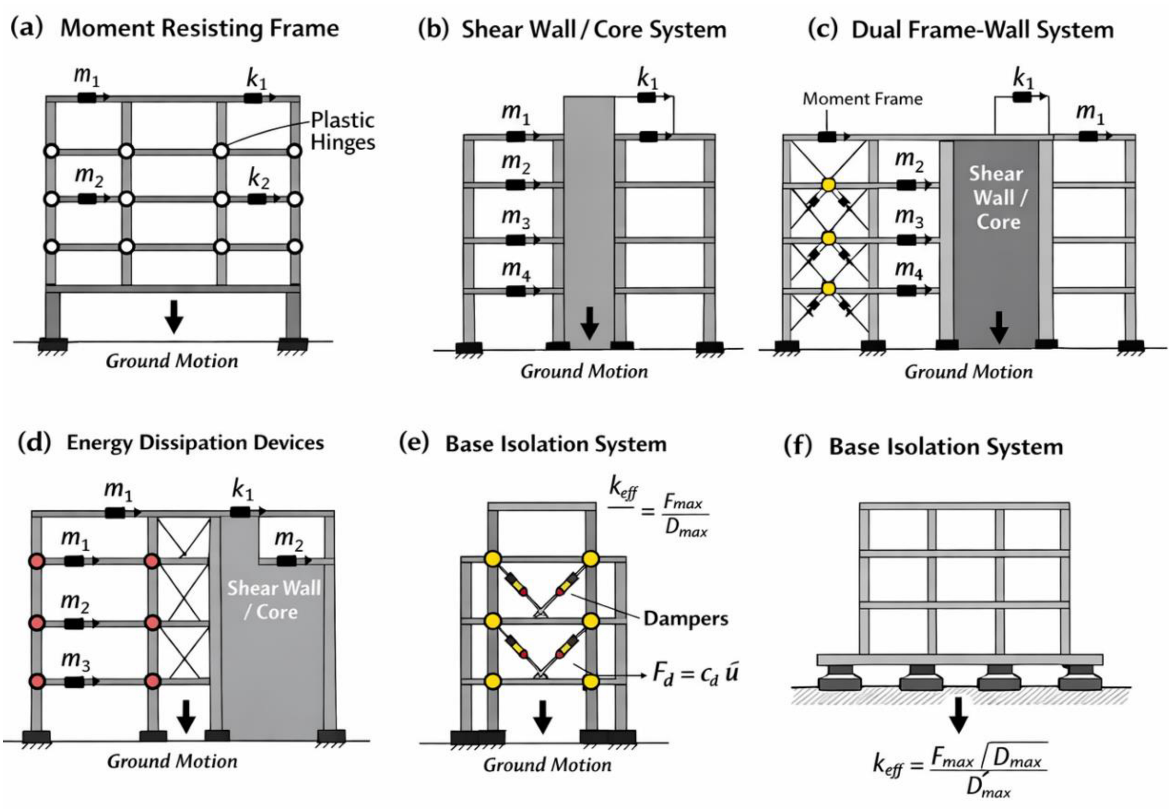

Figure 1: *Seismic-Resistant Structural Systems*

2.1. Ram (ram) constructive systems

Structural frame systems (Figure 1a), especially reinforced concrete and steel frames, continue to be the basis of seismic design in a large number of buildings. Their seismic resistance is based on the formation of plastic joints in predefined zones, whereby the energy of the earthquake is dissipated through the hysteresis behavior of the material [5, 16]. Modern approaches insist on the principle of "strong pillar – weak beam", which provides a stable mechanism of behavior and prevents progressive collapse [11, 17, 18].

Advances in numerical modeling have made it possible to accurately simulate the nonlinear behavior of frame systems, including stiffness and strength degradation, as well as cumulative damage due to cyclic loading [3, 7, 9]. Particular attention is paid to the detailing of nodes, which represent critical zones from the point of view of seismic reliability [1, 5].

Figure 1a shows a classic frame system (torque frame) without walls/stiffeners, where columns and beams are connected to transmit torques.

- *m_1, m_2:* a lot of floors.
- *k_1, k_2:* floor stiffness (the sum of the stiffness of the columns and frame fields).
- *Plastic Hinges:* marked zones where plasticity is intentionally expected (usually in beams at the ends), as part of capacity design ("strong column-weak beam").

MRF achieves seismic resistance through ductility and hysteresis energy dissipation in plastic joints. The advantage is the robustness and distribution of damage, and the disadvantage is the relatively higher drift if there is not enough stiffness.

2.2. Stiffening walls and core

Stiffening walls, whether in the form of classical seismic walls or central cores, play a key role in controlling horizontal displacements and limiting interfloor displacements [17, 18]. In modern multi-storey buildings, these elements are often

combined with frame systems, thereby forming the so-called dual systems [2, 11].
Modern research points to the importance of proper arrangement of walls in the floor plan, in order to minimize torsional effects and uneven seismic behavior [7, 34]. Particular attention is paid to the nonlinear behavior of the walls, the appearance of sliding and bending fracture mechanisms, as well as the interaction with the foundation structure [18, 35].
Figure 1b shows the dominance of the reinforced concrete wall/core as the main lateral resistance.

- The wall/core significantly increases the K (lateral stiffness).
- I've got a lot of stiffness and stiffness that is now "under control" of the wall.

The system gives high rigidity → less drift, but requires attention to:

- layout in the floor plan (torsion),
- nonlinear wall mechanisms (bending/sliding shear),
- interaction between the foundation and the wall.

2.3. Dual Systems and Hybrid Solutions

Dual systems are a combination of framework systems and stiffening walls, with both subsystems actively participating in the assumption of seismic effects. Such solutions allow for optimal distribution of internal forces, increased redundancy and a higher level of seismic reliability [2, 11, 36].
Hybrid solutions, which include a combination of different materials (reinforced concrete-steel, steel-wood), are increasingly being used in modern construction. Their advantage is reflected in the ability to adjust the seismic response of the structure, while improving sustainability and reducing the mass of the object [20, 32].
Figure 1c shows the combination:

- frames (distributed ductility and redundancy),
- wall/core (stiffness and drift control).

In the panel, you can see the Shear Wall/Core as the central rigid element + frames with stiffeners.
The dual system is often the "golden mean":

- the wall carries a large part of the lateral shear and controls the drift,
- RAM contributes to ductility and redistribution of forces.

It is important to properly "adjust" the ratio of stiffness and load-bearing capacity (so that one subsystem does not "suffocate" the other or does not take over everything).

2.4. Energy dissipation systems

Systems with additional energy dissipation are one of the most important innovations in the field of seismic engineering. These systems include viscous, viscoelastic, and metal dampers, which are designed to absorb a significant portion of seismic energy and reduce the demands on the primary load-bearing elements [6, 19].
The application of energy dissipation systems enables the design of structures with reduced damage, which increases their functionality after earthquakes [12, 20, 32]. Modern approaches integrate these systems into digital models of structures, which allows them to be optimized in the early stages of design [33].
Figure 1d shows additional elements (dampers, metal fuse-zones, BRB, viscous dampers) that "subtract" the energy of the system.

- The red dots in the panel symbolize the locations of the dissipative elements.
- The essence is to increase **C** (effective attenuation) without a large increase in K.

Instead of wasting energy on damaging the primary elements, "sacrificial" or dissipative elements are introduced:

- Reduce drift and/or acceleration.
- They can be very suitable for repairs and extensions,
- It is possible to design for "low-damage" concepts.

2.5. Base seismic isolation

Baseline seismic isolation is one of the most effective approaches to protecting structures from earthquakes. By installing insulating elements between the structure and the ground, a significant reduction in the transmission of seismic forces is achieved, as well as an extension of the object's own oscillation period [3, 15].

Modern insulation systems, such as lead-rubber bearings and friction-controlled sliding insulators, provide high reliability and predictable behavior[]. These systems are particularly suitable for facilities of strategic importance, such as hospitals, bridges and critical infrastructure facilities [20, 32].

The development of basic insulation is closely related to advances in experimental research and numerical simulations, which allow detailed examination of the long-term behavior of insulating elements, including the impact of aging and repeated seismic events [8, 15].

Figure 1e shows the insulation at the foundation level that is changing global dynamics. Insulation increases the effective period of construction (T increases), reduces spectral accelerations in the superstructure, "displaces" most of the displacement to the insulation plane. That is why it is great for hospitals, terminals, bridges, critical infrastructure facilities.

Figure 1f shows the emphasis on the physical layer of the insulator. This panel is a "clean" representation of a building standing on insulators (bearings). Panel f serves as a visual "summary" of the insulation: the main constructive concept is the separation of the superstructure from the movement of the ground and the control of the transmission of forces.

2.6. Comparative analysis of the system

Eurocode 8 and ASCE 7 are clearly defined (Table 1):

- the hierarchy of load-bearing capacity,
- permissible deformities,
- requirements for ductility,
- I'm using isolation and dissipators.

