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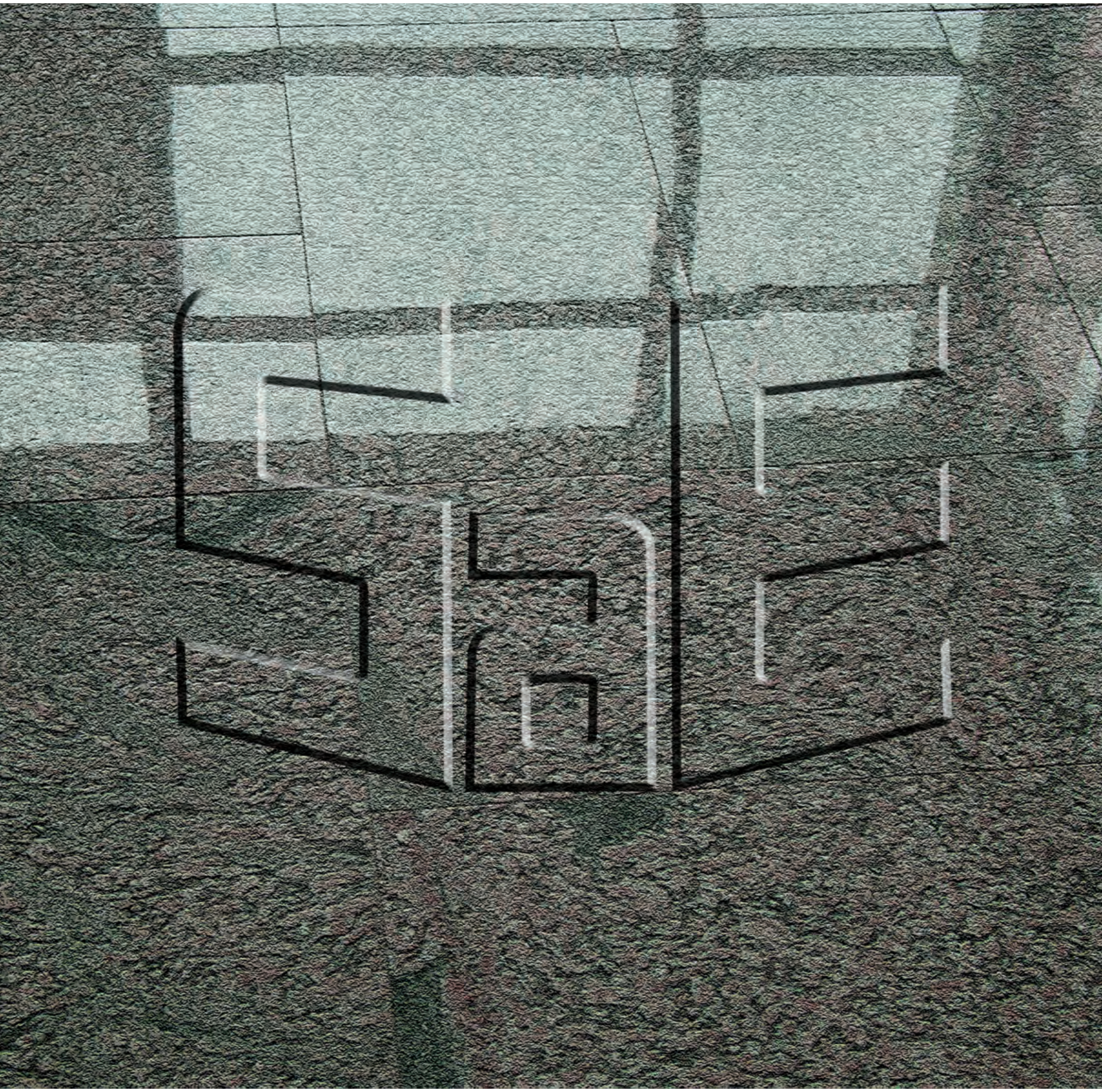

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HAVE WE ENTERED THE FOURTH ERA OF BIM? FROM THE ERA OF OPEN STANDARDS TO THE ERA OF ARTIFICIAL INTELLIGENCE

CZY WKROCZYLIŚMY W CZWARTĄ ERĘ BIM? OD ERY OTWARTYCH STANDARDÓW DO ERY SZTUCZNEJ INTELIGENCJI

Andrzej Szymon Borkowski*
Warsaw University of Technology, Poland

Abstract

Building Information Modeling (BIM) has been the hottest topic in the construction sector over the last decade. The evolution from CAD to BIM systems has been going on for over 40 years. The current periodization indicates that we are now in the third era of BIM development, the era of open standards, which was initiated by the idea of openBIM in 2012. Earlier evolutionary periods included the model federation (second era) and CAD3D (first era). Since 2022, there has been extremely dynamic development of artificial intelligence (AI), especially generative AI. AI tools automate some of the tasks that were previously performed by humans. Thus, the research question is: are we entering the next, fourth era of BIM development? The era of artificial intelligence? This chapter attempts to answer this reflective question. During an in-depth literature review, the directions of current and future research on BIM development are discussed.

Keywords: building information modeling, BIM, artificial intelligence, AI, development, periodization

Streszczenie

Modelowanie informacji o budynku (BIM) było najgorętszym tematem w branży budowlanej w ciągu ostatniej dekady. Ewolucja od systemów CAD do systemów BIM trwa już ponad 40 lat. Obecna periodizacja wskazuje, że znajdujemy się w trzeciej erze rozwoju BIM, erze otwartych standardów, zapoczątkowanej ideą openBIM w 2012 roku. Wcześniejsze okresy ewolucji obejmowały federację modeli (druga era) oraz CAD3D (pierwsza era). Od 2022 roku obserwuje się niezwykle dynamiczny rozwój sztucznej inteligencji (AI), zwłaszcza generatywnej. Narzędzia AI automatyzują niektóre zadania, które wcześniej były wykonywane przez ludzi. W związku z tym pojawia się pytanie badawcze: czy wkraczamy w kolejną, czwartą erę rozwoju BIM? Erę sztucznej inteligencji? W niniejszym artykule podjęto próbę odpowiedzi na to refleksyjne pytanie. W trakcie dogłębnego przeglądu literatury omówiono kierunki obecnych i przyszłych badań nad rozwojem BIM.

Słowa kluczowe: modelowanie informacji o budynku, BIM, sztuczna inteligencja, AI, rozwój, periodyzacja

1. INTRODUCTION

The current periodization (division into evolutionary periods) of BIM (Building Information Modeling) assumes the existence of three developmental periods in history (Borkowski, 2023). The first era covers the 1980s and 1990s as the time when the idea of BIM was born through the development of innovative applications – Archicad, Sonata, Reflex, Revit (in chronological order). In this era, users employ software (CAD2D, CAD2.5D, CAD3D), usually used closed

*Warsaw University of Technology, Poland, e-mail: andrzej.borkowski@pw.edu.pl

solutions, and modeled individual building objects. The second era saw the maturation of this concept, which began to cover an increasingly wider spectrum of professions and stakeholder groups. The advent of new tools and the spread of computers enabled the federation of models. Thus, more specialized professions were included in the digitization process, communication efficiency increased, and the number of collisions, errors, and antagonisms was minimized. The third era began with the announcement of the openBIM concept (in 2012) and the dynamic development of independent, open standards (Fig. 1). The developed norms and standards allow for the structuring of the BIM process and increase the productivity of companies and organizations. At the beginning of the second decade of the 21st century, it seemed that this era was continuing and that the much-anticipated interoperability was close to being achieved. However, the emergence of widespread generative artificial intelligence (AI) in 2022 changed the course of events. Scientists, practitioners, and innovators are wondering if this is the end of the era of open standards. Have we perhaps entered a new era of heavy machine use in the design, construction, and operation of buildings?

Currently, artificial intelligence tools can bring significant benefits, such as streamlining decision-making, optimizing processes, and increasing productivity. The construction industry faces various challenges, including low productivity, cost overruns, unskilled labor, and resource waste. Digital manufacturing, smart devices, and automation are seen as potential solutions to these problems. Although the integration of BIM and artificial intelligence is challenging, it could represent a significant paradigm shift in the construction industry (Heidari, Peyvastehgar, Amanzadegan, 2024). Previous research points to six advanced research areas in BIM-AI integration, including automated design and rule checking, 3D as-built reconstruction, event log exploration, building performance analysis, virtual and augmented reality, and digital twins (Pan, Zhang, 2023). A strongly emphasized area of research in the construction sector is prefabrication, a modern construction technique in which some or all of the structural elements are manufactured in a controlled environment and then installed on the construction site. The architecture, engineering, and construction (AEC) industry is gradually implementing prefabrication by integrating BIM with artificial intelligence and Internet of Things (IoT) applications (Rangasamy, Yang, 2024).

BIM is elective and optional. Many countries have opted for a BIM mandate (mandatory use of BIM in

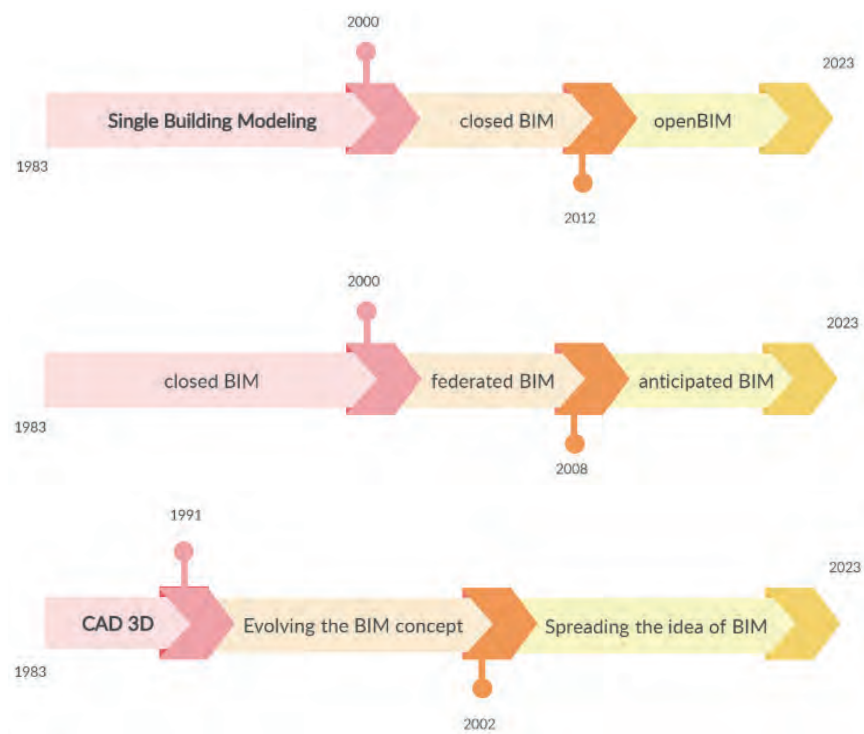

Fig. 1. The current periodization of BIM depending on various factors (from top): approach, organizational culture, idea
Source: Borkowski, 2023

public procurement), other countries encourage its use in a textbook approach, and others do not adopt it at all (Mitera-Kiełbasa, Zima, 2024). The reasons for these decisions vary, but without the digitization, robotization, and automation of the construction sector, which is the most burdensome for the natural environment, it is difficult to imagine achieving the ambitious goals of the circular economy. It therefore seems appropriate to ask a reflective question: has a new, fourth era in the development of BIM begun? The era of artificial intelligence? In order to fill this important research gap, a broad and inclusive literature review was decided upon. As a result of the analysis, synthesis, and evaluation of existing scientific and technical evidence, it was decided to raise the discussion on the future of BIM.

2. MATERIALS AND METHODS

This study adopted a deep literature study approach, which differs from systematic literature reviews conducted previously in this field (Ceccon, Villa, 2021; Bassir et al., 2023; Saleh et al., 2024; Du et al., 2024; Shamreeva, Doroschkin, 2021). The rationale for this methodological choice was twofold: first, comprehensive systematic reviews on BIM-AI integration already exist (Table 1), making another quantitative synthesis redundant; second, the rapid pace of AI development required a flexible, exploratory approach capable of capturing emerging phenomena not yet consolidated in the literature.

The literature search was conducted between September and November 2024 across three databases: Scopus, Web of Science, and Google Scholar. The search employed combinations of the following keywords: “BIM,” “Building Information Modeling”, “HBIM”, “Heritage BIM”, “artificial intelligence,” “AI”, “machine learning”, “ML”, “generative AI”, “deep learning,” and “IFC”. The selection criteria included: (1) publication date between 2020 and 2024 to capture recent developments; (2) thematic focus on the intersection of BIM with either AI technologies or open standards; (3) English language publications. From an initial pool of over 300 identified records, publications were screened based on relevance to the research question. Priority was given to empirical studies demonstrating practical BIM-AI applications, while purely conceptual works without implementation evidence were excluded. The final analysis encompassed both normative literature (peer-reviewed articles, monographs, conference papers) and gray literature (preprints, doctoral theses, industry reports) to ensure coverage of cutting-edge developments. It has already been established that the integration of artificial intelligence with BIM accelerates and improves decision-making processes (Zima, Wieczorek, 2024). Therefore, this study focused on qualitative analysis of how AI is transforming BIM practices across different phases of the building lifecycle.

3. LITERATURE REVIEW

Using BIM in AEC, construction project participants create digital models of buildings (buildings, infrastructure, public spaces, or entire cities) and generate vast amounts of information throughout the entire life cycle of a building. This generated

Table 1. Related works

No.	Authors	Title	Year of publication	Differences
1.	Bassir D., Lodge H., Chang H., Majak J., & Chen G.	Application of artificial intelligence and machine learning for BIM	2023	Overview of applications for quality monitoring
2.	Saleh F., Elhendawi A., Darwish A.S., & Farrell P.	A Framework for Leveraging the Incorporation of AI, BIM, and IoT to Achieve Smart Sustainable Cities	2024	Literature review on smart and sustainable cities
3.	Ceccon L., & Villa D.	AI-BIM interdisciplinary spill-overs: prospected interplay of AI and BIM development paradigms	2021	Analysis of approaches to BIM-AI integration
4.	Du S., Hou L., Zhang G., Tan Y., & Mao P.	BIM and IFC Data Readiness for AI Integration in the Construction Industry: A Review Approach	2024	Systematic literature review according to PRISMA
5.	Shamreeva A., & Doroschkin A.	Analysis of the influencing factors for the practical application of BIM in combination with AI in Germany	2021	Domestic market analysis – Germany
6.	Zima K., & Wieczorek D.	Overview of the possibilities of using artificial intelligence in BIM modeling	2024	Study of trends in the use of AI in BIM

digital data can be used for further evaluation, risk mitigation, analysis, and simulation using machines. Many specialized professions and a number of different stakeholder groups are involved in the investment and construction process. Often, their goals differ, and the lack of relational agreements and the use of contractual provisions alone results in the investment being staged. During these stages, stakeholders exchange databases or models, often losing some of the data in the process. The idea of open standards – openBIM – seeks to address the lack of seamless interoperability. It involves the use of independent standards such as IFC (Industry Foundation Classes) and BCF (BIM Collaboration Format), which have been developed over many years by the buildingSMART organization, as well as the ISO 19650 series providing international standards for information management using BIM (ISO, 2018). However, the experience of companies to date shows that despite the use of open standards, data is still lost or re-entered, which involves additional effort or loss of time, money, or energy.

Artificial intelligence methods, on the other hand, are used in various areas of application, such as building design, industrial prefabrication, construction site planning, and project management. The convergence of AI algorithms and BIM enables the creation of virtual environments where stakeholders can explore and evaluate different design options. This significantly reduces the time and manual effort required to design a layout. An example is the Particle Swarm Optimization (PSO) algorithm, which generates optimized 2D layouts, which in turn are seamlessly converted into 3D BIM models through visual programming performed in Dynamo (Alavi et al., 2024). This conversion allows stakeholders to visualize, analyze, and comprehensively monitor projects, facilitating informed decision-making. Another innovative approach to generating BIM models based on artificial intelligence algorithms involves analyzing architectural and structural drawings (Urbieta et al., 2023). A trained structure called "Mask R-CNN" automatically generates a BIM model corresponding to one of the multi-story buildings using the Industry Foundation Classes (IFC) format.

Generative artificial intelligence enhances the creative input of architects and engineers by generating innovative design alternatives rooted in BIM data. The collaborative ethos of BIM is extended through natural language interfaces such as ChatGPT, supporting seamless communication and idea exchange among project stakeholders (Rane, Choudhary, Rane, 2023). The synergy between BIM and generative AI is also leveraged in simulations and analyses, enabling predictions related to structural performance, energy efficiency, and environmental impact. The research introduces an innovative framework that seamlessly integrates BIM and generative AI, prioritizing interoperability, data consistency, and user-friendly interfaces. Another study integrated AI methods into Heritage BIM (HBIM) models. Currently, heritage reconstruction or historical building information modeling (HBIM) based on laser scanning or photogrammetric surveys is a manual, time-consuming, and overly subjective process, but the emergence of artificial intelligence techniques applied to existing architectural heritage offers new ways of interpreting, processing, and developing raw digital geodetic data such as point clouds (Croce et al., 2023).

Generative artificial intelligence systems can be very effective for BIM designers and modelers, especially during the conceptual design and project development stages. When text-image models are trained using architectural vocabulary and BIM terminology, they can be effective in generating innovative ideas for designers. In this context, it is crucial to create prompts that use BIM vocabulary and relevant datasets. Therefore, it may be necessary to formulate prompts that are based on BIM-specific terminology and reinforced with architectural, structural, and mechanical elements (Yönder, 2023). AI applications (e.g., Stable Diffusion) are already being used in visualization (Cao, Abdul Aziz, Mohd Arshard, 2024), thus replacing "offline" and "real-time rendering" engines (Borkowski, Nowakowski, 2023). Image generators are currently useful mainly in the initial stages of design (the ability to create a spectrum of directions) and in the later stages of variant creation (Gil, 2024). AI image generators based on diffusion models have recently attracted attention due to their ability to create images based on simple prompts. However, for practical application in AEC, they must be able to create specific construction plans for given requirements. One study tested the potential of current AI generators to address such challenges, specifically in the creation of simple floor plans. Several experiments showed that the accuracy of generated floor plans could be improved from 6% to 90% (Ploennigs, Berger, 2024).