The modern constructions presented in this paper are fully compliant with these standards, but also upgrade them with the use of digital technologies and sustainable materials.

Table 1: *Comparative analysis of the system*

System	Ductility	Cruelty	Damage	Cost	Standards
Ramovski	high	Medium	Controlled	Medium	EC8 / ASCE 7
Dual	high	high	small	Medium	EC8 / ASCE 7
Dissipation	very high	Medium	very small	Higher	FEMA
Base insulation	very high	Low	Minimum	high	EC8 / ASCE 7

3. DIGITAL TOOLS AND NUMERICAL MODELING OF SEISMIC BEHAVIOR

Modern structures are designed using BIM, nonlinear FEM analyses and digital twins. These tools make it possible to optimize structures in terms of weight, material consumption and seismic performance, which directly contributes to sustainability [33].

3.1. The Role of Digital Technologies in Seismic Design

Digital technologies are a key segment of the modern engineering approach to seismic design. The integration of advanced software tools enables engineers to analyze in detail the behavior of structures under seismic loading conditions, simulate complex interactions, and optimize structural solutions already in the conceptual design phases.

The use of Building Information Modeling (BIM) platforms enables the unification of geometric, material and functional data on the structure into a single digital model, which significantly improves the coordination of project teams and the accuracy of seismic analyses [10].

3.2. Numerical modelling methods

Although linear seismic analyses remain part of standard design practice due to their simplicity and lower computational requirements, their application is limited in structures subject to large deformations. Therefore, modern approaches rely on non-linear static (pushover) and dynamic analyses that allow more accurate prediction of the behavior of the structure in phases close to plastic fracture [38].
Nonlinear models include detailed modeling of material properties, degradation of stiffness and strength, as well as simulation of cyclic effects and cumulative damage [7].
The finite element method is a basic tool for simulating the seismic behavior of complex structures. Models can range in varying levels of complexity — from simplified macromodels for preliminary analyses to detailed micromodels involving material heterogeneity and complex contacts between elements [3].
The use of adaptive networks and parallel computational techniques allows for simulations of large models with high accuracy in a reasonable time frame.

3.3. BIM and digital twins

The integration of BIM technologies with seismic analysis enables the automatic exchange of data between building models and numerical software. This approach reduces data transfer errors, speeds up iterative design processes, and enables real-time visualization of deformation and failure [39].
Digital twins are dynamic digital representations of physical objects that are updated with data collected through sensors and structural health monitoring (SHM) systems. The application of digital twins in seismic engineering makes it possible to monitor the actual behavior of objects over time, predict potential damage, and make informed decisions about maintenance and repair [40].

3.4. Structural Health Monitoring (SHM) systems

SHM systems use sensors to measure vibration, displacement, and other parameters, allowing for continuous assessment of the condition of the structure. These systems are especially important for facilities exposed to frequent seismic events, where timely detection of damage can prevent catastrophic consequences [41].
The integration of SHM with digital twins and BIM platforms represents a promising direction in the development of smart and sustainable seismically resistant structures.

4. SUSTAINABLE ASPECTS AND LIFE CYCLE OF SEISMICALLY RESISTANT STRUCTURES

4.1. Sustainable construction in seismically active areas

The development of sustainable construction is one of the key challenges of modern engineering, especially in regions prone to seismic effects. Sustainable concepts include not only energy efficiency and the reduction of the carbon footprint during the construction phase, but also the long-term resilience and functionality of buildings [42].
Seismically resistant structures that successfully survive earthquakes have a direct impact on reducing the consumption of resources needed for rehabilitation and reconstruction, which contributes to the overall sustainability of the system. This promotes the concept of "resilience through sustainability," where the key goal is not only to survive a disaster, but also to quickly restore functionality [5].

4.2. Materials with a reduced environmental footprint

The use of materials with a low carbon footprint and high durability is one of the main directions of sustainable seismic design. These include:

- the use of recycled steel and concrete,
- application of innovative composite materials with fibers,
- development of concrete with the addition of industrial by-products (flyer, ash from thermal power plants),
- Research in the field of bio-based and carbon-neutral building materials [43].

These materials not only reduce greenhouse gas emissions, but often have better mechanical properties, which further contributes to seismic resistance.

4.3. Design for long service life and easy renewal

The design of seismically resistant structures should enable not only resistance to the immediate consequences of earthquakes, but also simple and fast restoration and maintenance procedures. This includes:

- modular structural elements with easily replaceable parts,
- design approaches with the possibility of repositioning or adapting the energy dissipation system,
- Implementation of structural health monitoring systems that enable timely identification of damage and planning of interventions.

This approach contributes to the reduction of overall maintenance costs throughout the life cycle of the building and increases its economic and environmental sustainability.

4.4. Life Cycle Assessment (LCA) and Seismic Resistance

Life Cycle Assessment (LCA) is a quantitative tool for evaluating the environmental impacts of buildings throughout their life cycle, including the stages of construction, exploitation, rehabilitation and recycling.

The integration of LCA with performance-based seismic design allows for design optimization not only in terms of safety and functionality, but also in terms of minimizing negative environmental effects [44]. This represents a new direction in research, where design is done through a holistic approach to sustainability.

4.5. Examples of good practice and standards

Standards and recommendations for sustainable seismic design increasingly include requirements to reduce the environmental footprint and increase the resilience of buildings. Examples of such documents are:

- Eurocode 8 in combination with EN 15804 (standard for LCA of construction products),
- FEMA P-58 (USA) that integrates performance and life cycle,
- Sustainability Assessment Frameworks in Earthquake-Prone Areas Developed in Pacific Countries.

The implementation of these standards in practice significantly contributes to the integration of safety and sustainability, which is the foundation of modern seismic construction.

5. CASE STUDIES OF MODERN SEISMICALLY RESISTANT STRUCTURES

5.1. Taipei 101 (Taiwan) – frame system with TMD

The Taipei 101 skyscraper is one of the most famous examples of the integration of frame systems and vibration control systems. The structure uses a massive TMD (tuned mass damper) weighing about 660 tons, which significantly reduces seismic and wind oscillations. This system makes it possible to preserve the usability of the building even during strong earthquakes [20].

The Taipei 101 uses one of the most famous tuned mass damper (TMD) systems in the world (weight ≈ 660 t), located at the top of the facility. The structure is a combination of steel frames and reinforced concrete cores.

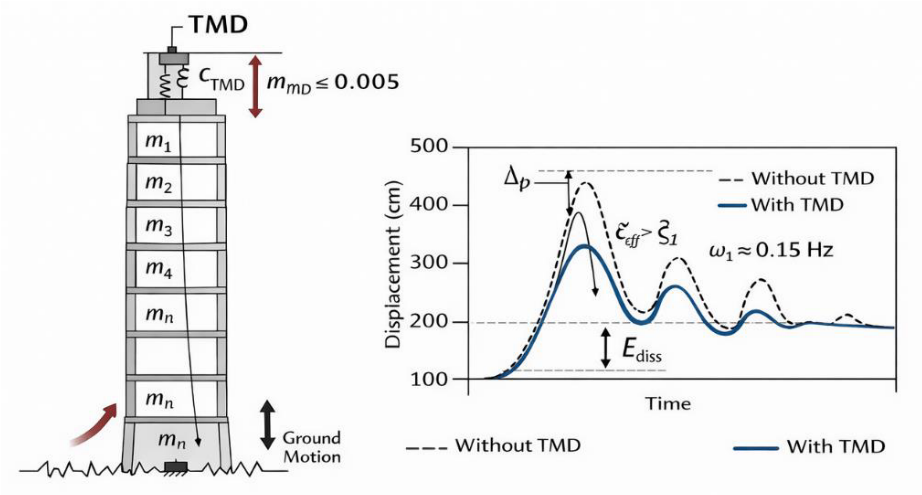

Figure 2: *Idealized dynamic model of the Taipei 101 skyscraper*

Figure 2 shows an idealized dynamic model of the Taipei 101 skyscraper, designed as a frame (torque-resistant) structural system with an additional vibration control system - a tuned mass damper (TMD), located on top of the object. TMD does not significantly change the payload capacity of the system, but it does drastically reduce the dynamic response, especially in long-term excitations.

The left side of Figure 2 shows a building modeled as a multi-stage system with discrete masses:

- The masses m_1, m_2, ..., mn represent the effective masses of the individual floors,
- interfloor stiffness (implicitly) comes from a frame system with rigidly bonded beams and columns, which provides resistance to bending and shearing,
- The seismic effect is shown as ground motion, which induces inertial forces in the masses of the floors.

This representation corresponds to the MDOF (multi-degree-of-freedom) model, standard in seismic dynamics of structures.

The right side of Figure 2 shows the comparative time response of the movement of the top of the building.