During the construction phase, BIM-AI integration improves real-time decision-making by on-site personnel by providing AI-generated insights based on BIM data. This ensures higher project productivity, cost efficiency, and risk management. For example, civil engineers optimize the construction site for logistics, while IT specialists improve the performance of pathfinding algorithms on reference maps. In one such study, logistical information from the BIM model, such as unloading and loading points, was used to find paths for multiple machines to improve the productivity of the entire construction fleet. Such an algorithm can quickly replan a path to resolve an emergency situation on a construction site (Xiang et al., 2021). IoT sensors, such as RFID, are also used on construction sites to track components or access to different areas of the site (Borkowski, Brożyna, Lesiuk, 2024). This ensures a higher degree of safety and faster project completion.

Another study on BIM-AI integration developed a system for detecting defects in railway infrastructure, using submerged joints and subsidence as examples of combined defects in railway infrastructure. Artificial intelligence techniques were used to detect defects. Deep neural networks and convolutional neural networks are used to develop predictive models for detecting defects in railway infrastructure and rolling stock. The results of the study show that the developed models have the potential to detect defects with 99% accuracy and are beneficial for railway system asset management in terms of risk management, passenger comfort, and cost-effectiveness (Sresakoolchai, Kaewunruen, 2021). A technical framework has already been developed that integrates BIM-AI for digital defect detection. The framework has been verified in a case study and has proven effective in twin defects regarding their position, geometry, and dimensions (Chen et al., 2022). This research opens up new possibilities for twin defects of objects at the street block level and even cities to support urban renewal.

During the operational phase, public (institutional) and private clients sometimes use open standards to manage a building. For example, resources that are relevant to the maintenance and repair phase are exported. Sometimes IFC models are used for retrofits, i.e., various types of modernization, renovation, or revitalization (Elagiry et al., 2020). However, when attempting to use IFC models from practice for automatic analysis, certain problems arise as a result of inconsistencies between what is recommended or available in the standard and the data sets that are created in practice (Noardo et al., 2021). It is noticeable that the overall quality of the models requires special additional care on the part of modelers before they can be used for automatic analysis, and there is a high level of variability in the storage of some important information (such as georeferences). This issue has direct implications for AI integration in BIM. The quality of training data fundamentally determines the reliability of AI models a principle commonly known as "garbage in, garbage out". If AI systems are trained on inconsistent, incomplete, or poorly structured IFC models, they will inevitably produce unreliable outputs. This challenge is particularly acute in the AEC industry, where no unified standards for AI training datasets currently exist. Unlike other domains where large, curated datasets are available (e.g., ImageNet for computer vision), the construction sector lacks comparable benchmark datasets for BIM-AI applications. Du et al. (2024) systematically examined IFC data readiness for AI integration, concluding that current BIM models frequently lack the semantic richness, geometric consistency, and attribute completeness required for effective machine learning applications. Their findings underscore that ensuring data quality is a prerequisite for successful AI deployment in BIM workflows. Establishing industry-wide standards for AI-ready BIM data – including minimum requirements for geometric accuracy, semantic richness, and attribute completeness – represents a critical research gap that must be addressed before AI can be reliably integrated into construction practice. On the other hand, BIM models, even native ones, can be managed by machines from the management application level. Fast, remote, real-time, and reliable structural health monitoring (SHM) techniques have already been developed. These intelligent SHM technologies often generate large amounts of data that require advanced data management, visualization, diagnostics, and predictive techniques (Fawad et al., 2023). Over the past few years, researchers have developed numerous methods for diagnosing and predicting damage based on machine learning and artificial intelligence. The development of artificial intelligence is faster than predicted, with new startups presenting interesting, innovative solutions and researchers developing new methods for automating everyday activities, e.g., those of designers.

4. DISCUSSION

BIM is both teleological and parateleological. People working in BIM are focused on achieving a specific goal and at the same time motivated to act by the result, not by the process itself. Other people involved in the BIM process derive pleasure from the process itself, not from the final goal. These people are often motivated by the moment rather than future benefits. Artificial intelligence only reinforces both processes. According to the law of least effort, we as humanity strive to automate our work using machines (Zipf, 2016). A significant barrier to the widespread adoption of AI in BIM is the unresolved question of legal liability. When AI systems make errors in structural calculations, fire safety assessments, or building code compliance, the allocation of responsibility remains unclear. Traditional professional liability frameworks assume human decision-making, where licensed architects and engineers bear responsibility for their designs. However, AI-assisted or AI-generated designs introduce multiple potential liable parties: the design professional who relies on AI outputs, the software vendor providing the AI tool, and the developers who trained the AI model. Currently, professional liability insurance policies typically do not cover AI-generated designs, creating a significant risk exposure for practitioners. Moreover, building codes and regulations worldwide are predicated on human professional judgment and do not yet accommodate AI-driven decision-making processes. The European Union's AI Act (Regulation 2024/1689) represents an initial regulatory response, classifying AI systems used in critical infrastructure-including construction-as high-risk applications requiring conformity assessments and human oversight. However, comprehensive legal frameworks specifically addressing AI liability in construction remain undeveloped. This legal vacuum constitutes a substantial impediment to mass AI adoption in the AEC industry and requires urgent attention from policymakers, professional organizations, and insurers. Nevertheless, one can venture to put forward a hypothesis: the era of open standards may be drawing to a close, and we may be entering the era of artificial intelligence in BIM development (Fig. 2). It should be acknowledged that most current BIM-AI applications remain at the proof-of-concept or early implementation stage, and the AEC industry's historically slow adoption of innovations often requiring several to over a dozen years suggests that full transition to an AI-driven paradigm will be gradual rather than immediate. With the advent of the first widespread generative artificial intelligence (ChatGPT – November 30, 2022), the perception of challenges in BIM has changed.

Closely related to liability is the challenge of validation and verification of AI-generated designs. Current regulatory frameworks require that construction documents be reviewed and stamped by licensed professionals who take personal responsibility for code compliance. However, the verification of AI-generated outputs poses unique challenges. Unlike traditional design processes, where the reasoning behind decisions can be traced and explained, many AI systems particularly deep learning models operate as "black boxes", making it difficult to understand how specific design decisions were reached. This opacity complicates the verification process: how can a licensed professional certify compliance when the underlying logic is not fully transparent? Emerging approaches to address this challenge include explainable AI (XAI) methods that provide interpretable justifications for AI recommendations, automated code compliance checking systems that can validate designs against regulatory requirements, and hybrid workflows where AI generates design options while humans retain final decision-making authority. Nevertheless, the fundamental question of professional responsibility remains regardless of AI involvement, licensed architects and engineers must currently stamp and take legal responsibility for construction documents, effectively positioning AI as a tool rather than a decision-maker in the regulatory sense.

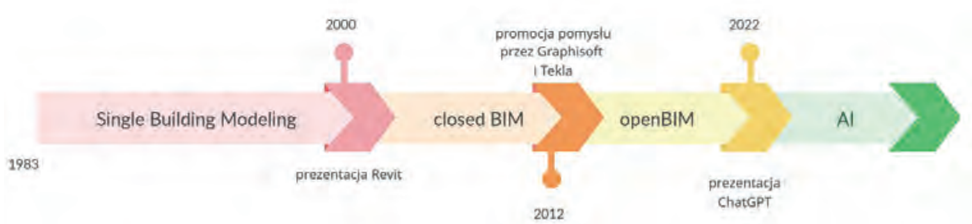

Fig. 2. Periodization of BIM based on approach. A new era in BIM development – the growing use of artificial intelligence
Source: own work

5. CONCLUSION

The observation that we may be entering a new, fourth era in BIM development the era of artificial intelligence appears justified based on current technological trajectories. This does not mean that the problems of digitization in the AEC industry are disappearing. Quite the contrary. In many cases, we are still in the phase of basic research into the processes surrounding BIM. Application research on BIM is extremely time-consuming and costly, and its results are slowly being adapted in national economies in the construction sector. Introducing innovations into organizations in the construction industry sometimes takes several to over a dozen years. Hence, artificial intelligence appears poised to become the decisive factor for broader BIM implementation in the construction sector by automating the enormous amount of manual work involved in modeling and information management. However, the transition from current proof-of-concept applications to mass adoption will require overcoming significant barriers including data quality standards, legal liability frameworks, and workforce adaptation. Without the support of machines, people will continue to make mistakes, which in turn will result in inefficiency, cost overruns, and conflicts. The relationship between BIM and AI seems congruent – full of compatibility.

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COMPARISON OF TRADITIONAL AND MODULAR CONSTRUCTION IN TERMS OF TECHNOLOGY, TIME AND COST

PORÓWNANIE BUDOWNICTWA TRADYCYJNEGO I MODUŁOWEGO POD WZGLĘDEM TECHNOLOGII, CZASU I KOSZTÓW

Krzysztof Zima*, Maria John
Cracow University of Technology, Poland

Abstract

Modular construction is a rapidly growing sector of the construction industry in recent years. This paper presents information on modular construction technology, including its characteristic features and the positive aspects resulting from its use. It discusses the scope of application, completion time, quality of workmanship and ways to minimise losses during the module production process, along with the possibility of reusing both the modules and the materials from which they are made. The comparative analysis covered technological and economic aspects as well as completion time, using the example of a single-family residential building for two technological variants: modular and traditional construction. Both technologies were discussed in detail. The economic analysis was based on market research of offers from companies specialising in the construction of buildings using the technology in question. The cost estimate for traditional construction was prepared using the BIMestiMate programme. A comparative analysis of the construction time for buildings using both technologies was also carried out.

Keywords: comparative analysis, modular construction, traditional construction

Streszczenie

Budownictwo modułowe to sektor branży budowlanej, który w ostatnich latach szybko się rozwija. Niniejszy artykuł przedstawia informacje na temat technologii budownictwa modułowego, w tym charakterystyczne cechy oraz korzyści wynikające ze stosowania tej technologii. Omówiono w nim zakres zastosowań, czas realizacji, jakość wykonania oraz sposoby minimalizacji strat podczas procesu produkcji modułów, a także możliwość ponownego wykorzystania zarówno samych modułów, jak i materiałów, z których są one wykonane. Analiza porównawcza objęła aspekty technologiczne i ekonomiczne, a także czas realizacji, na przykładzie budynku mieszkalnego jednorodzinnego dla dwóch wariantów technologicznych: konstrukcji modułowej i tradycyjnej. Obie technologie zostały szczegółowo omówione. Analiza ekonomiczna opierała się na badaniach rynkowych ofert firm specjalizujących się w budowie budynków z wykorzystaniem danej technologii. Kosztorys dla konstrukcji tradycyjnej został przygotowany przy użyciu programu BIMestiMate. Przeprowadzono również analizę porównawczą czasu budowy budynków przy użyciu obu technologii.

Słowa kluczowe: analiza porównawcza, konstrukcja modułowa, konstrukcja tradycyjna

1. INTRODUCTION

Modular construction is a dynamically developing sector that has gained popularity in recent years. It allows for a significant reduction in project completion times without compromising on quality. What is more, the use of modern technologies in modular construction often leads to improved quality, which makes this method even more attractive.

*Cracow University of Technology, Poland, e-mail: krzysztof.zima@pk.edu.pl

structure

The construction process is strongly linked to environmental protection, with consideration given at the design stage to minimising the negative impact on the environment during the construction of the modules and throughout the entire life of the building. Modular construction technology offers a new perspective on the construction process, while also streamlining it. It is used in various areas, such as hotels, commercial and service buildings, student residences, multi-family residential buildings and single-family homes.

At present, modular construction is undergoing extensive development and offers significant advantages in a number of areas. The key to further progress is to streamline the design process, shorten the development cycle and increase competitiveness. Consequently, it is imperative to establish and optimise the design process for modular buildings. For instance, [1] proffers modular construction as a response to contemporary challenges, including the ongoing global pandemic, the war in Ukraine, population migration, military relocations, natural disasters and housing shortages in European markets.

2. MODULAR CONSTRUCTION

2.1. Sustainable design

Modular construction is a process in which a building is constructed off-site, in controlled factory conditions, using the same materials and designs that meet the same norms and standards as conventionally built structures – but in half the time [2].

The focus of modular construction technology is on sustainable design, self-sufficiency and environmental compatibility. The following modern technologies are utilised: solar panels, geothermal systems, and energy-efficient glass. The latter allows for effective heat accumulation during the winter months and reflects sunlight in the summer months, thereby maintaining an optimal temperature indoors. Additionally, a mechanical ventilation system with a recuperator is employed, which enables the recovery of heat from the ventilated room. As asserted by [3], modular construction is regarded as one of the most sustainable building solutions for mitigating environmental degradation during the operational phase of a building. A growing number of investors are opting for the construction of small houses, drawn to these structures by their simplicity, cost-effectiveness and rapid assembly.

In the context of the construction of modular buildings, it is imperative to prioritise the minimisation of waste, which is defined as the amount of materials utilised. In the nascent stages of construction, the amount of construction waste is a pertinent consideration. The fabrication process entails the utilisation of precise machinery to meticulously execute the cutting of repeatable elements to the precise dimensional parameters delineated in the design specifications. The potential exists for a 90% reduction in waste. The consumption of natural resources is also subject to limitations imposed by the utilisation of inter-module connections. These connections facilitate the straightforward disassembly and subsequent reuse of modules in alternative locations, thereby reducing the environmental impact. The elements from which the modules are made, or the entire modular structure, can be dismantled, and the materials used can be reused to create a new modular structure or recycled for use in other types of structures, not necessarily modular. The modules can be relocated to an alternative location or expanded in a variety of ways on site. The potential for reuse significantly reduces the requirement for further raw materials in the construction of new elements, thereby reducing energy consumption.

2.2. Development of modular construction

The expanding global population signifies a shared challenge confronting both developing and developed countries, namely the provision of adequate urban and industrial space. The construction sector must dedicate itself to continuous improvement and the pursuit of innovative solutions to facilitate the construction process. Modular construction offers the possibility of significantly reducing the time needed to complete buildings, thanks to advanced technology that involves prefabricating larger elements off-site.

Modular construction is a field that is undergoing constant development on the global market. Projections indicate the likelihood of sustained growth in this construction sector during the period from 2023 to 2030. A recent analysis by Data Bridge Market Research [4] has revealed that the average growth rate between 2015 and 2030 is projected to be 6.4%, with the value of the global modular market anticipated to reach USD 93.42 billion by 2030. In order to enhance the intricacy of the analysis, the modular construction market was segmented into regions, with local factors affecting the market being

Table 1. An examination of developmental trends across diverse geographical regions worldwide

Region	Key trends
 North America	The objective of sustainable urban development is twofold: firstly, to consider the quality of construction, and secondly, to ensure safety and comfort during work.
 Europe	The potential for reducing the construction time of a building facilitates accelerated urban development.
 Asia-Pacific	The design is uncomplicated, allowing for straightforward dismantling, expansion, or repositioning of the completed structure.
 South America	The construction of healthcare facilities can be accomplished expeditiously.
 Middle East and Africa	The propensity to invest is positively correlated with income level, and is further facilitated by convenient access to financial resources and loan opportunities.

Source: [4].

taken into account, including trends, trade routes and changes in building regulations. The analysis presented in Table 1 also takes into account potential investors and competition in the local and national markets, as well as technological developments. The report is based on three main criteria: the type of modules (PMC – Permanent Modular Construction and RC – Relocatable Construction), the materials used (wood, concrete, steel) and the building's purpose (hospitals, education, housing, hotels).

According to forecasts, China is set to assume a particularly prominent role in the field of modular construction in the forthcoming years, given its substantial impact on the construction sector. The country has the largest construction market in the world, accounting for approximately 20% of all global investments. China is a country undergoing significant population growth and improved living standards, which are increasing the demand for housing. This indicates that modular construction can grow rapidly to meet the needs of a growing population. This is particularly evident during the critical period of the 2020-2022 COVID-19 pandemic, when numerous hospital shelters were constructed rapidly across China, including the Wuhan Huoshen Mountain Hospital. This rapid construction is a testament to the significant benefits of modular construction. Nevertheless, a considerable proportion of modular buildings continue to exhibit substandard quality. Many manufacturers of modular buildings utilise rudimentary equipment and employ low-level assembly techniques. They have not established a comprehensive research and development and production system, which hinders the assurance of the quality of the buildings [5]. Figure 1 illustrates the global levels of development of modular construction.

Fig. 1. Areas of development in modular construction
Source: [6]

3. COMPARATIVE ANALYSIS OF MODULAR AND TRADITIONAL CONSTRUCTION

3.1. Analysis of manufacturing technology

A comparative analysis was conducted on two single-family residential buildings, each with a usable area of approximately 90 m², constructed using both modular and traditional technologies. The fundamental distinction between the two technologies pertained to the load-bearing structure of the edifice. In traditional construction methods, ceramic hollow brick walls were utilised, whereas in the context of modular technology, these walls were composed of a steel frame. This single-family residential building, constructed using modular building technology, consists of three modules based on a steel frame structure; it is a two-story building. Two modules make up the ground floor, which has a usable area of 61.48 m², while the first floor consists of one module with a usable area of 30.62 m² and a terrace located on one of the ground floor modules. The building's interior includes an entryway, a utility room, hallways, a living room with a kitchenette, 3 bedrooms, and 2 bathrooms. The total usable area is 92.35 m², and the building footprint is 83.03 m². The base modules (Module I and Module II) are set on a foundation-foundation footings-which the investor must construct on their own before proceeding with the installation of the modules.