5.2. Seismically Resistant Buildings in Japan

Japan is one of the most active seismic areas in the world and is an example of cutting-edge engineering expertise in the field of seismically resistant design. Buildings in urban centers such as Tokyo and Osaka are designed using advanced construction systems that integrate:

- Base seismic insulation with rubber-lead bearings that reduce force transmission by up to 70% [45],
- high ductile steel frames with dissipative connections,
- Sophisticated vibration control systems that include active and passive dampers.

In addition to technical solutions, Japan uses developed digital tools and SHM systems to monitor the condition of objects in real time, enabling timely assessment of safety after the earthquake [46].

5.2.1. Tokyo Skytree (Tokyo) – central column vibration control system (shinbashira concept)

Tokyo Skytree integrates a vibration control system inspired by traditional pagodas ("shinbashira"), where the central pillar and outer frame oscillate with different phases, effectively reducing global response. Expert descriptions state that the concept can significantly reduce wobble (e.g., up to ~50% in certain regimes) [25]. Although it is primarily a vibration control system, it conceptually belongs to the class of "response modification systems" that are complementary to capacitive design.

Figure 3 clearly demonstrates that the Tokyo Skytree uses an advanced seismic concept based on the interaction of two dynamically distinct systems, with the central pillar acting as:

- internal mass damper,
- system for the redistribution of seismic energy,
- and a key element in reducing the global response.

This approach is a prime example of modern seismic engineering, with strong potential for application in future super-tall structures.

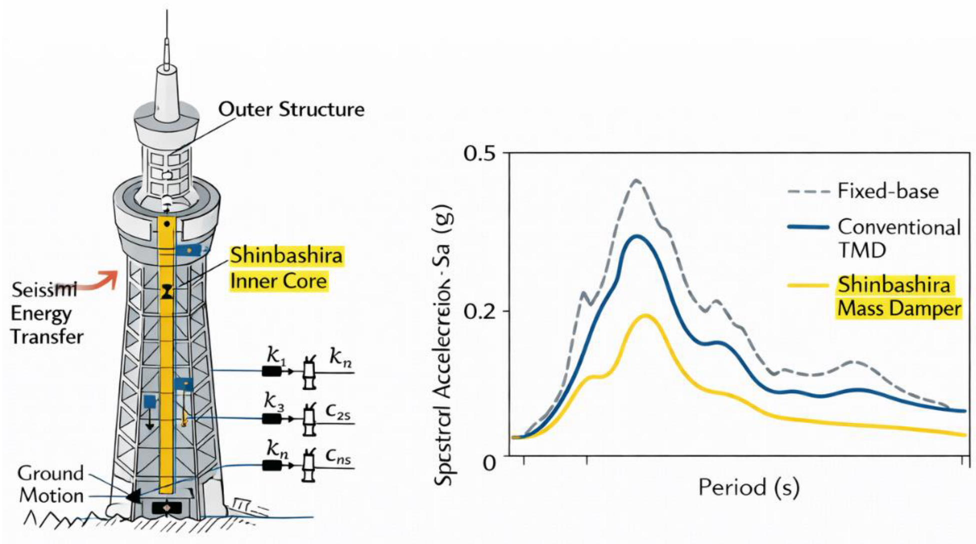

Figure 3: *Seismic performance of Tokyo Skytree utilizing a central mass damper (shinbashira)*

Figure 3 shows the constructive-dynamic concept of the Tokyo Skytree, based on a central column vibration control system, known as *the shinbashira* concept, which originates from traditional Japanese wooden architecture (pagodas). Left part of Figure 3 (constructive and dynamic model) - The tower's outer structure (designated as *the Outer Structure*) represents the main load-bearing system of the steel frame-truss type, which takes on vertical loads and part of the seismic forces. In its interior there is a central pillar – shinbashira, clearly marked and highlighted in yellow (*Shinbashira Inner Core*).

The graph on the right side of Figure 3 shows *the Spectral Acceleration (Sa)* spectra as a function of the oscillation period for three cases: Fixed-base (dashed line), Conventional TMD (blue line) and Shinbashira Mass Damper (yellow line). The Shinbashira concept reduces maximum acceleration, works efficiently in multiple oscillation modes, and provides more robust behavior compared to classic TMD systems.

5.2.2. Sendai Mediatheque (Japan) — Innovative Ram System

The facility uses a unique spatial frame system with large-diameter steel pipes, enabling exceptional ductility and energy dissipation. This example illustrates the combination of architectural freedom and seismic safety.

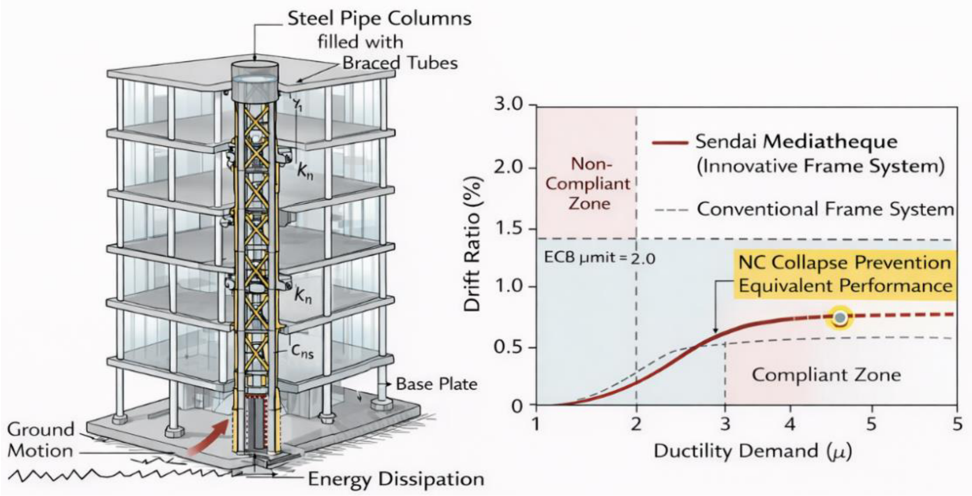

Figure 4: *Sendai Mediatheque – an innovative frame system*

The essence of Figure 4 is that Sendai Mediatheque is an example of an unconventional but high-ductile frame system, where the load-bearing elements are also energy dissipators. This approach shows how architectural freedom and high seismic capacity can be integrated into a single structural solution, in accordance with the modern principles of performance-based design.

5.3. Friction Pendulum, Dissipative Stiffening and Base Insulation in the USA

California faces a constant threat of powerful earthquakes, so seismic reinforcement measures are key to keeping existing structures safe. Renovation projects include:

- installation of base insulators in old reinforced concrete buildings,
- implementation of metal frames for energy dissipation in combination with original structures,
- Digital monitoring of the performance of reconstructed objects.

An example of a successful renovation is the San Francisco School Complex, where a combination of seismic isolation and SHM was used, significantly increasing the safety of children and faculty [47].

5.3.1. SFO International Terminal (San Francisco) – steel ball isolators

The San Francisco International Terminal is a classic example of base insulation in public infrastructure, with insulators that allow the superstructure to slide/swing independently of the ground. Expert reviews list 267 steel insulators (steel ball / friction pendulum concept), with a conceptual reduction of seismic forces of approximately ~70% compared to the fixed foundation [14, 22-24].

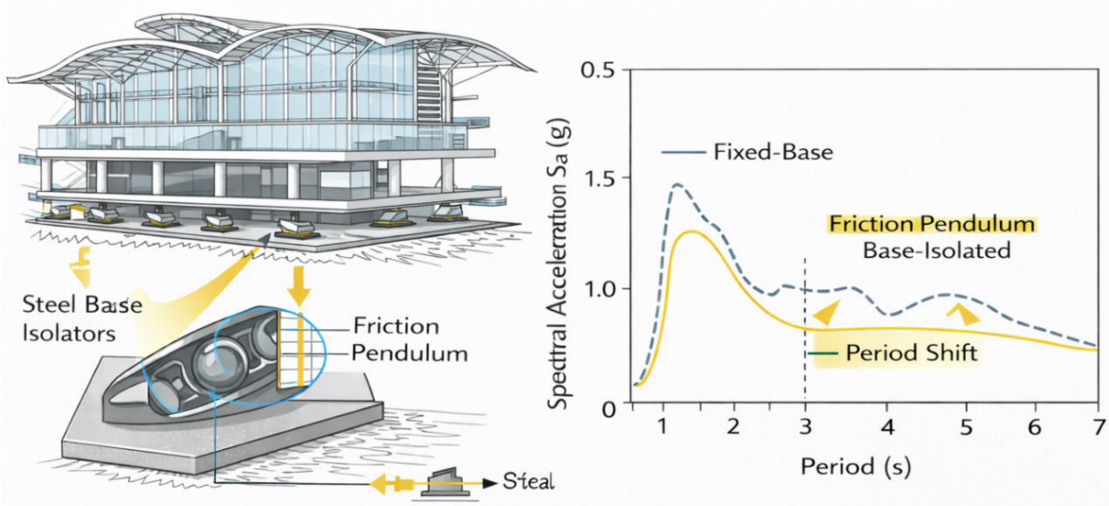

***Figure 5:** SFO International Terminal (San Francisco) – steel ball isolators*

The left part of Figure 5 shows an airport terminal that is base-insulated by steel ball/friction pendulum insulators placed between the superstructure and the foundation. Insulators allow the superstructure to move and slide over a curved surface in a controlled manner during an earthquake, whereby seismic energy is dissipated by friction. This achieves a separation of the movement of the ground and the structure, so the seismic forces acting on the object are significantly reduced. The bottom detail shows the principle of operation of the insulator: a steel pendulum ball moves along the concave surface and automatically returns the structure to its starting position.