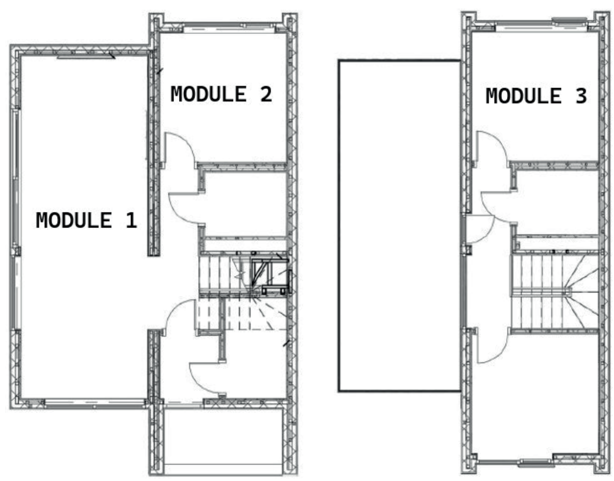

Fig. 2. Floor plan of the modular building-ground floor and first floor-including the assigned module numbers

Modules I and II have a simple cuboid structure, while the module on the second story has a gable roof covered with standing seam aluminum sheet metal. Dimensions of the modules used: Module I – 3.35 m × 3.60 m × 9.7 m, Module II – 3.35 m × 3.60 m × 12.30 m, and Module III – 3.85 m × 3.60 m× 12.30 m. The

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structure

Figure 2 shows the floor plans for the ground floor and first floor of the proposed modular building.

It is evident that both structures satisfy the criteria for ensuring adequate load-bearing capacity of the building and those relating to the heat transfer coefficient, in accordance with WT. As illustrated in Table 2, the heat transfer coefficient Uc for individual partitions was utilised as the fundamental metric for evaluating the quality of these elements. The U_c coefficient is a pivotal parameter in the assessment of the quality of building partitions. It is evident that a reduction in the value of the partition results in enhanced thermal properties, leading to diminished heat losses within the building and subsequent reduction in operating costs. The analysis indicates that partitions constructed using modular construction technology exhibit superior parameters in comparison to those produced by traditional methods.

Table 2. A comparison of the heat transfer coefficients for a selection of partitions

Thickness [cm]	Traditional technology	Heat transfer coefficient U_c [W/m²K]	Thickness [cm]	Modular technology	Heat transfer coefficient U_c [W/m²K]
	External walls above ground level	**0.19**		**External walls above ground level**	**0.16**
1.5	Ceresit CT36 thin-layer façade		0.30	Quartz sintered facade panel	
18.0	Termo Organika polystyrene foam		3.70	Ventilation layer	
28.8	Max 220 ceramic block		10.00	Ventirock Super rock wool with veil	
1.0	Cement-lime plaster		1.20	Duripanel B1 cement-bonded particle board	
			11.00	Rockton Super rock wool	
			-	Vapour barrier membrane	
			1.25	Nida Cicha plasterboard	
			1.25	Nida Ogień+ plasterboard	
	Monolithic reinforced concrete ceiling with unidirectional reinforcement	**0.30**		**Modular ceiling – module II (ceiling) and module III (floor)**	**0.10**
5.0	Concrete screed		1.50	Finishing layer	
-	Polyethylene foil		1.80	Brio 18 gypsum fibreboard	
10.0	EPS polystyrene foam		2.50	EPS 300 polystyrene board	
12.0	Reinforced concrete slab		2.20	Duripanel B1 cement-bonded particleboard	
2.7	Steel grating		-	Vapour barrier membrane	
1.3	Plasterboard		20.00	Rockton Super rock wool	
1.0	Cement-lime plaster		0.06	Galvanised steel sheet	
			8.00	Ventilation layer	
			-	Vapour-permeable membrane	
			0.06	Galvanised steel sheet	
			12.00	Rockton Super rock wool	
			8.00	Ventilation layer	
			-	Vapour barrier membrane	
			1.25	Nida Cicha plasterboard	
			1.25	Nida Ogień+ plasterboard	
	Floor on the ground	**0.28**		**Floor on the ground**	**0.13**
5.0	Concrete screed		1.50	Finishing layer	
-	PE foil		1.80	Brio 18 gypsum fibreboard	
10.0	XPS polystyrene foam		2.50	EPS 300 polystyrene board	
15.0	Concrete slab		2.20	Duripanel B1 cement-bonded particleboard	
-	KMB compound		-	Vapour barrier membrane	
10.0	B-10 concrete		16.00	Rockton Super rock wool	
20.0	Gravel (compacted)		7.00	Purteco PSC35 closed-cell foam	
			0.06	Galvanised steel sheet	

Source: own

3.2. Economic analysis

A cost estimate for the single-family residential building under analysis was prepared using the BIMestiMate programme, with the aim of facilitating a comprehensive and detailed calculation of the construction costs. The estimated price of the facility incorporates both direct and indirect costs, in addition to profit and VAT. The unit prices were adopted in accordance with the Sekocenbud price list for the fourth quarter of 2025. The construction of the building was estimated to cost PLN 480.000 gross. The roofing and external wall cladding had the greatest impact on the cost of construction using traditional technology for the analysed building.

The estimated cost of constructing the building using modular technology amounted to approximately PLN 460.000 gross, a figure derived from a tender conducted among companies involved in construction using the technology in question. As illustrated in Figure 3, the diagrammatic representation provides a visual representation of the percentage distribution of costs for a specified phase of construction, utilising both modular and traditional methodologies.

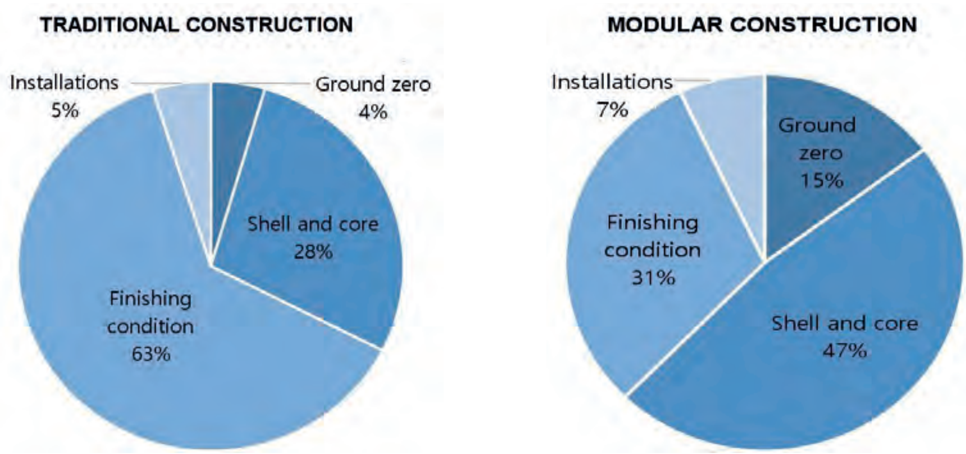


Fig. 3. Diagrams showing the percentage share of modular and traditional construction stages in economic terms
Source: own study

3.3. Analysis of construction time

Construction time is a key determinant of project efficiency, cost control, and client satisfaction. The method of construction-traditional or modular-has a significant impact on overall project duration. This section analyzes the differences in construction time between traditional construction and modular construction, highlighting the stages, influencing factors, and empirical data from relevant studies.

A detailed analysis of the construction time for a modular building, which averages 120 days, demonstrates that the construction time for a single-family house using modular technology is 30%-50% shorter (Fig. 4). This finding is consistent with the claim of a 50% reduction in construction time presented in [2] and cited in the introduction.

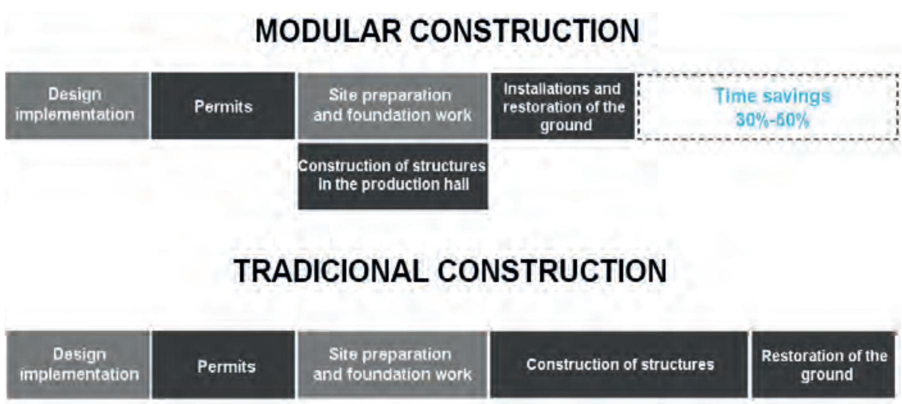


Fig. 4. Cost diagrams for individual stages in modular and traditional construction
Source: [7]

Table 3. Overview of Construction Processes – a differences between tradicional and modular construction

Stage	Traditional Construction	Modular Construction
Design Phase	Sequential – detailed design completed before construction begins.	Parallel – design and module manufacturing can overlap.
Site Preparation	Conducted before structural work begins; delays affect the schedule.	Can occur simultaneously with off-site module fabrication.
Structural Construction	On-site, weather-dependent, often labor-intensive.	Off-site, in factory-controlled conditions, faster and less weather-dependent.
Installation & Finishing	Occurs after structure completion.	Modules are installed rapidly; only final connections and finishes done on-site.

The construction time for a modular building is significantly shorter, mainly due to the repeatability of partition construction and the technology used to connect individual layers. The work is carried out in a closed production hall, which means that weather conditions do not cause delays due to forced interruptions to ongoing work. The MS Project programme was used to create a schedule for the construction of a single-family house using traditional technology, for which the construction time was set at 205 days.

The Table 3 provides a synopsis of the primary phases of the construction process in both traditional and modular terms, highlighting the fundamental discrepancies in the implementation of individual phases.

In the context of traditional construction methodologies, the process is characterised by its sequential nature, whereby each stage of construction commences only upon the completion of the preceding one. For instance, design work must be fully completed before construction can begin on site, and earthworks and foundation work must be completed before the structure can be erected. This arrangement frequently results in an increase in the overall project completion time and an elevated risk of delays due to meteorological conditions, material logistics or the coordination of construction teams.

Conversely, modular construction is distinguished by concurrent processes. In practice, this signifies that design work, prefabrication of modules in the factory and preparation of the construction site can be undertaken concurrently. The modules are manufactured in controlled factory conditions, regardless of weather and construction site constraints, which significantly reduces completion time. Subsequent to the completion of prefabrication, the finished elements are transported to the site and assembled expeditiously, with only finishing work and installation connections remaining on site.

Consequently, the implementation of modular technology in construction processes leads to enhanced integration, reproducibility, and temporal efficiency. In contrast, traditional methodologies are more prone to delays and external influences.

While modular construction significantly reduces on-site construction time, it requires more upfront planning and design coordination. Delays in manufacturing or transport can also affect schedules. However, once fabrication begins, the controlled factory environment enables consistent progress unaffected by external factors such as weather or site congestion. Traditional methods, although flexible for design changes, are slower due to sequential scheduling and dependency on multiple subcontractors.

4. DISCUSSION

The cost analyses are based on calculations and information obtained directly from companies, while the time analysis is based on frequently reproduced diagrams and analyses presented by various researchers. As illustrated in Table 4, a meta-analysis of select publications has been undertaken, with the objective of providing specific time-saving figures for comparisons between modular and traditional technologies.

As demonstrated in Table 4, an analysis of the data indicates that there is an average time saving of 28.9% when comparing modular and traditional technologies. It is evident from the publications cited that modular technology is significantly advantageous. With regard to the issue of cost comparisons, the mean cost saving was found to be 23.4%, whilst in one case, costs were identified as being 6.67% higher.

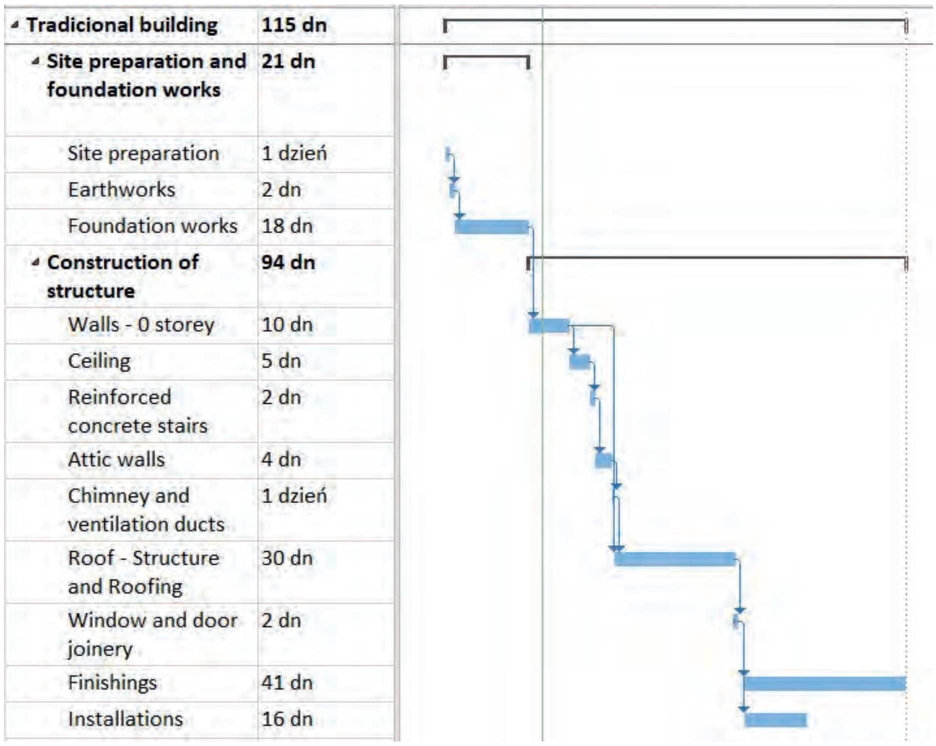
Table 4. A brief meta-analysis of differences in construction duration and costs between traditional and modular building methods

Type / scope of research	Time savings (modular vs traditional)	Cost savings (modular vs traditional)	Reliability assessment / type of methodology	Source
Industry-specific, analysis of numerous cases/clients	20–50% (the midpoint of **35%** was used in the calculations)	**≈20%**	Industry report, high practical relevance, but not peer-reviewed (weight: 1)	Bertram N., Fuchs S., Mischke J., Palter R., Strube G., Woetze J., Modular construction: From projects to products, McKinsey & Company, 2019.
17 PMC projects (empirical)	**45%** (averange)	**16%**	Empirical case studies (weight: 2)	https://www.enr.com/articles/16684-study-finds-modular-can-be-faster-safer-and-less-costly?utm_source=chatgpt.com
Case study / industrial buildings	**10.5%**	**39%**	Peer-reviewed (case study) (weight: 2)	Salih A., Wang C.C., Tian R., Mojtahedi M., A Case-Study-Based Comparative Analysis of Using Prefabricated Structures in Industrial Buildings. Buildings 2025, 15, 2416.
30 large-scale projects (residential, commercial, industrial)	**35%**	**22%**	Empirical quantitative (peer-reviewed/conference) (weight: 2)	Gómez M.F., Sánchez R.J., Impact of modular construction techniques on cost and time efficiency in large projects, International Journal of Civil Engineering and Construction 2024; 3(2): 43-47.
Single project (MS Project analysis)	**13%**	**-6.67%** (modular = 6.67% more expensive)	Empirical case; demonstrates variance (weight: 2)	Manjarekar A., Gadhave Y.A., Evaluating Modular Construction: Effects On Timelines, Costs, And Resource Efficiency Using MS Project. (2025). International Journal of Environmental Sciences, 95-104.
Systematic literature review	**35%** (often 20–50%)	**≈20%**	Systematic review (peer-reviewed) (weight: 1.5)	Zohourian M., Pamidimukkala A., Kermanshachi S., Almaskati D., Modular Construction: A Comprehensive Review. Buildings 2025, 15, 2020.

The cost analyses presented in the article by the authors did not reveal any significant differences in costs. In the case presented, the difference was 4.2% in favour of the modular technology.