The right-hand diagram (response spectrum) compares a fixed-based object (higher spectral accelerations) and a base-isolated object (lower accelerations). The key effect is the "period shift" – the extension of its own oscillation period, which moves the object to a more favorable part of the seismic spectrum.

Base insulation with a friction pendulum enables a drastic reduction of seismic forces and damage, which is crucial for the functionality of the airport after an earthquake and makes this facility one of the reference examples of modern seismic protection in the world.

5.3.2. Wilshire Grand Center (Los Angeles) – high-rise building with dissipative stiffening (BRB)

The Wilshire Grand Center is an example of a high-rise building designed for high seismic exposure, with the use of stiffening systems and dissipative elements (Figure 6). Expert reviews indicate the use of buckling-restrained braces (BRBs) in significant numbers (e.g., hundreds of pieces), thus providing stable hysteresis energy dissipation and drift control [28, 29]. This concept is compatible with the PBSD approach that is common in high-rise buildings on the West Coast.

Construction concept: The high-rise building uses BRB type steel dissipative couplings embedded in the core and peripheral frame, thus ensuring high ductility and stable behavior under cyclic seismic loading.

BRBs are designed to equally carry tension and pressure without buckling, allowing for reproducible hysteresis behavior and efficient dissipation of seismic energy.

Seismic forces are taken over the frames and cores, and plastic deformation is intentionally localized in the BRB elements, while the primary load-bearing elements are protected.

Graphical representation (right): The diagram shows that the system with BRB achieves less interfloor drift for the same level of ductility compared to conventional couplings, while meeting the Collapse Prevention (CP) criteria according to modern standards.

Engineering significance: This system is a typical example of performance-based design (PBSD) for high-rise buildings in zones of high seismicity and is in line with ASCE7/ASCE41 practice, and conceptually with dissipative systems in Eurocode 8.

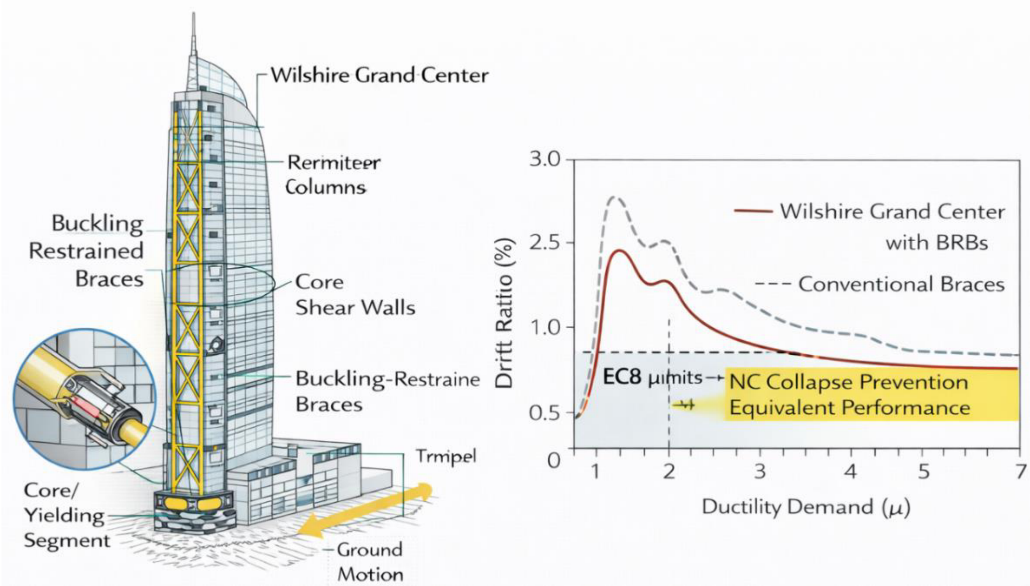

***Figure 6:** Wilshire Grand Center (Los Angeles) – tall building with dissipative stiffening (BRB)*

5.3.3. Apple Park (Cupertino) – base isolation of the corporate complex

Apple Park ("Ring") is widely publicized as a complex with a large-scale base insulation system, which allows for significant relative displacements while preserving the functionality of the facility [26, 29]. The role of isolation is twofold: reducing spectral accelerations and protecting equipment and finishing systems, which is crucial for a quick return to service.

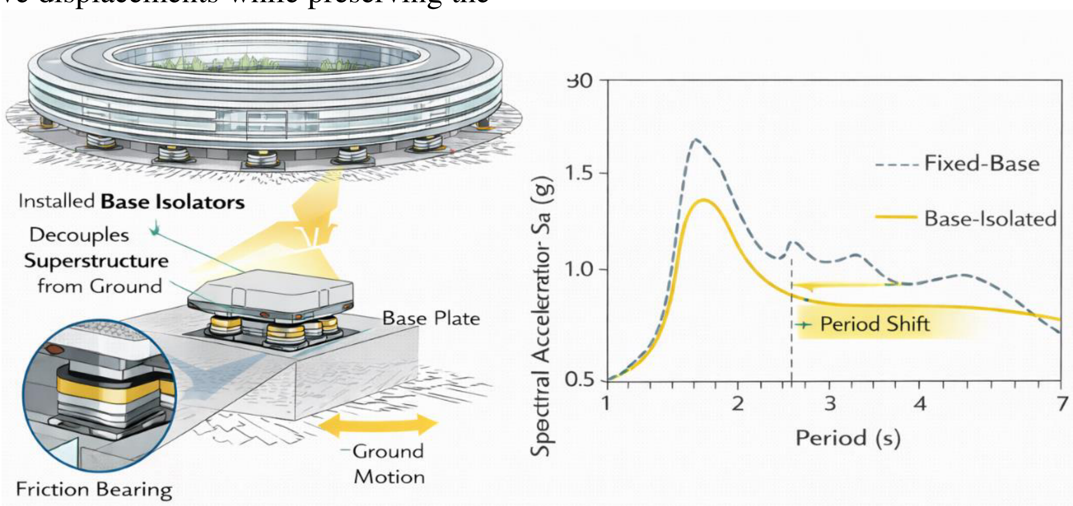

***Figure 7:** Apple Park (Cupertino) – base isolation of the corporate complex*

Base insulators are placed between the foundation and the superstructure, mechanically separating (decouples) the object from the movement of the ground during an earthquake (Figure 7).

The earthquake movement of the ground is mostly "absorbed" in the plane of the insulation, while the superstructure remains much calmer.

The details in Figure 7 show the base insulators that allow for controlled movement and dissipation of energy.

The diagram on the right in Figure 7 shows the period shift:

- A fixed object has higher spectral accelerations.
- A base-isolated object has significantly reduced accelerations over the relevant period range.

The key effect of the system is to reduce seismic forces, damage to the structure and non-structural elements, while preserving the functionality of the complex after an earthquake.

5.4. Torre Mayor, Mexico City – Energy Dissipators

Torre Mayor uses more than 90 viscous silencers integrated into the frame system. During strong earthquakes, the structure showed minimal damage, confirming the efficiency of the system with additional energy dissipation [19].

A tall building with peripheral steel stiffening is shown, in which fluid (viscous) energy dissipators are installed (Figure 8). Dissipators are placed between oblique/perimeter couplings and convert some of the kinetic energy into heat (damping) during an earthquake. This reduces seismic accelerations, forces, and interfloor displacements of the structure.

The diagram on the right in Figure 8 compares the response with and without the dissipator and shows clearly lower spectral accelerations in energy-dissipated systems.

The concept allows for ductile, controlled behavior without significant damage to the primary load-bearing elements, which is crucial for objects in strong seismic zones such as Mexico City.