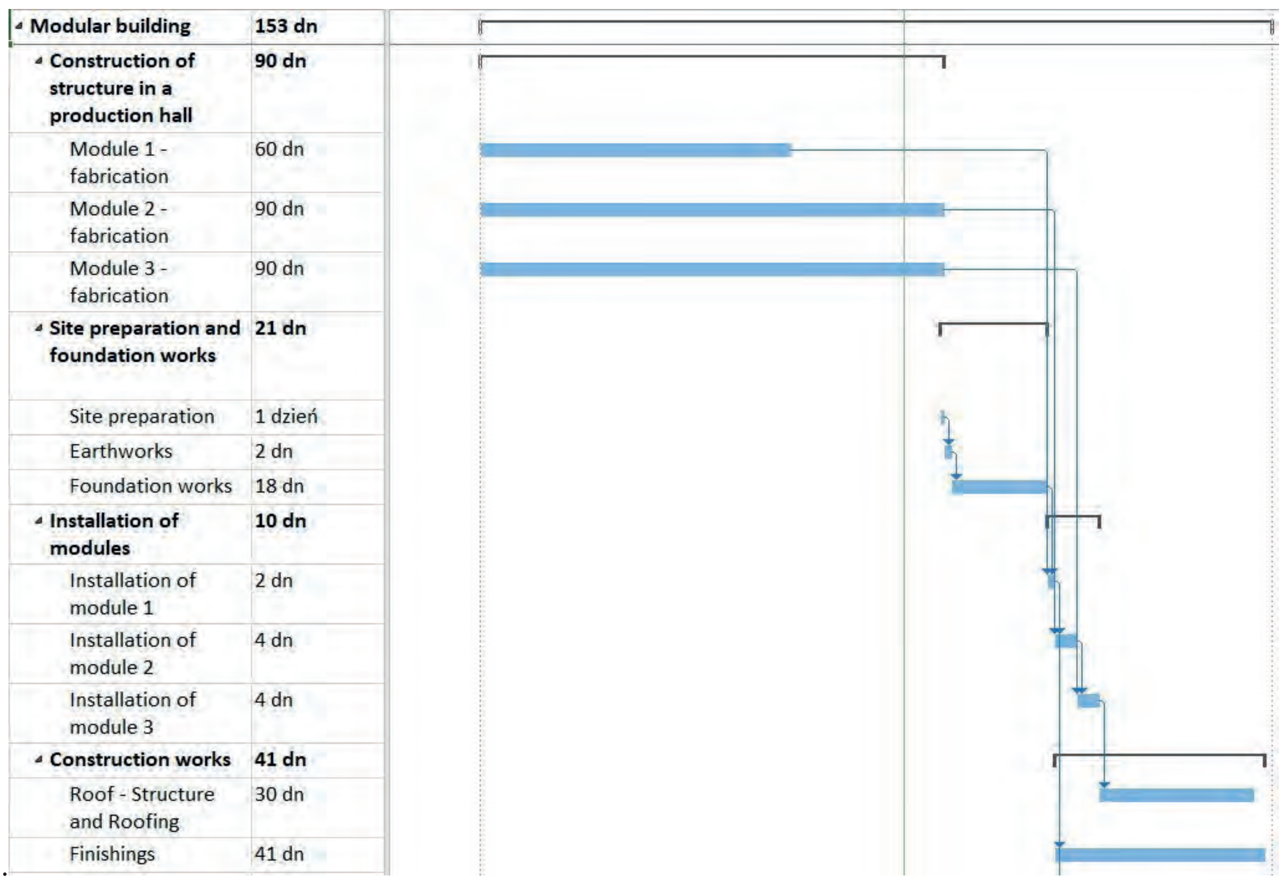
In order to verify the duration time differences for the analysed building construction examples using both technologies, the authors prepared construction schedules. Simplified versions of these are presented in Figures 5 and 6.

The provided schedules demonstrate that the construction of a building under identical site conditions using modular technology required 153 days, in contrast to the 115 days required when traditional methods were employed. Nevertheless, the protracted construction period for the modular approach was primarily attributable to the time allotted for the fabrication of modules 1-3 within the production hall. The timeframe is primarily influenced by the waiting time for the materials required for construction, as well as their availability during a given period and the number of orders. When analysing the time period during which construction was conducted on-site, excluding the production of the modules in the factory, it can be concluded that the actual construction time was 63 days. This result indicates a 45% reduction in construction time using modular technology compared to traditional methods.



Tradicional building	**115 dn**
Site preparation and foundation works	**21 dn**
Site preparation	1 dzień
Earthworks	2 dn
Foundation works	18 dn
Construction of structure	**94 dn**
Walls - 0 storey	10 dn
Ceiling	5 dn
Reinforced concrete stairs	2 dn
Attic walls	4 dn
Chimney and ventilation ducts	1 dzień
Roof - Structure and Roofing	30 dn
Window and door joinery	2 dn
Finishings	41 dn
Installations	16 dn

Fig. 5. Construction schedule for the construction of a sample building using traditional methods
Souce: own study



Modular building	**153 dn**
Construction of structure in a production hall	**90 dn**
Module 1 - fabrication	60 dn
Module 2 - fabrication	90 dn
Module 3 - fabrication	90 dn
Site preparation and foundation works	**21 dn**
Site preparation	1 dzień
Earthworks	2 dn
Foundation works	18 dn
Installation of modules	**10 dn**
Installation of module 1	2 dn
Installation of module 2	4 dn
Installation of module 3	4 dn
Construction works	**41 dn**
Roof - Structure and Roofing	30 dn
Finishings	41 dn

Fig. 6. Construction schedule for the construction of a sample building using modular technology
Souce: own study

5. CONCLUSIONS

Modular construction is an evolving field, with advances in technology and solutions being developed continually. This construction method introduces a novel approach to the building process, emphasising the optimisation of work and its independence from weather conditions, as the majority of the work is conducted within the controlled environment of a production hall. This methodology facilitates expedited construction without compromising quality, increasing costs or deteriorating the technical parameters of the building. The modular construction market is undergoing continuous development, which attests to the expanding potential of this technology. A growing number of investors are opting for modular construction, acknowledging its capacity to substantially reduce the time required to complete a project. The advantages of modular construction, particularly the reduced time needed for completion on site, the reduced impact on the environment and the reduced influence of weather conditions on the construction process itself, are well-documented. Consequently, its continued dynamic growth is to be expected.

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EVALUATION OF THE INFLUENCE OF RECYCLED GLASS AND CARBON GEOGRIDS ON THE STIFFNESS MODULUS OF ASPHALT CONCRETE

OCENA WPŁYWU RECYKLOWANEJ GEOSIATKI SZKLANEJ I WĘGLOWEJ NA MODUŁ SZTYWNOŚCI BETONU ASFALTOWEGO

Artur Kowalczyk*
Kielce University of Technology, Poland

Abstract

The paper presents the findings of a study on the influence of fibers derived from recycled geogrids on the stiffness modulus of asphalt concrete. The preliminary stage of the research involved a survey, which confirmed the escalating issue of reclaimed asphalt pavement (RAP) contamination with glass and carbon geogrid fibers, as well as the limited existing knowledge regarding their impact on asphalt concrete properties. The experimental program encompassed AC16W and AC22W mixtures modified with fibers ranging from 1 cm to 5 cm in length and at concentrations of 0.2% to 1.0% by weight. Analysis of the test results revealed that the application of carbon geogrid fibers did not lead to a significant increase in the stiffness modulus compared to the reference mixtures; conversely, glass fibers exhibited a tendency to reduce it. It was established that excessive fiber length and content lead to a reduction in the stiffness modulus. Based on the analyses, optimal parameters for maintaining high stiffness modulus values were determined: a fiber content of <0.2% and a length of <1 cm, regardless of the mixture's aggregate grading. The results indicate that geogrid recycling may represent an effective and rational approach supporting the circular economy and the development of sustainable asphalt technologies.

Keywords: geogrid recycling, sustainable development, reclaimed asphalt pavement, asphalt mixtures, glass and carbon fibers, experimental design

Streszczenie

W artykule przedstawiono wyniki badań nad wpływem włókien pozyskiwanych z recyklowanych geosiatek na moduł sztywności betonu asfaltowego. Elementem rozpoznawczym były badania ankietowe, które potwierdziły narastający problem zanieczyszczenia destruktu asfaltowego włóknami geosiatek szklanych i węglowych oraz ograniczoną wiedzę na temat ich wpływu na beton asfaltowy. Program badań obejmował mieszanki AC16W i AC22W modyfikowane włóknami o długości 1–5 cm i zawartości 0,2–1,0%. Analiza wyników badań wykazała, że zastosowanie włókien geosiatki węglowej nie powodowało istotnego wzrostu modułu sztywności względem mieszanek referencyjnych, natomiast włókna szklane wykazywały tendencję do jej obniżania. Stwierdzono, że nadmierna długość i udział włókien prowadzą do redukcji modułu sztywności. Na podstawie analiz określono wartości optymalne sprzyjające utrzymaniu wysokiej wartości modułu sztywności: zawartość włókien <0,2% oraz długość <1 cm, niezależnie od rodzaju uziarnienia mieszanki. Uzyskane rezultaty wskazują, że recykling geosiatki może stanowić efektywny i racjonalny kierunek wspierający gospodarkę o obiegu zamkniętym oraz rozwój zrównoważonych technologii asfaltowych.

Słowa kluczowe: recykling geosiatek, zrównoważony rozwój, destrukt asfaltowy, mieszanki mineralno-asfaltowe, włókna szklane i węglowe, plan eksperymentu

*Kielce University of Technology, Poland, e-mail: akowalczyk@tu.kielce.pl

1. INTRODUCTION

In European Union countries, more than 2.1 billion tones, of waste are generated annually, of which as much as 36% is accounted for by construction and demolition waste, encompassing materials such as concrete, ceramics, wood, glass, metals, and polymers [1]. An additional 26% is attributed to mining and quarrying waste, while the combined share of municipal, industrial, agricultural, service-related, and hazardous waste constitutes the remainder of the waste stream. In this context, waste generated by construction activities represents the largest share and remains one of the most critical areas for the development of the Circular Economy and the European Green Deal [2, 3]. In 2022, 14.8 million tones, of reclaimed asphalt pavement (RAP) were recovered in Germany, with as much as 87% being reused in the production of new asphalt mixtures [4]. In Poland, by contrast, reclaimed asphalt pavement is extensively utilized for road shoulder stabilization, which, as researchers point out, does not fully exploit its inherent potential [5]. Meanwhile, in accordance with the principles of the Circular Economy, waste should be treated as a secondary raw material and retained within the economic cycle for as long as possible [6]. In road engineering, reclaimed asphalt pavement (RAP) is a typical secondary waste material generated during the milling of pavement surfaces [7]. A critical problem that has been escalating in recent years is the presence of geogrid fragments within reclaimed asphalt pavement (RAP). Geogrids employed for the reinforcement of asphalt layers are manufactured from glass or carbon fibers, which are classified as synthetic, chemically stable, and inorganic materials [8]. In light of the guidelines [9] the permissible content of foreign matter – including synthetic materials – in reclaimed asphalt (RAP) is limited to <0.1% by mass [9,10]. Exceeding this threshold classifies the reclaimed asphalt as contaminated and precludes its use in the production of asphalt mixtures. Contamination of RAP with geogrid fibers is becoming increasingly prevalent, as glass and carbon geogrids are currently widely employed in maintenance treatments for flexible pavements [7, 11]. Geogrid fragmentation occurs during the milling process, and the resulting residues are incorporated into the reclaimed asphalt (RAP), presenting both technological and environmental challenges. Although geogrids are chemically inert and do not release hazardous substances [8], they are classified as foreign matter from the standpoint of technical standards. Their presence may restrict the recycling potential of RAP and pose a risk of secondary waste generation [10]. It is paradoxical that virgin glass, carbon, and synthetic fibers – in dosages of up to 4% by mass of the asphalt mixture – are described in both literature and road engineering practice as legitimate reinforcing additives [12-14], that improve, among other properties, rutting resistance, stiffness, and fatigue life [15-20]. Conversely, in the case of fibers derived from geogrid recycling, the situation is reversed; despite their similar mechanical properties, they are treated as contaminants that degrade the quality of the reclaimed asphalt [10]. However, international research findings indicate that post-service geogrid residues can be fully functional. Studies conducted by S&P Clever Reinforcement GmbH confirmed that fragmented glass geogrids retain desirable properties during the milling process and can be reintroduced into asphalt mixtures in compliance with German regulations [21, 22]. Furthermore, it has been demonstrated that their presence does not adversely affect rutting resistance [22]. In Poland, however, the issue of geogrid recycling remains largely unexplored; available industry data [5] indicate that while 80% of companies declare the use of RAP, the stringent limit on synthetic material contamination (<0.1%) significantly hampers its full utilization [10]. Against the background of these technological conditions and the existing research gaps regarding the impact of recycled geogrids on asphalt mixture properties, this study evaluates the influence of glass and carbon geogrid fibers derived from RAP on the stiffness modulus of asphalt concrete. The analysis was focused on identifying the optimal ranges for fiber content and length that allow for the retention of the favorable mechanical properties of the AC. Thus, the study verified the validity of treating recycled geogrid exclusively as technological contamination, considering its potential role as a structural modifier for asphalt concrete. This issue aligns with the strategic objective of rational secondary raw material management in road engineering.

2. METHODS AND MATERIALS

2.1. Geogrid

The study utilized virgin fibers obtained from glass and carbon geogrids, characterized by a tensile strength in both longitudinal and transverse directions exceeding 100 kN/m. These materials are commonly employed as reinforcement in asphalt pavement layers and bituminous overlays. Both geogrid types comply with the requirements of the PN-EN 15381 standard [23], which enables their full application in road engineering

Fig. 1. Virgin geogrid fiber after the simulated aging process in a Los Angeles machine

and provides a basis for analyzing their potential for reuse in the recycling process. The selection of these specific geogrids for the research was based on an assessment of RAP contamination and the results of a research survey [7], which confirmed the dominance of glass and carbon fibers as primary contaminants in reclaimed asphalt pavement. To replicate the real-world conditions of geogrid occurrence in RAP as closely as possible, the fibers underwent pre-treatment and a length-based selection process. Furthermore, the fibers were subjected to a simulated aging process in a Los Angeles (LA) machine (Fig. 1), where a cycle of 1,500 revolutions was performed for each 1 kg batch of geogrid fibers.

This procedure was intended to reflect the long-term service life of the geogrid within the pavement structure and the mechanical degradation occurring during the milling of the bituminous layers. Three fiber lengths were employed in the study: 1 cm (micro), and 3 cm and 5 cm (macro), which allowed for a comprehensive analysis of the influence of both fiber dimensions and type on the properties of the asphalt concrete. The laboratory aging and the selection of fiber dimensions made it possible to obtain a material that closely resembles the one found in actual reclaimed asphalt pavement (RAP) after the milling process. The fibers prepared in this manner were then incorporated into the asphalt mixtures, enabling an assessment of their impact on the mechanical and physical properties of the asphalt concrete in the context of the sustainable utilization of geogrids in the recycling process.

2.2. Asphalt Concrete Design

The design of the asphalt mixtures was preceded by a qualitative analysis of all components, including mineral aggregates, reclaimed asphalt pavement (RAP), the binder used, and the addition of glass and carbon geogrid fibers. The assessment was conducted in accordance with the material requirements specified in the guidelines and standards for asphalt mixture production [10, 24-27]. The composition of the mineral mixture was designed using the grading envelope method, which ensured an aggregate gradation meeting the criteria [9] for mixtures intended for the binder course [9]. The grading curves for the AC 16W KR3-4 and AC 22W KR3-4 mixtures are presented in Figures 2a and 2b.

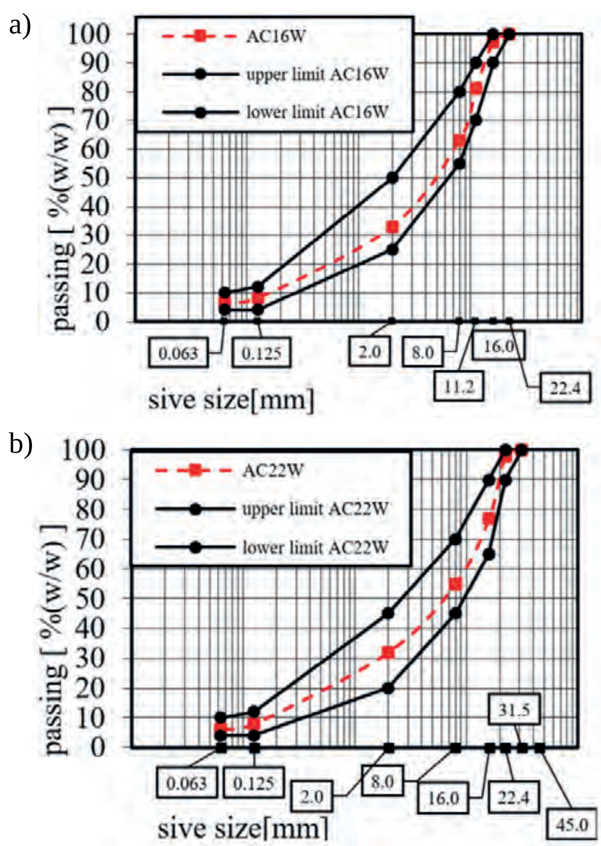

Fig. 2. Grading curves of the asphalt concrete (AC) mineral mixture: a) AC 16W KR3-4, b) AC 22W KR3-4

The composition of the asphalt mixtures is presented in Table 1.

Table 1. Percentage share of mineral and asphalt mixture components for AC 16W and AC 22W

Material	Description (Rock, Binder, Additive)	AC 16W 35/50 KR 3-4 Content [%] (m/m) mma	AC 22W 35/50 KR 3-4 Content [%] (m/m) mma
11.2 RAP 0/8*	Reclaimed Asphalt Pavement	19.3*	-
22.4 RAP 0/16**	Reclaimed Asphalt Pavement	-	19.3**
Aggregate 16/22 mm	Dolomite	-	21.2
Aggregate 8/16 mm	Dolomite	35.6	19.3
Aggregate 2/8 mm	Dolomite	20.2	15.5
Aggregate 0/2 mm	Dolomite	20.2	20.3
Limestone filler	Limestone	1.0	1.0
Bitumen 35/50	Paving grade bitumen	3.7	3.4
Adhesion agent	Adhesion agent	0.1	0.1
Total bitumen content	-	4.6	4.4

The asphalt mixture compositions designed in this manner ensured the stability of the mix and enabled an unambiguous assessment of the impact of recycled geogrid fibers on the properties of the asphalt concrete.

2.3. Experimental Design

The starting point for developing the experiment was determining the appropriate sampling method, which would allow for an unambiguous assessment of the impact of recycled geogrid fibers on the properties of the asphalt concrete. The research was based on a design incorporating diverse qualitative and quantitative input variables. Four independent variables were included in the experiment: two quantitative (fiber length and fiber content) and two qualitative (mixture type: AC 16W / AC 22W; and geogrid type: glass/carbon). The ranges for the quantitative variables were established at three levels, selected based on the research survey [7], and available literature concerning the impact of dispersed fibers-particularly glass and carbon-on the properties of hot-mix asphalt (HMA) [14]. The qualitative variables were introduced at two levels, covering the geogrids most commonly used in road construction and mixtures intended for the binder course, where the highest stress gradients in the pavement structure are typically observed. The adopted levels of the input variables are presented in Table 2.

Table 2. Input variables and their levels in the experimental design

Quantitative Variable	Levels	Qualitative Variable	Levels
Geogrid content, %	0.2; 0.6; 1.0	Geogrid type	Carbon; Glass
Geogrid length, cm	1; 3; 5	Asphalt mixture type	AC1 6W; AC 22W

To analyze the impact of geogrid fibers on the properties of asphalt concrete, a final plan comprising 11 variable combinations was developed (Table 3), enabling the fulfillment of the adopted criteria while maintaining testing efficiency. The number of replicates for each configuration was determined in accordance with the requirements of the relevant testing standards [28-31].

Table 3. Experimental matrix

No.	Geogrid Type	Asphalt mixture Type	Fiber content [%]	Fiber length [cm]
1.	glass	AC 16W	0.2	1
2.	glass	AC 16W	0.6	3
3.	glass	AC 16W	1.0	5
4.	glass	AC 22W	0.2	1
5.	glass	AC 22W	1.0	5
6.	carbon	AC 16W	0.2	1
7.	carbon	AC 16W	0.6	3
8.	carbon	AC 16W	1.0	5
9.	carbon	AC 22W	0.2	1
10.	carbon	AC 22W	0.6	3
11.	carbon	AC 22W	1.0	5

To facilitate further evaluation of the fiber-reinforced mixtures, the individual test series were coded according to the following system:

- G16021-1 – AC 16W KR3-4 mixture (16) with glass fibers (G), a fiber content of 0.2% (02), a fiber length of 1 cm (1), and the experimental design sequence number (-1);

- C16021-6 – AC 16W KR3-4 mixture (16) with carbon fibers (C), a fiber content of 0.2% (02), a fiber length of 1 cm (1), and the experimental design sequence number (-6);
- G22021-4 – AC 22W KR3-4 mixture (22) with glass fibers (G), a fiber content of 0.2% (02), a fiber length of 1 cm (1), and the experimental design sequence number (-4);
- C22105-11 – AC 22W KR3-4 mixture (22) with carbon fibers (C), a fiber content of 1.0% (10), a fiber length of 5 cm (5), and the experimental design sequence number (-11).

2.4. Physical and Mechanical Properties of Asphalt Concrete

To assess the impact of recycled glass and carbon geogrid fibers on the properties of the asphalt concrete, a comprehensive suite of standardized tests was first conducted to verify the compliance of the mixtures with the requirements of the relevant standards and guidelines [9, 26]. The scope of the asphalt mixture analysis included the evaluation of physical, mechanical, and volumetric properties. These parameters, along with their respective test codes and normative references, are summarized in Table 4.

Table 4. Tested parameters of the asphalt concrete

No.	Tested Property	Test Standard
1.	Air void content (V_a)	PN-EN 12697-8 [31]
2.	Water sensitivity (ITSR)	PN-EN 12697-12 [30], annex 1 for WT-2 p. I
3.	Resistance to permanent deformation (WTS_{AIR}), mm/1000 cycles, small device, method B, in air, 60°C, 10 000 cycles,	PN-EN 12697-22 [31]
4.	Resistance to permanent deformation (PRD_{AIR}), mm/1000 cycles, small device, method B, in air, 60°C, 10 000 cycles	PN-EN 12697-22 [31]
5.	Stiffness modulus (IT-CY)	PN-EN 12697-26 [28]

The completion of the basic tests enabled the transition to the main research stage, which involved determining the stiffness modulus (S_m) using the Indirect Tension Test on Cylindrical specimens (IT-CY). This was conducted in accordance with the test procedure described in PN-EN 12697-26, Annex C [28]. The target horizontal displacement was 5 µm ±2 µm, and the load rise time was 124 ms ±4 ms. The stiffness modulus was calculated according to the relationship shown in Equation (1), while the Poisson's ratio was determined based on the analytical relationship given in Equation (2):

$$S_m = \frac{F \cdot (\nu + 0.27)}{z \cdot h} \quad (1)$$

$$\nu = 3.59 \cdot \frac{z}{\Delta V} - 0.27 \quad (2)$$

where:

S_m – stiffness modulus of the specimen [MPa],
F – peak load applied to the specimen [N],
ν – temperature-dependent Poisson's ratio,
z – amplitude of the horizontal displacement of the specimen under loading [mm],
h – specimen thickness [mm],
ΔV – maximum vertical displacement of the specimen (corresponding to the peak horizontal displacement) [mm].

The specimens were prepared by compacting the asphalt mixture using a Marshall impact compactor, with 75 blows applied to each face (2 × 75) [32]. Immediately prior to testing, the specimens were conditioned for a minimum of 4 hours at the test temperature to ensure full thermal equilibrium throughout the material cross-section. Measurements were performed along two mutually perpendicular diameters.

3. RESULTS AND DISCUSSION

The evaluation of the impact of recycled geogrid on the properties of asphalt concrete is a highly complex issue, arising from the multidimensional nature of the interactions between the asphalt mixture composition and the parameters of the recycled geogrid fibers. As part of the preliminary research characterization, the basic properties of the asphalt mixtures were evaluated to determine their baseline state. The scope of the testing included air void content (*Va*), water sensitivity (ITSR), and resistance to permanent deformation, expressed by the WTS_{AIR} and PRD_{AIR} parameters (small device, Method B, in air, 60°C, 10,000 cycles). In this study, these basic test results, presented in Table 5, serve as an interpretative background for the in-depth analysis focused on the stiffness modulus (S_m), which is the key parameter characterizing the influence of the recycled geogrid on the mechanical behavior of the asphalt concrete.

Table 5. Basic test results of the asphalt mixtures

Mix code	V_a [% (v/v)]	ITSR [%]	WTS_{AIR}	PRD_{AIR}
G16021-1	2.4	78	0.07	5.6
G16063-2	3.9	108	0.08	6.8
G16105-3	4.3	102	0.07	6.5
G22021-4	5.4	79	0.06	5.5
G22105-5	6.0	103	0.07	7.5
C16021-6	4.1	105	0.06	5.8
C16063-7	5.2	97	0.05	6.6
C16105-8	7.3	97	0.09	8.5
C22021-9	5.7	95	0.06	5.5
C22063-10	6.4	100	0.07	6.2
C22105-11	7.8	101	0.07	6.5

The primary objective of the analyses was a detailed evaluation of the asphalt mixtures containing geogrid fibers, with a particular focus on the stress and strain distribution within the asphalt concrete intended for the binder course. To this end, special attention was paid to the stiffness modulus determined by the Indirect Tension Test on Cylindrical specimens (IT-CY), as an indicator sensitive to both changes in the mixture composition and the characteristics of the applied fibers. The stiffness modulus tests were conducted at five temperature levels: −10°C, 5°C, 13°C, 25°C and 50°C, in accordance with the requirements of PN-EN 12697-26 [28]. The obtained modulus values, presented in Figure 3, were subjected to aggregation and statistical analysis, taking into account the influence of the geogrid type, fiber content, and the type of asphalt mixture.

The use of a full temperature range allowed for determining the actual susceptibility of the material to service loads. The generalized stiffness moduli for glass and carbon geogrids, determined using the IT-CY method, showed an unambiguous dependence on the test temperature. As the temperature increased, a significant reduction in S_m values was observed, which is typical for thermoplastic materials where the susceptibility of the asphalt binder plays a dominant role in deformation. The highest values were recorded at −10°C, while the minimum values were found at 50°C, confirming the mixtures' transition to a state significantly more susceptible to permanent deformation. The statistical dispersion of the results increased significantly as the temperature decreased, indicating a stronger interaction between the asphalt binder and the presence of recycled fibers at low temperatures. Consequently, the obtained stiffness modulus values were the result of the cumulative influence of the test temperature. To illustrate the

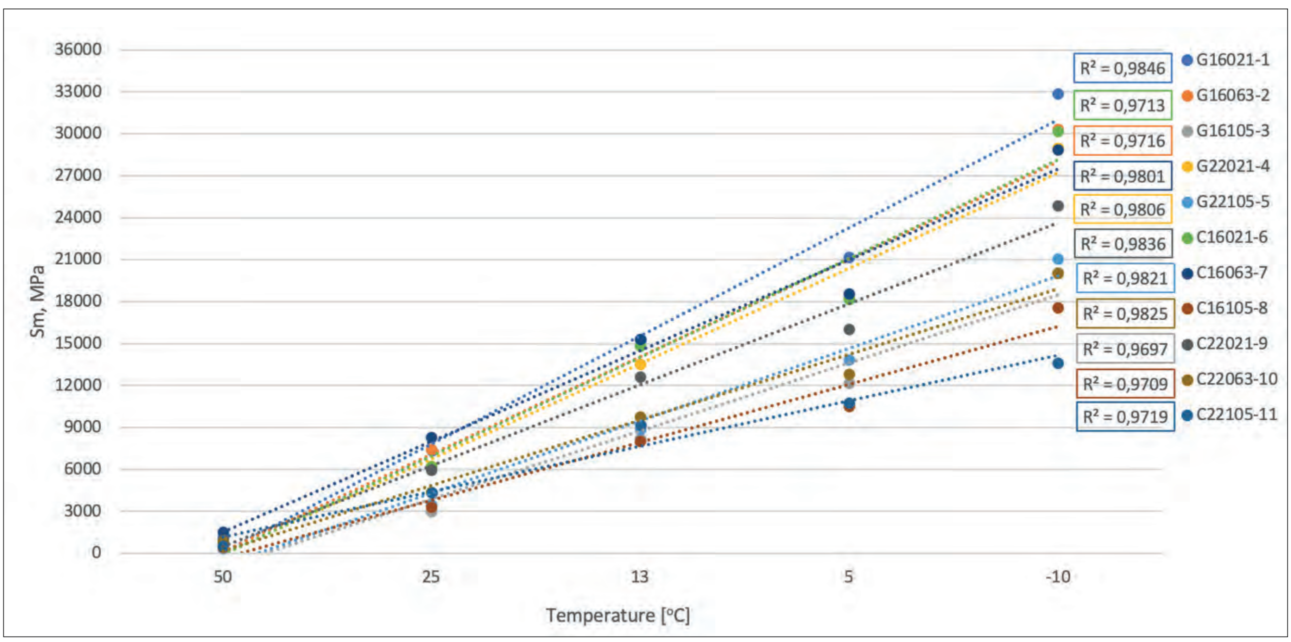

Fig. 3. Results of the stiffness modulus S_m (IT-CY) versus temperature

nature of the changes in the S_m parameter, it was aggregated with respect to individual temperature levels (Fig. 4).

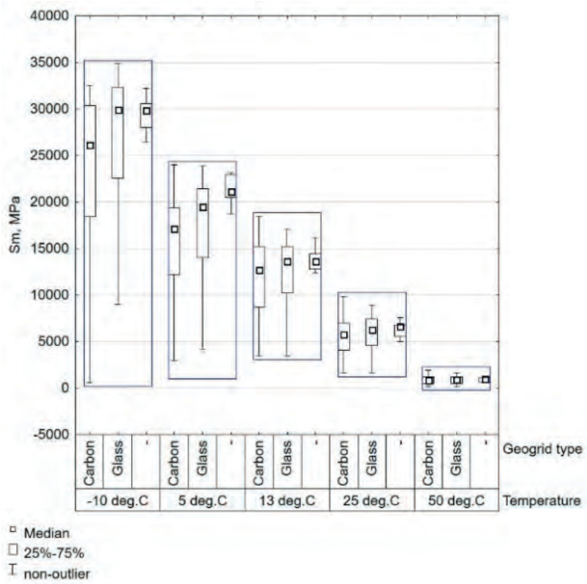

Fig. 4. Stiffness modulus S_m versus temperature categorized by geogrid material type

The results indicated that the application of carbon fibers had a stabilizing effect and, in most cases, led to a slight increase in S_m values. However, compared to the reference mixtures, the presence of the carbon geogrid did not cause a significant increase in the stiffness modulus S_m. At the same time, the carbon fiber-reinforced system exhibited lower variability of results than analogous compositions based on glass geogrid. This suggests that carbon fibers more effectively transfer and distribute stresses within the asphalt matrix, particularly at intermediate and high temperatures. A different trend was observed for mixtures containing glass geogrid, where a decrease in the stiffness modulus was noted in some systems. This confirms that glass geogrid does not provide the same level of reinforcement as carbon fibers introduced at the same dosages. It was observed that increasing the aggregate size of the asphalt mixture from 16 mm to 22 mm resulted in a reduction of the stiffness modulus, which was also evident in combinations with an excessive geogrid dosage (>0.2%). The overall median stiffness modulus determined for all mixtures at 13°C (Fig. 5) was 13.187 MPa, which is higher than the value of 10.300 MPa specified for road structures in the Catalogue of Typical Flexible and Semi-Rigid Pavement Structures [11].

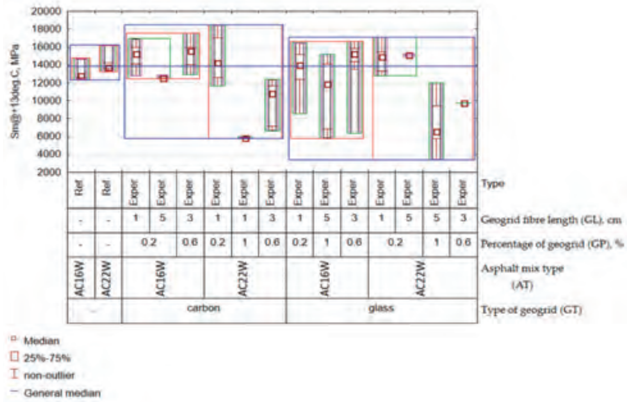

Fig. 5. Variation of the stiffness modulus S_m at 13°C

Obtaining slightly higher stiffness modulus values indicates a significant potential for increasing the pavement structure's resistance to permanent deformation, particularly in zones subjected to heavy traffic loads.

4. CONCLUSIONS

The conducted research and analyses led to the following detailed conclusions:

- The results of the analyses clearly indicate the need for in-depth studies regarding the presence of geosynthetic materials in Reclaimed Asphalt Pavement (RAP). The current permissible contamination limit of < 0.1% significantly restricts the practical utilization of RAP containing geogrid fragments. Simultaneously, the obtained results demonstrate that properly identified and classified RAP with recycled geogrid additives can positively influence asphalt concrete parameters, emphasizing the importance of precise identification of the feedstock material.
- The research demonstrated that the application of carbon geogrid fibers does not lead to a significant increase in the stiffness modulus (S_m) compared to the reference mixtures, whereas the presence of glass fibers in many combinations resulted in a reduction of stiffness. This underscores the necessity of distinguishing the geogrid material type during the suitability assessment of reclaimed asphalt.
- In line with the thermoplastic characteristics of asphalt materials, S_m values decreased as temperature increased, with the greatest dispersion observed at low temperatures. This suggests a dominant contribution of the interactions between the asphalt binder and the recycled geogrid fibers.

- The overall median S_m obtained for all results at 13°C (13.187 MPa) slightly exceeded the catalog value for AC mixtures (10.300 MPa). This confirms the beneficial potential of recycled geogrid in reducing the susceptibility of the pavement structure to permanent deformation. Furthermore, no significant degradation of stiffness was observed in mixtures containing recycled glass geogrid fibers.
- Analysis of the stiffness modulus S_m revealed that the most significant decrease in the modulus occurred with an increase in fiber length and percentage content, which was particularly evident at test temperatures of 13°C and 5°C. This indicates that an excessive amount of fibers may weaken the structural matrix of the asphalt mixture, especially within the range of low and moderate service temperatures.
- The results of the analyses clearly indicated that the optimal values for ensuring high stiffness S_m are: fiber content <0.2% and fiber length <1 cm, regardless of the aggregate gradation (AC 16W or AC 22W).
- A controlled amount of recycled geogrid fibers can provide an effective means of improving selected mechanical parameters, especially stiffness at higher service temperatures, while maintaining stability within the temperature range relevant to European climate conditions.