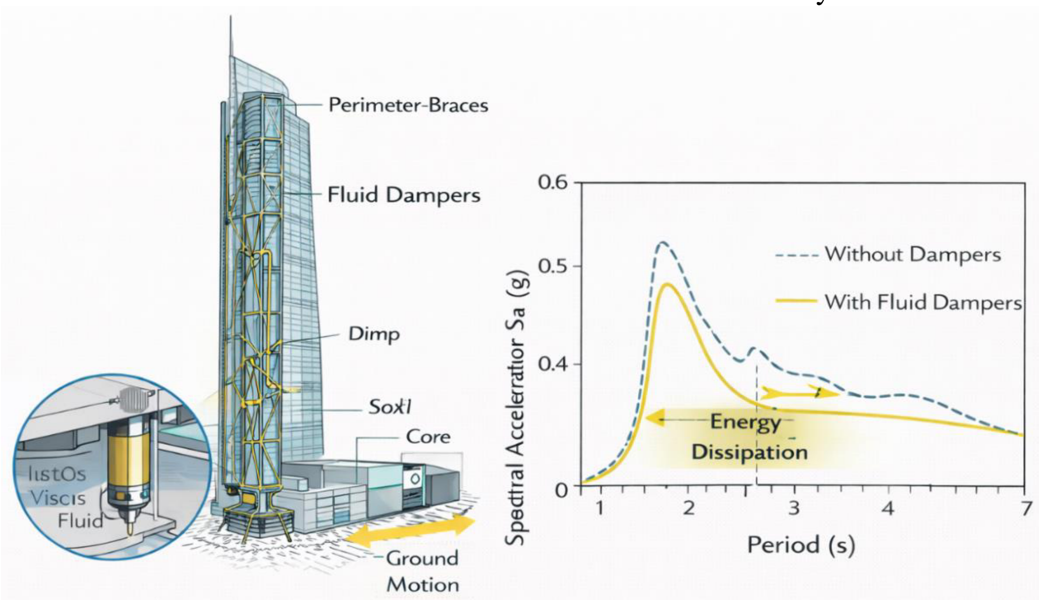

Figure 8: *Torre Mayor, Mexico City – energy dissipators*

5.5. Base Insulation and Hybrid Systems in Turkey

5.5.1. Başakşehir Çam & Sakura City Hospital (Istanbul) – Large-Scale Base Isolation

This complex is cited in expert sources as one of the largest (often the largest) seismically isolated buildings, with about ~2,000+ isolators in the main hospital building, with the aim of ensuring uninterrupted operability during and after strong earthquakes (nky.com.tr; Daily Sabah, 2025) (Figure 9). The dominant concept is the reduction of acceleration and damage to non-load-bearing elements, with displacement control at the level of insulation. For hospital-grade facilities, this approach directly supports the operational performance targets in PBSD Frameworks [12, 30, 31].

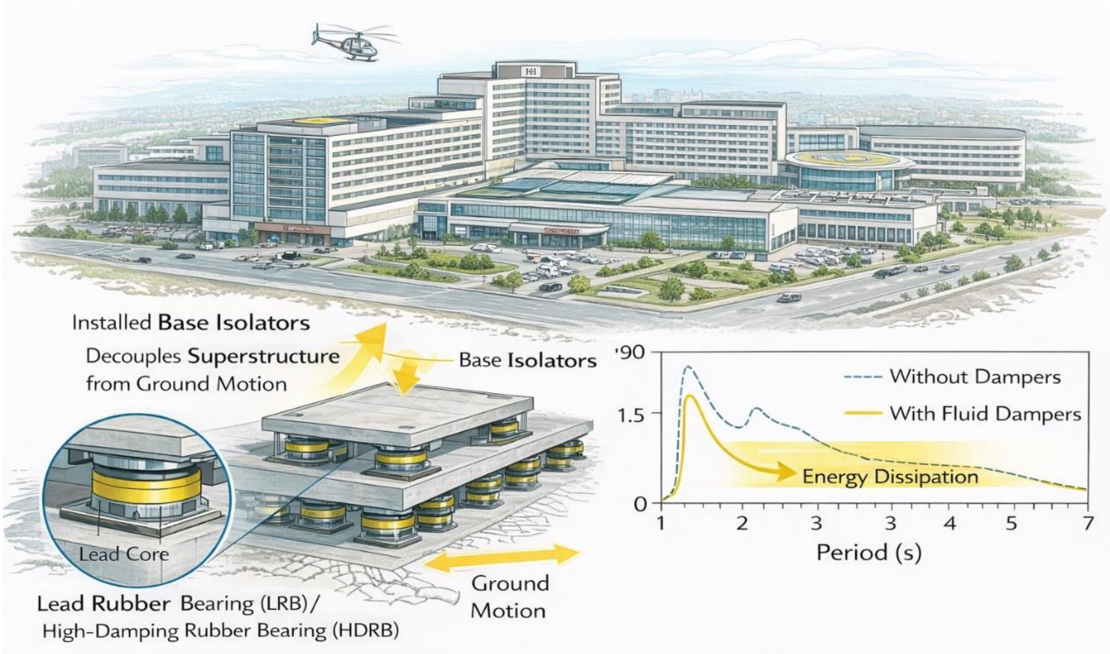

Image 9: *Başakşehir Çam & Sakura City Hospital (Istanbul)*

5.5.2. Bosphorus Bridge Retrofit (Turkey) — Hybrid Systems

The Bosphorus Bridge is an example of hybrid seismic reinforcement that combines base insulation, dissipators, and local element reinforcement. The project is in line with modern seismic regulations and is a reference for infrastructure facilities [20].

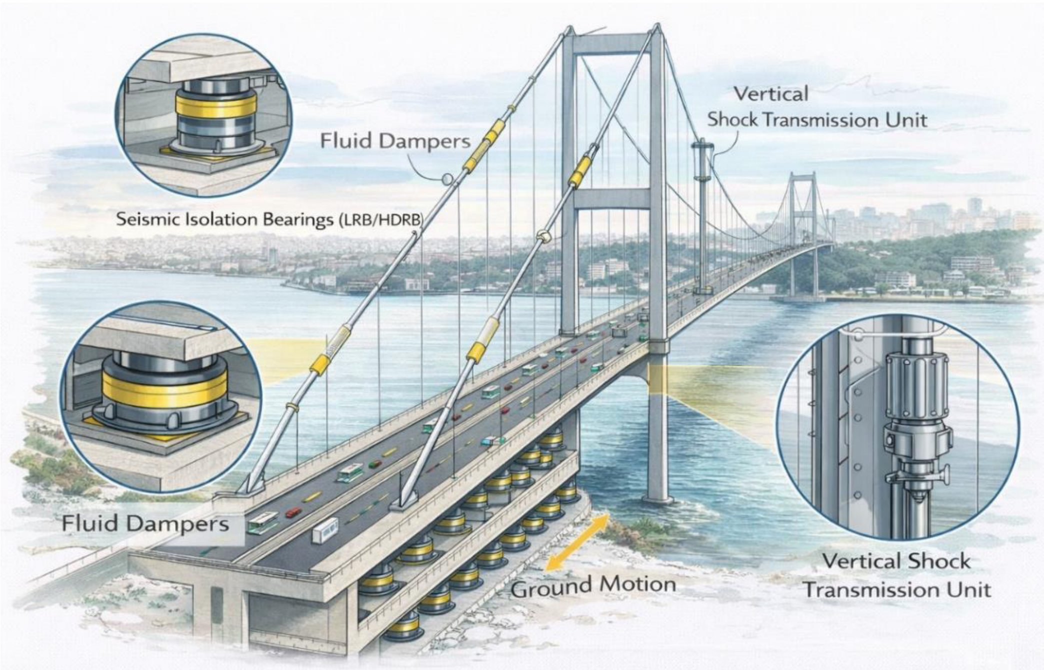

Figure 10: *Bosphorus Bridge Retrofit (Turkey) – hybrid systems*

Figure 10 shows the seismic reinforcement (retrofit) of the Bosphorus Bridge using a hybrid protection system, which combines basic seismic isolation, energy dissipation, and displacement control. Elastomeric seismic bearings (LRB/HDRB) are installed on the bridge abutments to reduce the transfer of seismic forces from the ground to the structure, while fluid dampers are installed along the cables and span structure to dissipate energy during earthquakes and limit relative displacements. In addition, vertical shock transmission units provide a rigid response under slow loads (e.g. temperature, traffic) and a flexible and dissipative response under rapid seismic action. This combination of systems allows for a significant reduction in seismic demands, control of deformation and increase the reliability of the bridge without compromising its functionality and aerodynamic behavior.

5.6. A Comparative Review of Five Case Studies and Dominant Seismic Systems

A comparative tabular overview (Table 2) of five case studies systematizes different contemporary approaches to seismic protection through clearly observable differences in the dominant structural system, energy dissipation mechanism, and performance targets. The Taipei 101 and Tokyo Skytree are vibration control systems (TMD and shinbashira) in which seismic energy is reduced through phase shift and additional mass, predominantly to reduce the acceleration and oscillation of tall objects. Sendai Mediatheque and the Wilshire Grand Center rely on the ductile and dissipative behavior of the primary structure, through innovative frame systems, steel tubular columns and buckling-restrained braces (BRBs), thus achieving high ductility and reliable protection against collapse. SFO International Terminal and Apple Park are examples of baseline seismic isolation, where the superstructure effectively separates from the ground, shifts its own period, and drastically reduces seismic forces and damage, which is especially suitable for facilities that need to remain operational. Finally, the Bosphorus Bridge retrofit demonstrates a hybrid approach, in which insulators, shock absorbers and shock transmission devices are combined, thereby simultaneously controlling displacements, forces and shock effects. The table clearly shows that modern practice is moving from universal solutions to purposefully designed systems, where the choice of seismic concept depends on the type of object, the requirements of functionality and the acceptable level of risk, in accordance with the principles of Eurocode 8 and ASCE 7/41.