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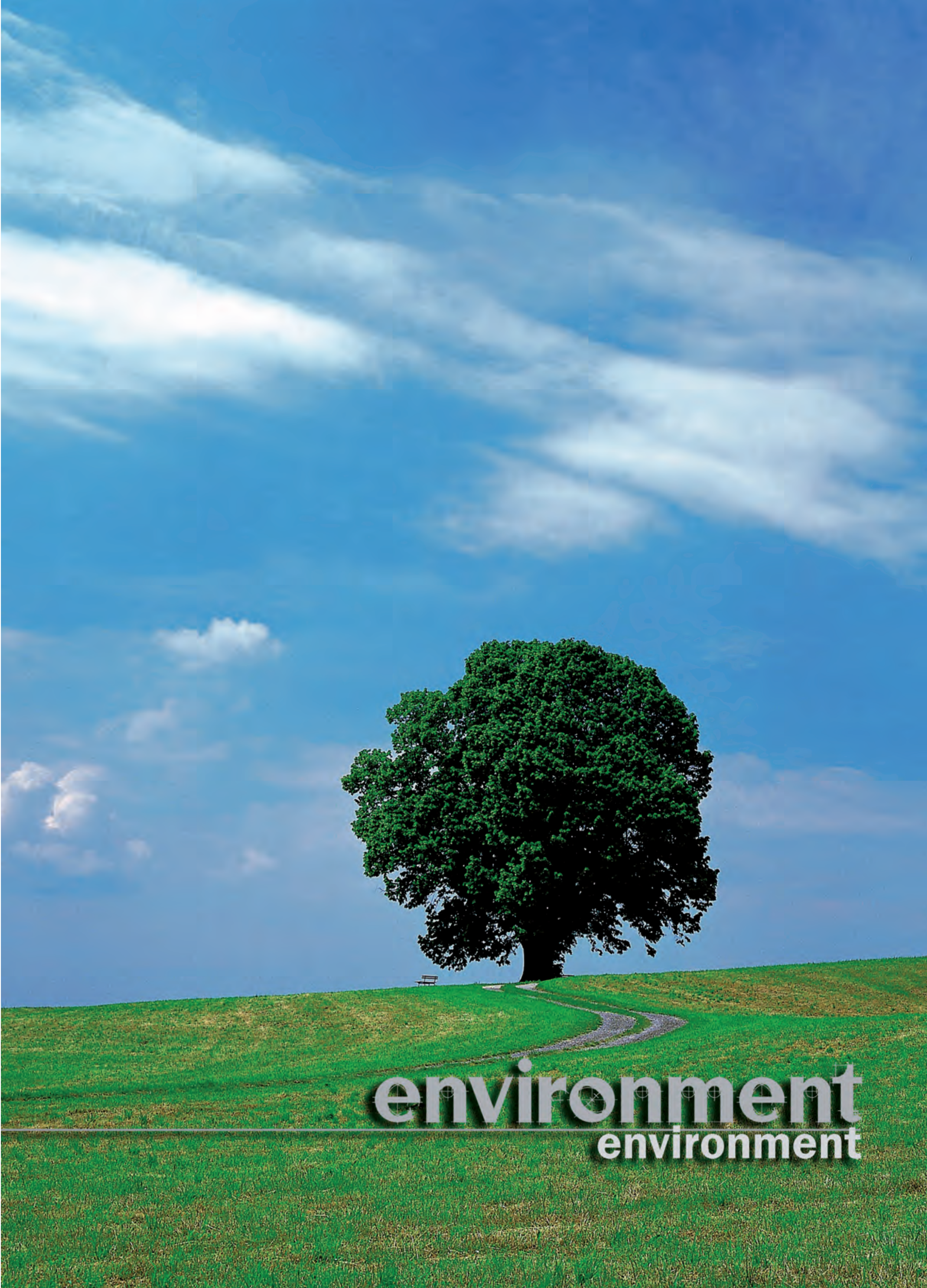
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VEGETAL COVER CHANGE AND COMMERCIAL CHARCOAL PRODUCTION IN THE SOUTHERN REGION OF NIGER STATE, NIGERIA

ZMIANA POKRYCIA ROŚLINNEGO I KOMERCYJNA PRODUKCJA WĘGLA DRZEWNEGO W POŁUDNIOWYM REGIONIE STANU NIGER W NIGERII

Jibrin Katun Mohammed*, Usman Abubakar Dzukogi
Federal Polytechnic Bida, Nigeria
Abdulafeez Adewale Olawale,
Federal University of Technology, Minna, Nigeria

Abstract

Vegetal cover change is a threat globally, a phenomenon with less attention concerning charcoal production. This study investigates vegetal cover loss and commercial charcoal production by analyzing three major charcoal depots in Niger south, Nigeria: Tatabu, Badeggi, and Batati. Utilizing a quantitative approach, primary data were collected through 663 questionnaires and secondary data via Landsat satellite imagery of 2010, 2015, and 2020 within a five-kilometer radius of the depots. Relative importance index (RII) was used to analyse primary data, while satellite imageries were processed using ArcGIS 10.8 software. Findings indicate a decrease in vegetative cover in Badeggi from 472.65 ha in 2010 to 269.92 ha in 2020. Key drivers of vegetation loss include deforestation (0.763 RII), farming (0.700 RII), and construction (0.690 RII). The region produces an average of 132 bags of charcoal weekly and ten truckloads monthly. The study emphasizes the urgent need for sustainable environmental management and alternative energy sources.

Keywords: charcoal production, deforestation, land cover change, Niger south, vegetal cover

Streszczenie

Zmiana pokrycia roślinnego stanowi globalne zagrożenie, a zjawisku temu poświęca się mniej uwagi w kontekście produkcji węgla drzewnego. Niniejsze badanie analizuje utratę pokrycia roślinnego i komercyjną produkcję węgla drzewnego, analizując trzy główne składy węgla drzewnego w południowej części stanu Niger w Nigerii: Tatabu, Badeggi i Batati. Wykorzystując podejście ilościowe, zebrano dane pierwotne za pomocą 663 kwestionariuszy oraz dane wtórne za pomocą zdjęć satelitarnych Landsat z lat 2010, 2015 i 2020 w promieniu pięciu kilometrów od składów. Do analizy danych pierwotnych wykorzystano względny wskaźnik ważności (RII), a zdjęcia satelitarne przetworzono za pomocą oprogramowania ArcGIS 10.8. Wyniki wskazują na zmniejszenie się pokrywy roślinnej w Badeggi z 472,65 ha w 2010 r. do 269,92 ha w 2020 r. Głównymi czynnikami powodującymi utratę roślinności są wylesianie (0,763 RII), rolnictwo (0,700 RII) i budownictwo (0,690 RII). Region produkuje średnio 132 worki węgla drzewnego tygodniowo i dziesięć ciężarówek miesięcznie. Badanie podkreśla pilną potrzebę zrównoważonego zarządzania środowiskiem i alternatywnych źródeł energii.

Słowa kluczowe: produkcja węgla drzewnego, wylesianie, zmiana pokrycia roślinnego, południowy Niger, pokrycie roślinne

*Federal Polytechnic Bida, Nigeria, e-mail: jibrinkatun@gmail.com

1. INTRODUCTION

Vegetation is one of nature's most valuable gifts to mankind which is vital to the survival of a large section of the world's population, both humans and animals (Belayneh, Ru, Guadie et al., 2018). Vegetal cover removal is the most usually mentioned impact of charcoal production. In Africa and South America, charcoal consumption is increasing at a faster rate than firewood consumption, and it is now accounting for a huge share of overall wood energy use (Pennise, Smith, Kithinji et al., 2001). Although, investment in forest plantation-based charcoal production is increasing in tropical regions, majority of biomass for charcoal production comes from natural forests, where spontaneous regeneration is the primary source of forest recovery (Chidumayo & Gumbo, 2013). The main reasons why governments, non-governmental organizations and civil society are conscious of the environmental impacts of wood fuel are this general pattern – almost complete reliance on forest resources for charcoal production – as well as perceived unsustainable harvesting and poor post-harvest forest management (World Energy Corporation, 2004).

Rapid changes in Land Use and Land Cover (LULC) due to urbanization have significant effects on biodiversity, ecosystem dynamics, and regional and national climate (Choudhury, Das & Das, 2019). One third (2.4 billion) of the global population depends on charcoal and firewood for most of their cooking and heating requirements (FAO, 2017). For 29 countries primarily in sub-Saharan Africa (SSA), woodfuel constitutes more than 50% of total national energy supply (FAO, 2014). It is estimated that worldwide, approximately half of the wood extracted from forests is used as woodfuel, 17% of which is converted to charcoal (FAO, 2017). In woodfuel-dependent nations, over extraction of woody biomass to supply the energy sector can jeopardize the status of forests and their ability to fulfill their regulatory functions (Bazilian et al., 2011).

An integral part of every human society is the use of forests and trees by human being for various activities ranging from lumbering to construction without leaving behind the use of forest for charcoal production which serve as fuel for cooking in many third world nations. Apart from serving as a strategic measure in environmental conservation, forests and vegetation cover equally present man with various socioeconomic advantages which aids sustainable development. Many studies have attempted a study into vegetal cover change also viewed most times as Land Use and Land Cover Change (LULCC) (Choudhury, Das, & Das, 2019; Belayneh, Ru, Guadie, Teffera, & Tsega, 2018; Arowolo & Deng, 2018; Akbari, Shea Rose, & Taha, 2003; Hailua, Mammoa, & Kidan, 2020). The impact of LULCC on temperature change was studied by (How Jin Aik et al., 2020; Choudhury et al., 2019). Also, Belayneh et al. (2018) studied the driving forces behind forest cover change while Arowolo and Deng (2018) explored the driving factors of variation and transition of cultivated land use, Akbari et al. (2003) evaluated the effects of landscaped surfaces and urban vegetation on meteorology and air quality while Kiruki et al. (2016) appraised land cover change and the role of charcoal production in woodland degradation.

In the aspect of commercial production of charcoal as a fuel for cooking and its resultant effects on physical and economic environment (Ekpo & Mba, 2020; Chidumayo & Gumbo, 2013; Lynch et al., 2004; Máliš et al., 2021). Historical charcoal burning and coppicing suppressed beech and increased forest vegetation heterogeneity was the focus of Máliš et al. (2021) while Lynch et al. (2004) studied charcoal particle production, size, and transport during the International Crown Fire Modelling Experiment. Choudhury et al. (2019) assess the effects of charcoal production in world tropical ecosystems. It is observed from the literature that none of the research investigates vegetal cover removal and charcoal production as it affect the social, economic and environmental sustainability. It is on this backdrop that this study attempts to fill the gap by evaluating the vegetal cover change and commercial charcoal production in the southern region of Niger State, Nigeria using remote sensing and GIS, in a bid to reveal the level of variation in LULCC over the years while unveiling the endemic effects of charcoal production in commercial volume for cooking fuel on the sustainability of the environment. The study therefore examine; the variation in vegetal cover change from 2011 to 2021 alongside level of commercial charcoal production and factors responsible for removal of vegetal cover in the southern region of Niger State.

2. LITERATURE REVIEW

2.1. Vegetal Cover Change

In many earth system processes, vegetal cover is a critical factor (Hansen et al., 2000). Humans and other creatures rely heavily on vegetation as a natural resource. For resource management and challenges related to land cover change, monitoring and evaluating the types and extent of vegetation is critical (Rakiya et al., 2018). Today's vegetation is predominantly influenced by human activity, and any understanding of global change must take into account the widespread impact of human activity on land surface conditions and processes. Anthropogenic influences are having a dramatic effect on the urban environment, redefining vegetation and presenting new problems and research opportunities as the human population grows and more people move to urban areas (Rakiya et al., 2018).

The impact of competing biophysical processes on Earth's surface energy balance varies regionally and seasonally, and depending on specific vegetation changes and baseline temperature, can result in warming or cooling (Duveiller et al., 2013). LULCC studies have become an important part of modern natural resource management and environmental monitoring techniques. Recently, the decreasing vegetal cover over Nigeria gives an accurate assessment of the spread and health of the world's grassland, water, agricultural, and land resources being/becoming a top issue (Fanan et al., 2011; Fashae et al., 2017).

2.2. Charcoal Production

Despite the move to cleaner and more energy-efficient fuels like as gas and electricity, charcoal remains a major source of energy for many urban and peri-urban families in Sub-Saharan Africa (SSA), Southeast Asia, and Latin America (FAO, 2017). Affordability and cultural preferences for charcoal, together with high rates of population growth and urbanization in these countries, predict that demand will keep growing for the next thirty to fifty years before it begins to decline (Santos et al., 2017). Because most charcoal comes from natural forests (Chidumayo & Gumbo, 2013; FAO, 2017), addressing this expanding demand is already causing issues in the tropics' energy, forestry, and environmental sectors.

Charcoal is utilized as a fuel in domestic cooking and some companies; particularly those specialized in casting bronze and other metals can be produced all year round, involving woodland exploitation, which enhances deforestation, having varieties of negative consequences such as the loss of valuable resources and the environment, as well as driving climate change through the release of greenhouse gases, reducing the bio-productivity of natural ecosystem by altering the habitats of numerous species, and exposing bare surfaces vulnerable to runoff, thus making the product more expensive (Mwampamba et al., 2018; Silva et al., 2019; Ekpo & Mba, 2020).

Increased accessibility and improved satellite imagery have greatly assisted current understanding of charcoal production technologies over the years, resulting in a revived interest in evaluating the larger consequences of commercialized charcoal production on vegetal cover and habitat (Sedano et al., 2016; Ahrends et al., 2010; Bailis et al., 2017; Ghilardi et al., 2016). Nearly 80% of people in African cities use charcoal as their primary cooking fuel (Zulu & Richardson, 2013). People in rural hinterlands with few economic options accelerate charcoal manufacturing as demand rises as a result of growing urbanization (Chidumayo & Gumbo, 2013; Jagger & Jumbe, 2016; Mulenga, Hadunka, & Richardson, 2017). Commercial charcoal production contributes significantly to environmental degradation and sustainable livelihoods by removing vegetation and disrupting the ecosystem (Hosonuma et al., 2012; Ryan, Berry, & Joshi, 2014).

2.3. Effects of Charcoal Production on Vegetal Cover

Charcoal production entails woodland mining, which contributes to deforestation, which has a lot of negative implications, including the loss of precious resources and severe environmental interference (Martin et al., 2012). As a result, by depleting our natural habitats, deforestation has a negative influence on society and economies in the long run, and sustainable forest management has been a top priority given the potential impact on global biodiversity. Charcoal production necessitates the cutting of trees and the removal of natural vegetation, both of which contribute to species extinction. The loss of genes, populations, species, and ecosystems through removal of tree is rapid and irreversible if fundamental ecological processes are disrupted (Chidumayo & Gumbo, 2013). Biodiversity is the foundation of ecosystem health and ecological service supply. According to Rockstro et al. (2009), species interaction exists in an ecosystem, as such the decline or extinction of one species has an effect on the life span of other organisms and the ecosystem as a whole.

When forest cover is removed, wildlife loses habitat and becomes more prone to poaching (Bailis et al., 2005). Emissions of greenhouse gases from charcoal production in tropical ecosystem in 2019 are estimated at 71.2 million t of carbon dioxide and 1.3 million t for methane (Chidumayo & Gumbo, 2013). Smoking and carbon emissions from wood burning cause physical and mental health problems. Also contributes to climate change that has some health effects. Many trees inside forest reserves serve as source of local herbs for the fringe community, which they use to take care of their health issues. According to the local

environment

homeopathic medicine dealers, deforestation has made them to lose many trees that they use for treatment and some are on extinction (Ekpo & Mba, 2020). Millions of people rely directly on forests for their livelihoods, whether through small-scale agriculture, hunting and gathering, or the collection of forest products like rubber. Vegetal cover change continues to cause serious socioeconomic issues, even violent conflict in certain cases. In the year 2000, global wood production totalled 3.9 billion m^3, of which 2.3 billion m^3 were used as charcoal, meaning that around 60% of the world's total wood removals from forests and trees are used for energy purposes (FAO, 2008).

2.4. Relative Importance Index

The Relative Importance Index (RII) is one of the widely adopted statistical techniques for assessing variables according to their priority and ranking, especially in social sciences disciplines and sustainability studies. RII provides standardized scores for the relative importance of each factor analyzed. The RII is calculated using the following formula:

$$RII = \frac{\sum W}{A \times N}$$

where:
W – weight assigned to each response,
A – highest possible weight,
N – total number of respondents.

In environmental science research, RII has been extensively adopted to identify and rank risk factors, and performance indicators. For example, RII was adopted by Gündüz et al. (2013) in assessing and ranking delay factors in construction projects, Khatib et al. (2020) used RII to rank delay factors in reconstruction and rehabilitation of projects, while Genc (2023) identified principal risk factors using RII. Rooshdi et al. (2018) adopted RII to analyzed design and construction activities for sustainable green highways. In contrast, Aghili et al. (2019) applied RII to assess green building management. Recent study by Ibrahim et al. (2025) adopted fuzzy RII model to assess lean construction practices.

3. METHODOLOGY

The study area is located between latitudes 8°20'N and 9°45'N and longitudes 4°85'E and 6°80'E. It is an extensive lowland region with about 100-200 metres in height covering eight Local Government Areas of Mokwa, Edati, Lavun, Katcha, Agaie, Bida, Gbako and Lapai, respectively (see Fig. 1).

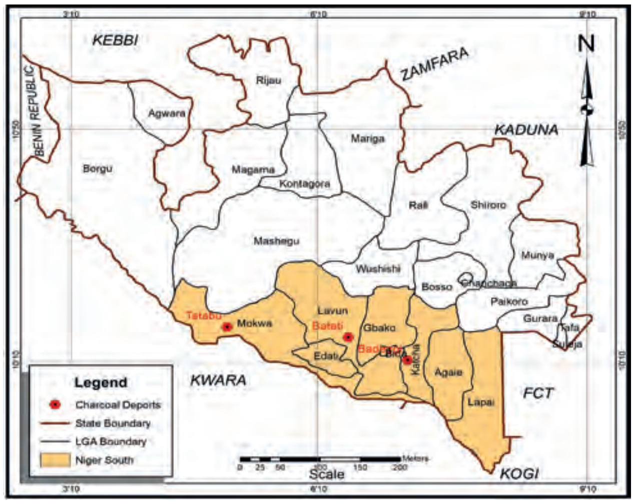

Fig. 1. Location of the Study Area in Niger State, Nigeria
Source: Niger Ministry of Lands and Housing, 2022

Data were be sourced from both primary and secondary sources with the help of GIS and remote sensing, physical observations relevant to the study were observed, measured, and recorded with the help of structure closed ended questionnaire and discussion with selected respondents across the eight regions. Secondary data were obtained from relevant texts, journals, newspapers, government publications, magazines, and the internet, which served as a concrete source of insight into charcoal production and deforestation. The sample size was determined based on the entire population of the study area in general, and each of the locations or districts of the region in general. The estimated households of the area were adopted as sample size for more representative and realistic questionnaire administration.