Table 2: *Comparative review of five case studies and dominant seismic systems*

Object	The dominant system.	Key implementation	Performance target	Binding with codes
Başakşehir Çam & Sakura City Hospital (TR)	Base Insulation (LRB/HDRB)	~2000+ insulators	The hospital's operability; Acceleration reduction	EC8: insulation (EN 1998-1) + national annexation; ASCE: Insulation (ASCE 7/41)
Apple Park (U.S.)	Base insulation (sliding/bearings)	A large number of insulators (public announcement)	Functionality and protection of equipment	ASCE frames; Conceptually analogous to EC8 solutions.
SFO International Terminal (US)	Friction pendulum/steel ball isolators	267 insulators	Reduction requirement ~70% (sources)	ASCE; An Early Reference Example of Isolation
Tokyo Skytree (JP)	Vibration control (central pillar + frame)	The Shinbashira Concept	Reduction of wobble (sources say up to ~50%)	It is not directly codified as isolation; It is connected to vibration control.
Wilshire Grand Center (US)	Dissipative stiffening (BRB)	320 BRB (case study)	Drift control and energy dissipation	ASCE; Compatible with the EC8 dissipative element concept.

5.4. Seismic resilience in the Balkans – examples and challenges

Seismically active areas of the Balkans face a number of challenges, including outdated infrastructure and limited resources for modernization. Examples of successful projects include:

- reconstruction and reinforcement of public buildings in Belgrade and Zagreb using composite materials (e.g. CFRP tapes) to increase ductility [48],
- application of traditional reinforced concrete wall systems with modern detailing of reinforcement in new buildings,
- the introduction of digital technologies in the planning and monitoring of the construction of new infrastructure facilities.

The main challenges remain in harmonizing standards and raising awareness of the importance of seismic resilience, which is necessary to reduce the catastrophic consequences of future earthquakes.

6. ADVANTAGES AND LIMITATIONS OF MODERN APPROACHES TO SEISMIC DESIGN

The Advantages of Modern Construction Systems

Modern systems, including base insulation, energy dissipators and hybrid designs, allow for a significant reduction in seismic damage and increase user safety. Performance-based design leads to structures that can better withstand extreme seismic events, reducing the risk of collapse [49].

The use of recycled and innovative materials in structures reduces the carbon footprint, while longevity and renewability increase, contributing to the overall sustainability of the construction sector [43].

Digital tools and BIM models enable more efficient coordination, reduce errors in the design and construction phases, as well as better control over the quality and performance of structures [10].

Limitations and challenges

The implementation of advanced systems such as base insulation and energy dissipators increases construction costs and requires a high level of expertise in design and construction. This can be a barrier in countries with limited budgets [15].

While international and regional standards exist, the harmonisation of regulations on advanced technologies and sustainability is still under development, making it difficult to apply them widely [12].

Numerical models depend on the accuracy of input data and assumptions, and their application in complex buildings requires significant computational time and expert interpretation of the results [7].

The effectiveness of SHM systems and digital twins depends on proper maintenance and continuous calibration of the sensors, which can pose an operational challenge throughout the lifetime of the facility [41].

Prospects for future development

The improvement of seismic engineering is expected through further integration of artificial intelligence in analysis and decision-making, the development of new sustainable materials with improved properties, as well as the wider application of smart systems for monitoring and adaptation of structures in real time. Also, interdisciplinary approaches that combine seismic resilience with urban planning and crisis management will become key to increasing the overall resilience of societies to earthquakes [5].

7. CRITICAL DISCUSSION AND LINKING WITH EUROCODE 8 AND ASCE 7/41

Eurocode 8 (EN 1998-1) and ASCE 7 use related logic, but different terminology and reduction coefficients. In EC8, the reduction of requirements is introduced through the behavior factor q and ductility

class (DCL/DCM/DCH), with strictly prescribed rules of capacitive design and detailing, while ASCE 7 uses R (reduction), Cd (drift amplification) and Ω0 (overstrength), with the categorization of seismic risk and detailing requirements through accompanying standards (e.g. ACI/AISC). In both frameworks, for PBSD and non-linear procedures, it often relies on additional documents (e.g., FEMA P-58; ASCE 41).
For base insulation, both systems require explicit consideration of displacement in the insulation plane and verification of the load-bearing capacity and stability of the insulator, with special requirements for objects of importance. Case studies (hospitals in Istanbul; Apple Park; The SFO terminal confirms that the insulation is moving from a "special" technology to a standard solution for facilities with an operability requirement. For dissipative systems (BRBs), ASCE practice is highly developed, while EC8 formally supports dissipative behavior with detailed classification and rules, but implementation depends on national appendices and industry practice.
In tall objects, the critical point is the control of drift and secondary effects (P–Δ), as well as the interaction of the core, frame, and dissipative elements. Therefore, the PBSD, along with model validation and robust detailing, represents a practically indispensable framework [7, 18].

CONCLUSION

Modern structures in the era of digital and sustainable construction are integrated systems that combine advanced construction concepts, digital tools and sustainable principles. The analyzed examples confirm that seismic resilience today does not only mean preventing collapses, but also preserving functionality, reducing economic losses and long-term sustainability of buildings. Future developments will be geared towards even greater integration of digital technologies and adaptive constructions.
The analysis of modern seismically resistant structural systems shows that global practice is shifting towards solutions that ensure not only the prevention of demolition but also the preservation of functionality, especially for critical infrastructure facilities. Base insulation demonstrates the highest potential for reducing acceleration and damage in non-load-bearing systems, while dissipative systems (dampers/BRB) allow for economical control of drift and demands on primary elements. For tall buildings, combining cores, frames, and dissipative elements remains the most common path to robust performance.
Digital tools (BIM, digital twins and SHM) enable the transition to "life-cycle" seismic risk management, while sustainability requires that seismic resilience be seen as a key component of reducing overall emissions and resource expenditure through the avoidance of reconstructions. Coupling with Eurocode 8 and ASCE 7/41 demonstrates conceptual compatibility, with the need for careful translation of coefficients and detailing requirements depending on standards and local conditions.

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REMOTE EMPLOYMENT IN THE DIGITAL ERA: AN ANALYSIS OF KEY CHALLENGES IN CYBERSECURITY AND INFORMATION TECHNOLOGY (IT) SYSTEMS MANAGEMENT

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Review article
https://doi.org/10.58952/nit20251302101
UDC 004.056:331.105.44

Abstract

The rapid development of the internet and digital technologies has significantly transformed modern lifestyles and work organization. Remote work, which intensified especially during the COVID-19 pandemic, has become a sustainable practice for many public and private institutions. This work model offers substantial economic and organizational benefits for both employers and employees, including reduced operational costs, greater flexibility, and improved work-life balance. However, moving work environments outside traditional infrastructures has considerably increased exposure to cybersecurity threats. The use of unsecured networks, personal devices, and the lack of well-defined security policies represent critical risk factors for information technology (IT) systems. This paper analyzes the main cybersecurity challenges associated with remote employment and examines appropriate measures and best practices for protecting data and IT systems. The study aims to raise awareness and contribute to the improvement of cybersecurity management strategies in remote work environments.

Keywords: *Remote Work, Cybersecurity, IT Systems, Data Protection, Digital Transformation, Network Security.*

JEL Classification: M15, J81, O33

1. INTRODUCTION

Cybersecurity, often referred to as information security, has evolved dramatically over the decades and has become an essential component of modern life. Its origins trace back to the need to protect physical locations, hardware, and software from threats, a need that intensified during World War II. During this period, the first mainframe computers were developed to assist with code-breaking operations. These machines, extremely rare and large, required strict physical access controls, including personal key cards, locks, and facial recognition of authorized personnel, to ensure data integrity and system functionality [1]. In the following decades, cybersecurity emerged as a distinct field, particularly during the 1950s–1970s. Public awareness increased in the late 1980s following a series of incidents that highlighted the risks of inadequate protective measures. From the 1990s to the digital era of the 21st century, cybersecurity has become a crucial part of everyday life, encompassing not only personal data protection but also safeguardingtical infrastructures such as energy, transportation, aviation, healthcare, and other strategic sectors [2], [3]. The widespread use of technology has permeated nearly every aspect of human life, continuously generating vast amounts of data essential for communication among individuals and between technological systems. However, not all forms of online communication can be considered secure without appropriate protective measures. Failing to implement proper data security techniques may lead to information compromise and expose users to cyberattacks, including phishing, malware, ransomware, and other sophisticated threats [4], [5]. Understanding these risks is essential for both developers and ordinary users, as any individual can become a "targeted victim" using existing cyberattack tools [6]. The integration of Artificial Intelligence (AI) into cybersecurity has opened new opportunities for proactive threat detection and prevention. AI-based systems can analyze abnormal behaviors, identify attacks in real-time, and implement preventive measures, significantly improving system resilience against sophisticated threats [7]. Nevertheless, the development of digital services and increased online activity, particularly during periods of isolation such as the COVID-19 pandemic, has significantly heightened cyber risks. Remote work became a widespread practice in many organizations, increasing system exposure to attacks [8]. During the COVID-19 pandemic, many organizations had to rapidly adapt their work environments to remote models, relying on online platforms for communication, teaching, and collaboration. This shift underscored the urgent need for robust cybersecurity measures, as attacks targeting open networks, personal devices, and cloud services became more common. Preventive measures include data encryption, multi-factor authentication, regular user training, and clear information protection policies [9], [10]. Cybersecurity is not merely a technical issue; it is a strategic component of national security and the functioning of critical infrastructure. Every piece of information carries value, and the more critical it is, the higher the level of security required. This paper addresses the importance of cybersecurity measures, the risks associated with developing and using digital technologies, and the need to protect data and critical systems in the modern era [11], [12].

2. EXPERIMENTAL METHODS

In recent years, cybercrime has grown exponentially, prompting institutions and law enforcement agencies to adopt advanced strategies to counteract such threats [13]. The continuous digital transformation has introduced widespread use of technologies such as cloud computing, smartphones, and the Internet of Things (IoT). Cybersecurity is a combination of technologies, processes, and practices designed to prevent attacks that aim to damage, steal, or gain unauthorized access to networks, computers, programs, and data [14]. Given the integration of information technology across all scientific and social disciplines, cybersecurity has become essential. Advances in cloud computing, AI, and IoT have increased the potential for unwanted interference in every segment of digital operations. Cyberattacks targeting banking systems, healthcare software, and governmental institutions have become frequent, prompting the creation of specialized agencies and legal frameworks to protect data. Regulations such as the European Union's General Data Protection Regulation (GDPR) further support cybersecurity measures [14]. Cloud computing has become a widely adopted solution for data storage and management due to its scalability and accessibility. While cloud storage offers enhanced security compared to local storage, monitoring software is necessary to detect unusual account activity. Leading platforms such as Amazon Web Services (AWS), Microsoft Azure, and Google Cloud provide monitoring tools and security measures to safeguard user data. Cloud security helps mitigate risks associated with traditional infrastructure while reducing operational costs [16]. Critical infrastructure including energy grids, water treatment facilities, traffic control systems, financial institutions, hospitals, and commercial centers—requires advanced cybersecurity techniques. Even when not directly targeted, these systems can act as entry points for malware affecting connected endpoints. Organizations managing critical infrastructure must maintain emergency plans to mitigate cyberattacks. National agencies, such as the Albanian Authority for Electronic Certification and Cybersecurity (AKCESK), oversee compliance and resilience of critical systems [17]. Data Loss Prevention (DLP) measures prevent sensitive or critical information from leaving an organization's network. DLP software allows administrators to manage data access and usage, develop policies to prevent data leakage, and create recovery plans in case of security breaches. DLP protects personal data, intellectual property, and enhances overall data visibility [18]. Application security protects both software and hardware from external threats during development and deployment. Measures include antivirus software, firewalls, encryption, and specialized tools for securing sensitive datasets. Hardware-based security, such as routers that block unauthorized IP access, also contributes to application protection [19]. Information security focuses on protecting data from unauthorized access, modification, or deletion. Key methods include encryption, key management, intrusion detection systems, password policies, and regulatory compliance. Information security spans multiple domains including cryptography, computing, legal frameworks, and online media [20]. Network security safeguards internal networks from malicious interference. It includes physical protection, access restrictions, monitoring, and machine learning techniques to detect abnormal traffic. Two-factor authentication (2FA) and strong password policies are standard practices for securing network access [21]. IoT devices, from smart sensors to home appliances, introduce new security challenges. Unauthorized access can compromise sensitive personal or business data. Organizations integrate IoT analytics with security measures to maintain secure and resilient networks [22]. Website security protects databases, applications, source code, and files from unauthorized access. Techniques include continuous scanning, malware removal, firewall implementation, and application security testing. Blockchain technologies table 1 can further enhance website protection against cyberattacks [23], [24].

- Cybersecurity can be conceptualized as a seven-layer model, focusing on:
- Critical mission assets; protecting essential data.
- Data security; safeguarding data during storage and transfer.
- Application security; securing access and sensitive data within applications.
- Endpoint security; protecting devices connected to networks.
- Network security; preventing unauthorized access to internal networks.
- Perimeter security; integrating digital and physical security measures.
- Human layer; training users and managing insider threats [25].

Table 1: *The main cybersecurity areas, methods, and technologies*

Cybersecurity Area	**Description / Purpose**	**Key Technologies / Methods**
Cloud Security	Protects data stored and processed in cloud environments	Monitoring software, AWS, Microsoft Azure, Google Cloud, encryption
Critical Infrastructure Security	Safeguards vital systems (energy, water, finance, hospitals)	Emergency plans, access control, malware detection, national regulatory frameworks
Data Loss Prevention (DLP)	Prevents unauthorized transfer or leakage of sensitive information	Policy enforcement, data monitoring, recovery plans
Application Security	Protects software and applications from external threats	Firewalls, antivirus, encryption, access control, hardware security
Information Security	Ensures confidentiality, integrity, and availability of all types of data	Encryption, key management, intrusion detection, compliance, legal frameworks
Network Security	Secures internal networks from malicious interference	Firewalls, 2FA, access control, traffic monitoring, machine learning analysis

Cybersecurity Area	Description / Purpose	Key Technologies / Methods
IoT Security	Protects connected devices and sensors in the Internet of Things	Secure protocols, IoT analytics, monitoring, device authentication
Website Security	Protects websites and web applications from unauthorized access	Continuous scanning, malware removal, firewalls, blockchain, application security testing
Cybersecurity Layers / Defense	A multi-layered approach to protect critical assets, applications, endpoints, networks	Seven-layer model: assets, data, applications, endpoints, network, perimeter, human layer

3. METHODOLOGY

In recent years, the Internet has become an integral part of people's daily lives worldwide. Online crime, on the other hand, has increased along with the growth of Internet activity [27]. Cybersecurity has advanced significantly in recent years to keep up with rapid changes in the cyber space. Cybersecurity refers to the methods a country or organization can use to protect products and information in the cyberspace. A decade ago, the term "cybersecurity" was not widely known. Today, cybersecurity is not only an issue affecting individuals but also applies to organizations, businesses, and even public and educational institutions, where cyberattacks raise concerns for privacy, security, and finance [34]. This study on cybersecurity during the Covid-19 pandemic was developed using a combination of quantitative and qualitative methods to provide a clear overview of the changes and challenges presented in the field of cybersecurity during this period. The pandemic forced institutions, organizations, and even individuals to transition from classical methods to contemporary or online approaches, which opened the way for other significant challenges, particularly in the field of cybersecurity [28], [29]. The research is based on data collection from primary and secondary sources. Primary sources include reports on locally executed attacks and their assessments, while secondary sources include international reports and organizations involved in cybersecurity. These studies cover the period from 2020 to 2022 to track cyberattacks globally [30], [31]. This research faced significant challenges due to gaps in complete official data and the relatively small number of official reports on these attacks. Nevertheless, a multidimensional combination of sources made it possible to draw reliable conclusions about cyberattacks and propose concrete measures to improve the situation and raise cybersecurity levels, especially in potential cases similar to this one [32], [33]. Data for this study were primarily obtained from various studies, publications, and scientific articles related to cybersecurity, awareness of cybersecurity issues, and measures against cyberattacks. To obtain a current overview, the data and results were selected from recent sources that cover the latest technologies, measures, and treatment approaches in this direction. These studies cover various areas that may be exposed to cyberattacks, attacks executed, and protective measures undertaken [27], [28]. For this study, a broad search of worldwide literature, foreign publications and articles, and reports from governmental and non-governmental organizations related to cybersecurity was conducted. To ensure a focused approach with the most relevant articles during the search phase, keywords related to cybersecurity were used to locate studies pertinent to this topic. After creating a comprehensive database with numerous scientific and research articles, a filtered selection was made to provide the most effective and professional content on cybersecurity studies and the study's objective. The collected data were used and processed respecting academic standards and professional citation practices, protecting the rights of each publication used [29], [30], [34].