The total population of the LGAs were projected from 2006; the last known population census conducted in the country to one million, six hundred and ninety two thousand, two hundred and thirty three (1,692,233) in 2022. Bartlett sample size formular was adopted to ascertain the sampled respondents of six hundred and sixty three (663) for questionnaire administration (See appendix A). The percentage contribution of each LGAs and districts to the entire population was adopted for eventual administration of structured closed ended questionnaires with a five point likert scale to enable eventual ranking through the relative importance index for the factors contributing to the removal of vegetal cover.

For the vegetal cover analysis, data were collected and analysed via Landsat image classification which involves acquisition of multispectral images, followed by pre-processing (radiometric and geometric correction, and cloud removal) alongside supervised classification algorithms for categorizing vegetal cover types using training data, while ground trotting enables accuracy and validation as suggested by Mohajane et al. (2018) and You et al. (2022); post processing of data for analysis include spatial filtering and change detection for comparison of different time series/periods (2010, 2015 and 2020) respectively to identify the extent of vegetal cover loss overtime. This is then followed by quantitative and spatial analysis for classifying the extent of vegetal loss overtime and spatial illustration on maps via ArcGIS version10. Relative Importance Index (RII) was adopted in ranking the various factors contributing to vegetal cover loss in the study area.

4. DATA ANALYSIS AND PRESENTATION

4.1. Vegetal Cover Change from 2011 to 2021

The three major charcoal deports including Badeggi, Batati and Tatabu in the study area were selected as the place of interest in satellite image classification. The satellite imageries captured covers 5 km from the charcoal deports. This allows monitoring of the vegetal cover loss over time. The satellite image classifications are presented in Figures 2, 3 and 4.

Findings of the study in relation to Badeggi shown in Table 1 reveals that the vegetation cover in 2010 was 472.65 ha while built-up area covers 706.68 ha and bare land covers 638.69 ha respectively. However, the vegetation cover reduces to 333.94 ha in 2015 while built-up area coverage increased to 1,014.41 ha and bare land equally drops to 469.67 ha in Badeggi. Meanwhile, further decline was observed for 2020 where vegetation cover was estimated to be 269.92 ha, built-up area coverage further rose to 1,231.11 ha and bare land further drops to 316.99 ha in Badeggi axis. As further contained in the table, the 26% vegetal cover in 2010 had declined to 14.85% of the total coverage area in 2020 across the selected radius of the depot in Badeggi while built-up area coverage rose from 38.87% in 2010 to 67.72% in 2020 and bare land equally drops from 35.13% in 2010 to 17.44% in 2020.

Table 1. Classification of vegetal cover in Badeggi

Classification	2010		2015		2020	
	Ha	%	Ha	%	Ha	%
Vegetation	472.65	26.00	333.94	18.37	269.92	14.85
Built-Up Area	706.68	38.87	1,014.41	55.80	1,231.11	67.72
Bare Land	638.69	35.13	469.67	25.83	316.99	17.44

Source: Landsat image 2021.

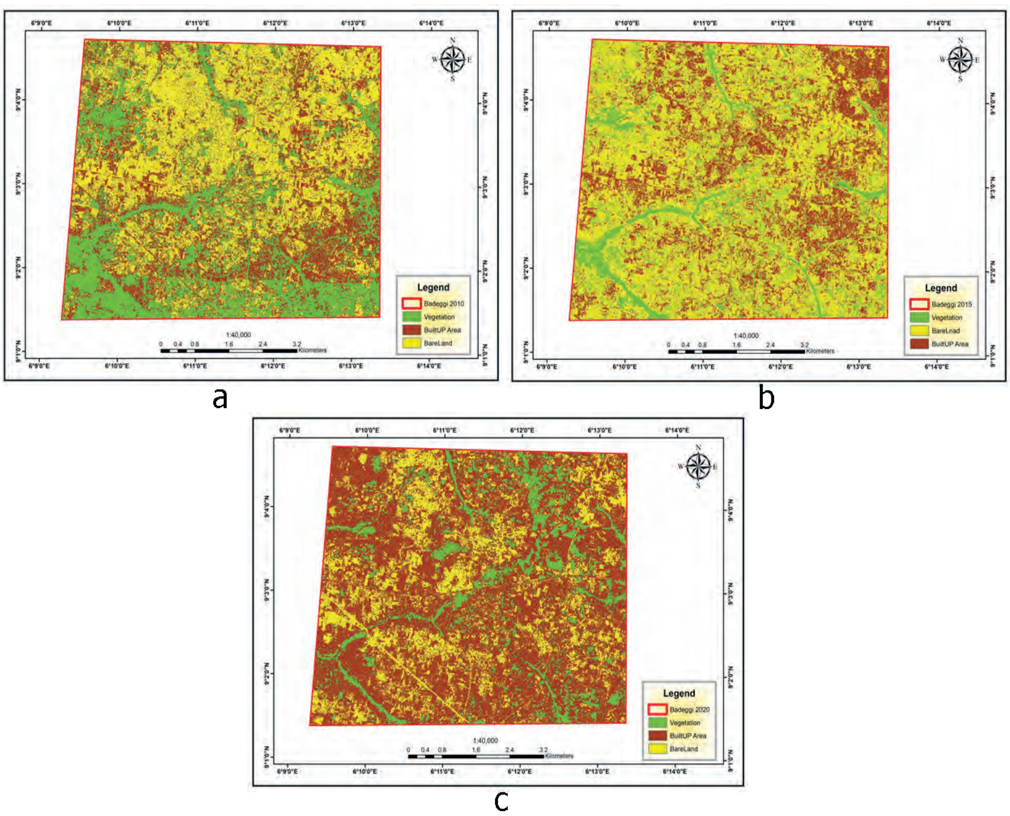

Fig. 2. Vegetal cover change in Badeggi: a) 2010, b) 2015 and c) 2020

The spatial representation of this finding in depicted in Figure 2 where in 2010, the vegetation cover was evidently present in Figure 2a; obvious change in vegetal cover is depicted in Figure 2b where significant increase was observed for built-up area and bare land and vegetation cover decline. A further significant decline in vegetal cover was observed in Figure 2c where greenery is almost invincible and disappearing from the location with more dominant built-up area and bare land resulting from various action of deforestation (farming, mining, construction, charcoal production among others) leading to loss of vegetation

Furthermore, results from Batati presented in Table 2 indicated that the vegetal cover in 2010 was 1,491.75 ha while built-up area covers 708.79 ha and bare land covers 102.43 ha respectively. Meanwhile, the vegetal cover reduces to 687.11 ha in 2015, built-up area coverage rose to 932.4 ha and bare land increased to 683.46 ha in Batati. Similar to the observation in Badeggi, further decline of vegetal cover was observed for 2020 with 351.74 ha vegetation, built-up area coverage further increased to 1244.2 ha and bare land further grew to 707.03 ha in Batati axis. As further depicted in the table, the 64.78% vegetal cover in 2010 had declined to 15.27% of the total coverage area in 2020 across the selected radius of the charcoal depot in Batati while built-up area coverage rose from 30.78% in 2010 to 54.03% in 2020 and bare land equally rose from 4.45% in 2010 to 30.70% in 2020.

Table 2. Classification of vegetal cover in Batati

Classification	2010		2015		2020	
	Ha	%	Ha	%	Ha	%
Vegetation	1,491.75	64.78	687.11	29.84	351.74	15.27
Built-Up Area	708.79	30.78	932.4	40.49	1244.2	54.03
Bare Land	102.43	4.45	683.46	29.68	707.03	30.70

Source: Landsat image 2021.

The spatial representation of this finding in depicted in Figure 3 where in 2010, the presence of green vegetation was evident in 2010 with over 50% of the entire radius shown in Figure 3a; obvious decline in vegetal cover is depicted in Figure 3b where significant increase was observed for bare land accompanied by declining vegetation. A further significant decline in vegetal cover was observed in Figure 3c where greenery is almost fading away while bare land and built-up area becomes more pronounced compared to Figure 3a as a result of various factors like farming, mining, charcoal production among others leading to loss of vegetation.

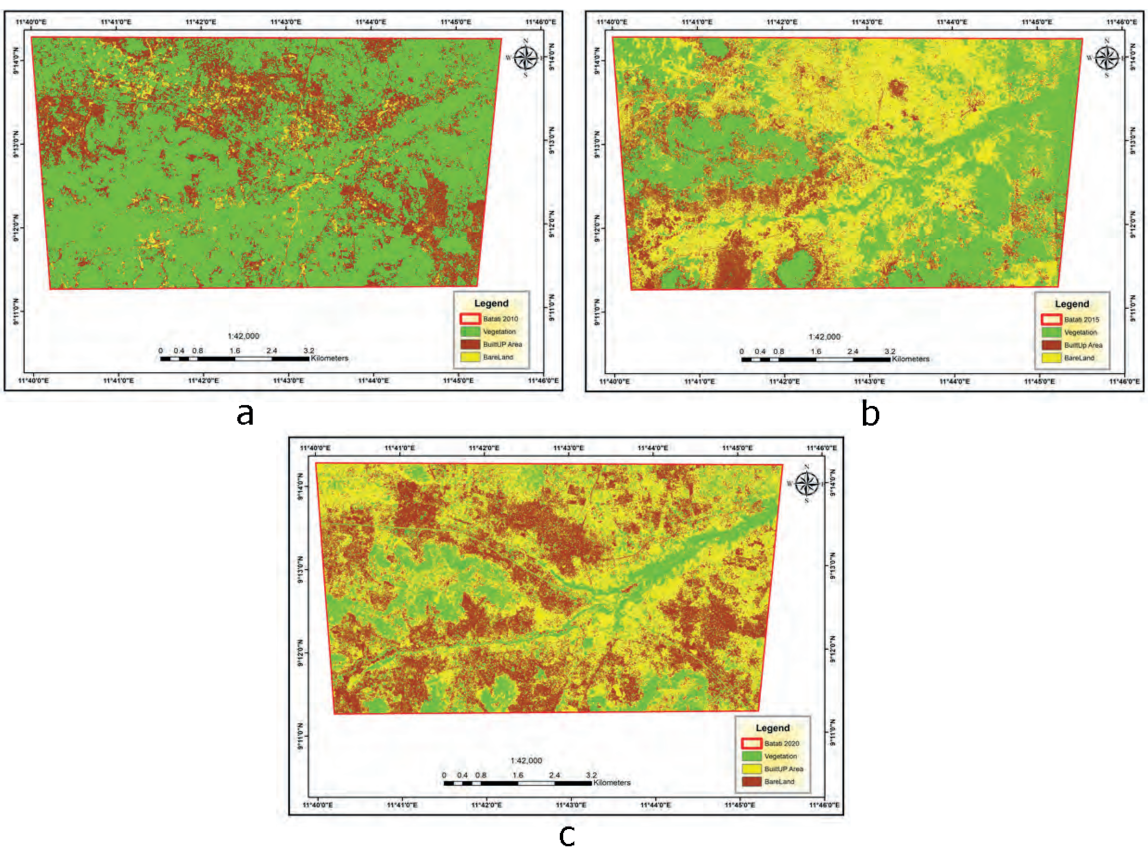

Fig. 3. Vegetal cover change in Batati: a) 2010, b) 2015 and c) 2020

In the same vein, findings of the study from the radius around Tatabu charcoal depot presented in Table 3 indicated 260.08 ha vegetal cover; 76.21 ha for built-up area and 795.69 ha for bare land in 2010 respectively. Variation in coverage was witnessed in 2015 with vegetal cover declining to 178.6 ha; built-up area rose to 197.74 ha while bare land slightly drops to 755.64 ha.

Another variation in coverage was witnessed across the three classifications in 2020 where vegetal cover was 158.49 ha, built-up area rose to 381.35 ha and bare land reduced to 592.14 ha in 2020. As further depicted in the table, the 22.98% vegetal cover in 2010 had declined to 14.00% of the total coverage area in 2020 across the selected radius of the charcoal depot in Tatabu while built-up area coverage rose from 6.73% in 2010 to 33.69% in 2020 and bare land declines from 70.29% in 2010 to 52.31% in 2020.

Table 3. Classification of vegetal cover in Tatabu

Classification	2010		2015		2020	
	Ha	%	Ha	%	Ha	%
Vegetation	260.08	22.98	178.6	15.78	158.49	14.00
Built-Up Area	76.21	6.73	197.74	17.47	381.35	33.69
Bare Land	795.69	70.29	755.64	66.75	592.14	52.31

Source: Landsat image 2021.

This finding is spatially presented in Figure 4 where in 2010, the presence of traceable green vegetation was evident in 2010 shown in Figure 4a; obvious decline in vegetal cover is depicted in Figure 4b where significant increase was observed for built-up areas accompanied by declining vegetation. A further significant decline in vegetal cover was observed in Figure 4c where greenery is almost fading away while built-up area equally drops and bare land and becomes more pronounced compared to Figure 4a as a result of various factors like farming, mining, charcoal production among others leading to loss of vegetation.

4.2. Level of Commercial Charcoal Production in the Study Area

As presented in Figure 5, seventy five (75) bags of charcoal are produced in Tatabu while Badeggi has a production rate of one hundred and twenty (120) bags of charcoal on a weekly basis and the highest charcoal production was observed in Batati with an average of two hundred (200) bags per week. This indicates an average production of one hundred and thrity two (132) bags per week across the three major charcoal depots in the study area.

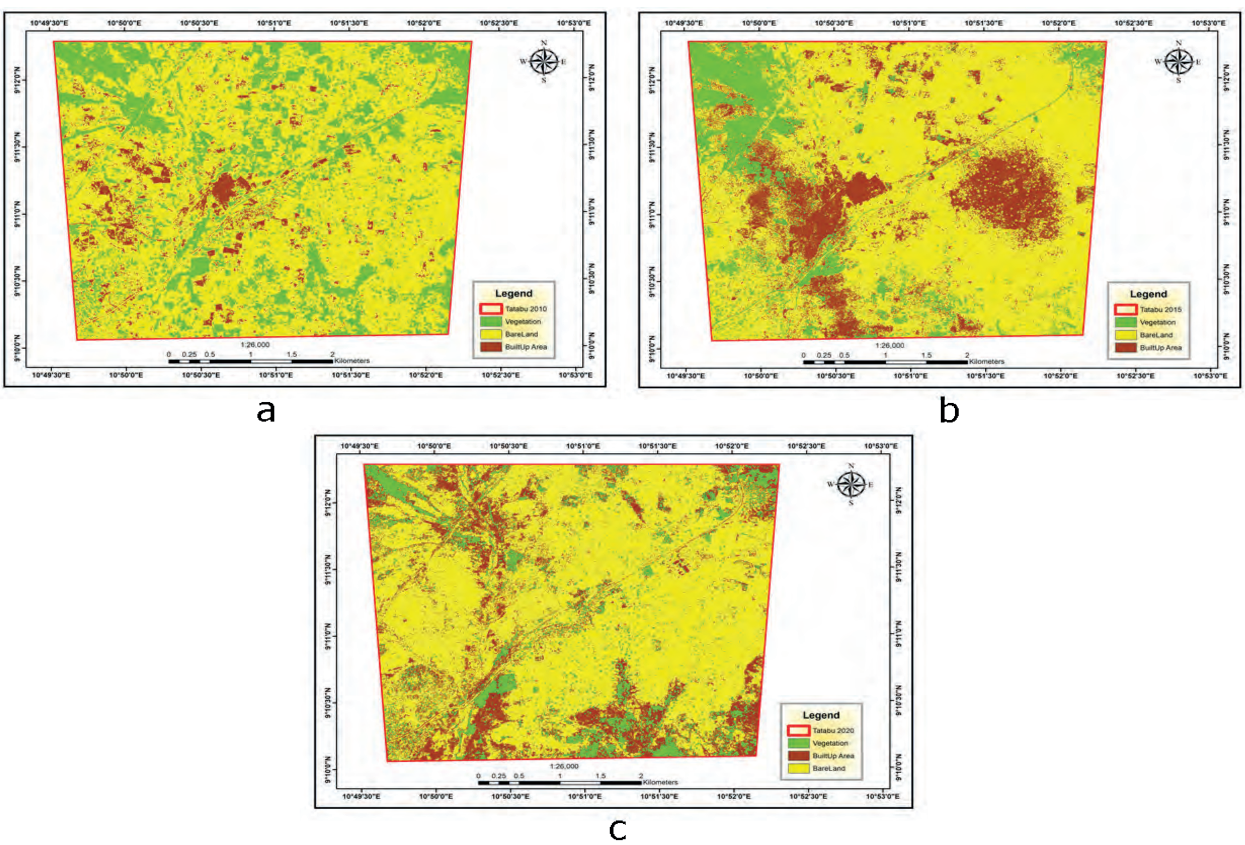

Fig. 4. Vegetal cover change in Tatabu: a) 2010, b) 2015 and c) 2020

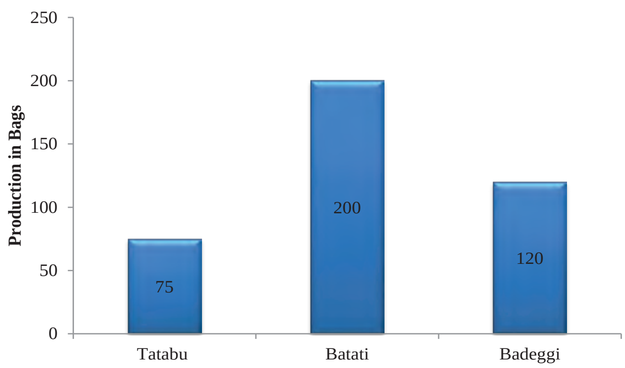

Fig. 5. Weekly production of charcoal (in bags)
Source: Field survey, 2021

Results of the findings in relation to the average kilogram of a bag of charcoal presented in Figure 6 indicated that 19.8% respondents submitting to less than 5 kg, 13.2% are of the opinion that an average bag of charcoal weighs between 6-10 kg, those with the view that it weighs between 11-15 kg are 15.5% while 42.7% submitted that a bag of charcoal has an average weight of 16-20 kg as the remaining 8.8% submitted that a bag of charcoal weighs above 20 kg. By implication, an average bag of charcoal is concluded to weigh between 11-20 kg seeing a total cumulative submission of 58.2% response.