4. RESULTS AND DISCUSSION

The literature analyzed was reviewed through a thematic and professional approach, well-structured to address the problem as comprehensively as possible. The aim was to identify key topics in the field of cybersecurity and protective measures during online work [35]. This phase involved organizing and categorizing studies, reports, and other materials on cyberattacks during online work and the preventive measures, as well as awareness processes. Through this selection process, a clear overview of the best practices in cybersecurity protection during online work, challenges, methods to advance, and increasing awareness of cyberattacks was obtained [35], [36]. To carry out this study and a comprehensive comparative analysis, various studies were examined to identify the risks of cyberattacks during remote work. The advantages and limitations of cybersecurity systems during online work were analyzed, forming the main focus for comparing the performance of these systems in protecting online activities [35], [36]. This comparative method provides a clear overview for identifying risks, accurately assessing threat levels, and understanding preventive measures. It also highlights the challenges and opportunities offered by protective cybersecurity systems for risk management and user awareness to prevent cyberattacks during online work [36]. This research adhered to all ethical principles in using and referencing academic literature, strictly following citation practices to protect authorship rights and avoid plagiarism. Critical and objective assessment of the existing data was emphasized to maintain accuracy and neutrality, increasing the originality and quality of the study, and providing a clear view of cyberattacks and challenges during online work [36].The study faced certain limitations. The lack of infrastructure and equipment limited the reporting of cyberattacks locally. The rapid and dynamic development of cybersecurity presents additional challenges in accessing and completing this study. Moreover, local access to reports on cyberattacks during online work was limited, requiring reliance on international literature and reports, which constrained the scope of regional-specific analysis [36], [37]. Figure 1 shows the distribution of cybercrime events by category, providing a clear overview of the most frequent digital threats [16]. Six major categories are identified: Phishing (86 cases), Malware (65), Extortion (15), Pharming (13), Financial Fraud (34), and DoS & Hacking (5 each), totaling 223 cyberattacks [35].

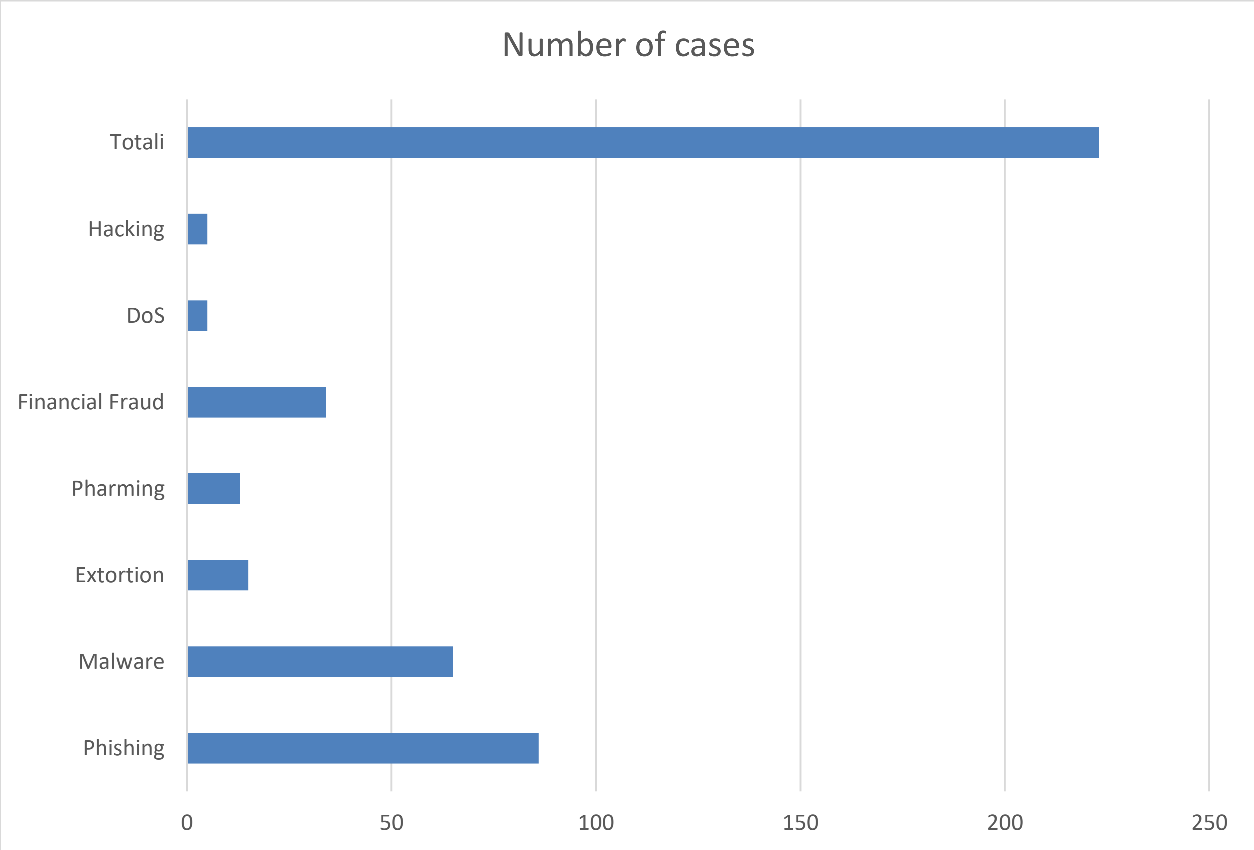

Figure 1: *Cybercrimes by category*

From surveys conducted by various institutions in 2019:

- 70% of financial institutions ranked cybersecurity as a priority.
- The cost of a cyberattack was highest in the banking sector, reaching $18.3 million per company annually.
- 70% of financial companies experienced a cybersecurity incident in 2019.
- 10% of IT budgets were spent on cybersecurity.
- 26% of financial institutions suffered a destructive cyberattack, a 160% increase from 2018 [36].

In the Table 2 presents the distribution of cybercrime interventions across different sectors, highlighting the impact on small, medium, and unidentified organizations [15].

Table 2: *Cybercrime interventions across different sectors*

Sector	Interventions	Small Organizations	Large Organizations	Unknown
Accommodation	72	40	10	22
Administration	25	8	10	7
Agriculture	5	3	1	1
Construction	18	9	5	4
Education	120	20	15	85
Entertainment	15	5	4	6
Finance	250	30	25	195
Healthcare	350	35	30	285
Information	180	25	20	135
Management	10	3	2	5
Production	95	15	25	55
Mining	20	3	6	11
Other Services	60	8	6	46
Professional	170	35	15	120
Public	340	20	85	235
Real Estate	18	7	3	8
Retail	150	50	20	80
Trade	20	5	9	6
Transport	40	4	10	26
Utilities	12	3	1	8
Unknown	300	0	120	180
Total	2400	360	471	1569

The data indicate that cybercrime interventions vary significantly across sectors, with the highest number of incidents reported in Healthcare (350), Public (340), and Finance (250) sectors. Small organizations, while fewer in number overall, remain highly vulnerable in sectors like Retail (50) and Professional services (35). Notably, a large proportion of interventions (1,569 out of 2,400) involve organizations classified as unknown, highlighting gaps in reporting and classification across sectors.

CONCLUSIONS

The results of this study provide a clear overview of the challenges and cyber threats during the Covid-19 pandemic. Analysis of the literature and sectoral data indicates that cyberattacks increased significantly during the massive transition from traditional to online work systems [35–38]. Phishing, Malware, Ransomware, and financial attacks were identified as the most frequent types of attacks, where the lack of preparedness and employee awareness played a key role [36]. Comparative sector analysis shows that public institutions, financial organizations, and healthcare systems are most exposed to cyber threats due to the critical nature of the data they manage and the rapid shift to online platforms [35]. Small organizations are also highly vulnerable due to limited capacity to invest in protective measures, while sectors with lower digitalization, such as agriculture, management, and municipal services, experienced fewer attacks [36]. The Covid-19 pandemic acted as a catalyst for rapid digitalization, exposing gaps in cybersecurity and demonstrating that security is not merely a technological issue but requires engagement across all sectors of society and institutions [37]. This transformation highlighted the urgent need for online training, as many employees were not adequately prepared to manage cyber threats, increasing organizational vulnerability [38]. On the positive side, the pandemic accelerated the adoption of global platforms and raised awareness of the need for more advanced protective measures. The results show that employee awareness and education are crucial in reducing attacks, emphasizing the importance of ongoing training and sustainable cybersecurity policies [35–38]. Combining comparative analysis, statistical data, and literature, the main cybersecurity challenges are identified as:

Rapid increase in attacks during global crises such as the pademic;

- Limited protective capacities of small organizations;
- Lack of sufficient awareness and training among employees;
- The need for a layered, global approach to cybersecurity.

Ultimately, the Covid-19 pandemic served as a global turning point, forcing institutions, companies, and individuals to treat cybersecurity as a necessity. Investments in technology, training, and professional personnel are essential to ensure effective protection against cyberattacks, especially during emergencies and global crises [35–38]. This study confirms that the higher the level of digitalization in an institution, the greater the exposure to cyberattacks and the more essential cybersecurity knowledge becomes for all stakeholders involved.

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