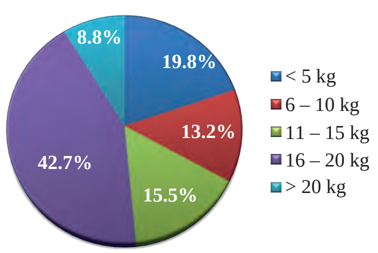

Fig. 6. Average Kilogram per bag of charcoal
Source: Field survey, 2022

Findings of the study according to the average number of tucks export out of the region per month from the major charcoal depots as shown in Figure 7 revealed an average of 3 trucks exported from Tatabu depot while 6 trucks are often exported per month from Badeggi depot while the highest 10 trucks export per month is observed for Batati charcoal depot respectively, giving an average of ten trucks per month with each truck containing within 200-500 bags. By implication, it can be inferred that the region is a large supplier of charcoal both locally across Nigeria and outside the country's border. It also revealed a large volume of trucks loading charcoal out of the region into the south-western part of the country with Lagos the most preferred destination where it is further loaded on ships for eventual exportation out of the country while Abuja and Kaduna are the preferred destination in the Northern part of the country. See plate 1 and 2 in appendix B for the removal of vegetation for charcoal production and bags of charcoal awaiting export out of the region.

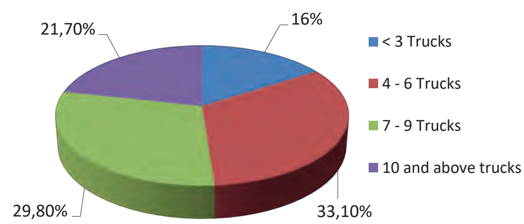

Fig. 7. Charcoal export by trucks per month
Source: Field survey, 2022

4.3. Factors contributing to Vegetal Land Cover Loss

Results presented in Table 4 regarding factors contributing to vegetal land cover loss indicated that; deforestation is ranked highest with 0.763 RII values followed by farming ranked second with 0.700 RII as 0.690 RII was observed for construction exercises ranked third while overgrazing and lumbering were ranked fourth and fifth with 0.682 RII and 0.663 RII values respectively alongside mining ranked sixth with 0.654 RII values. The factor ranked seventh was flooding and excessive rainfall followed by heavy winds with 0.650 RII, slope and gradient of the region was ranked ninth with 0.559 RII as 0.546 RII was recorded for nature of soil and topography while tectonic activity is ranked eleventh with 0.538 RII value and the lowest ranked factor contributing to and responsible for the removal of vegetal cover is climate and weather variation with 0.503 RII values.

Table 4. Summary of Factors Responsible for the Removal of Vegetal Cover

Factors	Mean	RII	Rank
Climate and Weather variation	2.513	0.503	12th
Nature of soil/Topography	2.728	0.546	10th
Tectonic activity	2.692	0.538	11th
Slope and Gradient	2.795	0.559	9th
Construction (Dam, Buildings, Infrastructures)	3.449	0.690	3rd
Flooding and Intense rainfall	3.267	0.653	7th
Overgrazing	3.408	0.682	4th
Heavy winds	3.248	0.650	8th
Deforestation	3.816	0.763	1st
Farming	3.499	0.700	2nd
Lumbering	3.317	0.663	5th
Mining	3.269	0.654	6th

Source: Field survey, 2022.

4.4. Discussion

The findings from the study area indicate significant declines in vegetal cover between 2011 and 2021, with corresponding increases in built-up areas and varying changes in bare land. This trend, which has been seen in Tatabu, Batati, and Badeggi, is indicative of widespread land conversion and deforestation efforts that are primarily motivated by the manufacturing of charcoal. The worst effects of these commercial activities on the environment are shown in Batati, where there has been a reported drop in vegetative cover from 1,491.75 ha to 351.74 ha. These developments are consistent with worldwide patterns in which economic activities like resource extraction, urbanisation, and agriculture drive changes in land use, especially in poor nations (Arifeen et al., 2021). Research from other continents, such as Southeast Asia and South America, also show that urbanisation and agriculture-related deforestation dramatically diminish the amount of forest cover (Destiartono & Hartono, 2022; Sylvester et al., 2024).

Comparatively, similar patterns have been seen throughout Africa, where deforestation is mostly caused by the conversion of forest areas for agriculture, urban development, and the manufacturing of charcoal (Kiruki et al., 2020; Nyarko et al., 2021; Sedano et al., 2022). For example, the growth of urban areas and agricultural land in West Africa has resulted in a significant loss of forest cover (Ziem Bonye et al., 2021). Studies from Kenya and Tanzania have shown that the production of charcoal is a major factor contributing to forest degradation in East Africa (Kiruki et al., 2020; Nyarko et al., 2021). The study's conclusions are consistent with these geographical patterns, suggesting that the economic forces driving up the production of charcoal and land conversion are widespread throughout the continent. This emphasises the necessity of sustainable land management techniques to counteract environmental deterioration while juggling financial requirements.

Deforestation, excessive grazing, mining, building, and farming are among the causes that have been shown to contribute to the loss of vegetative cover. These findings are in line with those from other parts of Africa and the world (Tsegaye, 2019; Musetsho et al., 2021; Hussein, 2023). The primary issue in Lapai and other research areas is deforestation, which is fuelled by activities like the manufacturing of charcoal. Similarly, in the Amazon Basin where deforestation is common for soybean farming and cattle ranching; similar drivers of vegetal loss have been observed (Hänggli et al., 2023; Alves et al., 2023). The high relative importance index (RII) values observed for mining and deforestation match trends observed in other African nations like Ghana and the Democratic Republic of the Congo, where land clearance for agriculture and mineral extraction are the main drivers of forest loss (Bas et al., 2024; Rieckmann & Muñoz, 2024). The intricacy of managing land resources in the face of many and conflicting economic activity is shown by the study's thorough analysis, which highlights the complex factors influencing changes in land cover.

5. CONCLUSION AND RECOMMENDATIONS

Using remote sensing and geographic information systems (GIS), this study assessed changes in vegetal cover and the production of commercial charcoal in the southern region of Niger State, Nigeria. The results show notable differences in land use and land cover change (LULCC) between 2011 and 2021, with widespread commercial charcoal production serving as the main driver. A striking drop in vegetative cover is shown by the analysis, especially in the vicinity of important charcoal depots like Badeggi, Batati, and Tatabu, where the greenery has been replaced by barren terrain and built-up regions. As revealed by the study, there is a significant amount of charcoal produced; Batati alone may produce up to 200 bags per week, highlighting the activity's economic importance. According to the study, the main causes of the loss of vegetative cover include overgrazing, farming, mining, and deforestation, with the manufacturing of charcoal being the most common reason. These results draw attention to the unsustainable use of forest resources as fuel, which presents serious problems for the sustainability of the ecosystem. In order to maintain the long-term viability of the region's natural resources, the report urges the rapid implementation of sustainable land management techniques that strike a balance between economic requirements and environmental conservation.

In order to tackle the noteworthy reduction in vegetative cover and issues related to environmental sustainability that the study uncovered, it is suggested that the southern part of Niger State adopt sustainable land management techniques. To lessen reliance on charcoal, this entails encouraging other energy sources, implementing stronger laws against deforestation, and stepping up reforestation initiatives. Furthermore, overgrazing and soil degradation may be lessened by implementing sustainable farming methods and managed grazing. In addition to supporting economic diversification to lessen reliance on ecologically damaging methods, community education and awareness campaigns on the environmental effects of charcoal manufacturing are essential. Ensuring long-term environmental sustainability and economic stability can be facilitated by collaborating with non-governmental organisations and government agencies.

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APPENDIX A

SAMPLE SIZE

S/N	LGAs	Districts	Population	% contributed	Sample Size	Returned Valid
1	Lapai	Lapai	64,403	3.6	24	19
		Shaku	13,108	0.8	5	5
		BirninMaza	10,349	0.6	4	5
		Duma	11,668	0.7	5	4
		Gulu-Vatsa	8,781	0.5	3	5
		Kpada	12,204	0.7	5	3
		Ebbo	5,447	0.3	2	5
		Bata	7,863	0.4	3	2
		Muye	14,741	0.8	5	3
		Gupa	9,099	0.5	3	5
		Total	**152,922**	**8.9**	**59**	**51**
2	Agaie	Agaie	78,149	4.5	30	28
		Kintifin	25,918	1.5	10	8
		Tagagi	11,468	0.6	4	4
		Baro	29,814	1.7	11	11
		Fogbe	12,668	0.7	5	5
		Kusoyaba	11,462	0.7	5	5
		Goyiko	8,617	0.5	3	3
		Total	**172,741**	**10.2**	**67**	**64**
3	Katcha	Katcha	74,107	4.2	28	27
		Kateregi	41,218	2.4	16	16
		Baddegi	27,681	1.6	11	11
		Bakeko	19,873	1.1	7	7
		Total	**157,982**	**9.3**	**62**	**71**
4	Bida	Bida	249,996	14.3	95	78
		Total	**242,479**	**14.3**	**95**	**78**
5	Gbako	Lemu	60,070	3.7	24	20
		EtsuAudu	65,608	3.8	25	23
		Edozhigi	41,281	2.4	16	15
		Total	**165,760**	**9.9**	**65**	**58**
6	Lavun	Kutigi	74,849	4.3	27	19
		Dabban	44,418	2.5	17	17
		Kp...	36,612	2.1	14	14
		Jima	39,841	2.3	15	12
		Doko	46,689	2.7	18	17
		Gaba	40,224	2.3	15	13
		Total	**274,135**	**16.2**	**107**	**94**
7	Edati	Enagi	119,248	6.8	45	39
		Sakpe	96,075	5.5	37	35
		Total	**208,849**	**12.3**	**82**	**74**
8	Mokwa	Mokwa	124,741	7.1	47	41
		Muwo	44,908	2.6	17	17
		Takuma	56,251	3.2	21	14
		Kudu	38,004	2.2	15	15
		KedeTifin	33,407	1.9	13	12
		KedeTako	29,892	1.7	11	10
		TOTAL	**317,365**	**18.7**	**124**	**107**
	GRAND TOTAL		***1,692,233***	***100***	***663***	***597***

Source: NPC (2006); NBS (2012); Authors projection (2022)

APPENDIX B

Plate 1. Vegetal removal during charcoal production
Source: Authors Survey, 2022

Plate 2. Bags of charcoal awaiting transport
Source: Authors Survey, 2022

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HAVE WE ENTERED THE FOURTH ERA OF BIM? FROM THE ERA OF OPEN STANDARDS TO THE ERA OF ARTIFICIAL INTELLIGENCE

CZY WKROCZYLIŚMY W CZWARTĄ ERĘ BIM? OD ERY OTWARTYCH STANDARDÓW DO ERY SZTUCZNEJ INTELIGENCJI

Andrzej Szymon Borkowski
Warsaw University of Technology, Poland

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Abstract

Building Information Modeling (BIM) has been the hottest topic in the construction sector over the last decade. The evolution from CAD to BIM systems has been going on for over 40 years. The current periodization indicates that we are now in the third era of BIM development, the era of open standards, which was initiated by the idea of openBIM in 2012. Earlier evolutionary periods included the model federation (second era) and CAD3D (first era). Since 2022, there has been extremely dynamic development of artificial intelligence (AI), especially generative AI. AI tools automate some of the tasks that were previously performed by humans. Thus, the research question is: are we entering the next, fourth era of BIM development? The era of artificial intelligence? This chapter attempts to answer this reflective question. During an in-depth literature review, the directions of current and future research on BIM development are discussed.

Streszczenie

Modelowanie informacji o budynku (BIM) było najgorętszym tematem w branży budowlanej w ciągu ostatniej dekady. Ewolucja od systemów CAD do systemów BIM trwa już ponad 40 lat. Obecna periodizacja wskazuje, że znajdujemy się obecnie w trzeciej erze rozwoju BIM, erze otwartych standardów, zapoczątkowanej ideą openBIM w 2012 roku. Wcześniejsze okresy ewolucji obejmowały federację modeli (druga era) oraz CAD3D (pierwsza era). Od 2022 roku obserwuje się niezwykle dynamiczny rozwój sztucznej inteligencji (AI), zwłaszcza generatywnej. Narzędzia AI automatyzują niektóre zadania, które wcześniej były wykonywane przez ludzi. W związku z tym pojawia się pytanie badawcze: czy wkraczamy w kolejną, czwartą erę rozwoju BIM? Erę sztucznej inteligencji? W niniejszym artykule podjęto próbę odpowiedzi na to refleksyjne pytanie. W trakcie dogłębnego przeglądu literatury omówiono kierunki obecnych i przyszłych badań nad rozwojem BIM.

COMPARISON OF TRADITIONAL AND MODULAR CONSTRUCTION IN TERMS OF TECHNOLOGY, TIME AND COST

PORÓWNANIE BUDOWNICTWA TRADYCYJNEGO I MODUŁOWEGO POD WZGLĘDEM TECHNOLOGII, CZASU I KOSZTÓW

Krzysztof Zima, Maria John
Cracow University of Technology, Poland

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Abstract

Modular construction is a rapidly growing sector of the construction industry in recent years. This paper presents information on modular construction technology, including its characteristic features and the positive aspects resulting from its use. It discusses the scope of application, completion time, quality of workmanship and ways to minimise losses during the module production process, along with the possibility of reusing both the modules and the materials from which they are made. The comparative analysis covered technological and economic aspects as well as completion time, using the example of a single-family residential building for two technological variants: modular and traditional construction. Both technologies were discussed in detail. The economic analysis was based on market research of offers from companies specialising in the construction of buildings using the technology in question. The cost estimate for traditional construction was prepared using the BIMestiMate programme. A comparative analysis of the construction time for buildings using both technologies was also carried out.

Streszczenie

Budownictwo modułowe to sektor branży budowlanej, który w ostatnich latach szybko się rozwija. Niniejszy artykuł przedstawia informacje na temat technologii budownictwa modułowego, w tym charakterystyczne cechy oraz korzyści wynikające ze stosowania tej technologii. Omówiono w nim zakres zastosowań, czas realizacji, jakość wykonania oraz sposoby minimalizacji strat podczas procesu produkcji modułów, a także możliwość ponownego wykorzystania zarówno samych modułów, jak i materiałów, z których są one wykonane. Analiza porównawcza objęła aspekty technologiczne i ekonomiczne, a także czas realizacji, na przykładzie budynku mieszkalnego jednorodzinnego dla dwóch wariantów technologicznych: konstrukcji modułowej i tradycyjnej. Obie technologie zostały szczegółowo omówione. Analiza ekonomiczna opierała się na badaniach rynkowych ofert firm specjalizujących się w budowie budynków z wykorzystaniem danej technologii. Kosztorys dla konstrukcji tradycyjnej został przygotowany przy użyciu programu BIMestiMate. Przeprowadzono również analizę porównawczą czasu budowy budynków przy użyciu obu technologii.

EVALUATION OF THE INFLUENCE OF RECYCLED GLASS AND CARBON GEOGRIDS ON THE STIFFNESS MODULUS OF ASPHALT CONCRETE

OCENA WPŁYWU RECYKLOWANEJ GEOSIATKI SZKLANEJ I WĘGLOWEJ NA MODUŁ SZTYWNOŚCI BETONU ASFALTOWEGO

Artur Kowalczyk
Kielce University of Technology, Poland

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Abstract

The paper presents the findings of a study on the influence of fibers derived from recycled geogrids on the stiffness modulus of asphalt concrete. The preliminary stage of the research involved a survey, which confirmed the escalating issue of reclaimed asphalt pavement (RAP) contamination with glass and carbon geogrid fibers, as well as the limited existing knowledge regarding their impact on asphalt concrete properties. The experimental program encompassed AC16W and AC22W mixtures modified with fibers ranging from 1 to 5 cm in length and at concentrations of 0.2% to 1.0% by weight. Analysis of the test results revealed that the application of carbon geogrid fibers did not lead to a significant increase in the stiffness modulus compared to the reference mixtures; conversely, glass fibers exhibited a tendency to reduce it. It was established that excessive fiber length and content lead to a reduction in the stiffness modulus. Based on the analyses, optimal parameters for maintaining high stiffness modulus values were determined: a fiber content of < 0.2% and a length of < 1 cm, regardless of the mixture's aggregate grading. The results indicate that geogrid recycling may represent an effective and rational approach supporting the circular economy and the development of sustainable asphalt technologies.

Streszczenie

W artykule przedstawiono wyniki badań nad wpływem włókien pozyskiwanych z recyklowanych geosiatek na moduł sztywności betonu asfaltowego. Elementem rozpoznawczym były badania ankietowe, które potwierdziły narastający problem zanieczyszczenia destruktu asfaltowego włóknami geosiatek szklanych i węglowych oraz ograniczoną wiedzę na temat ich wpływu na beton asfaltowy. Program badań obejmował mieszanki AC16W i AC22W modyfikowane włóknami o długości 1–5 cm i zawartości 0,2–1,0%. Analiza wyników badań wykazała, że zastosowanie włókien geosiatki węglowej nie powodowało istotnego wzrostu modułu sztywności względem mieszanek referencyjnych, natomiast włókna szklane wykazywały tendencję do jej obniżania. Stwierdzono, że nadmierna długość i udział włókien prowadzą do redukcji modułu sztywności. Na podstawie analiz określono wartości optymalne sprzyjające utrzymaniu wysokiej wartości modułu sztywności: zawartość włókien <0,2% oraz długość < 1 cm, niezależnie od rodzaju uziarnienia mieszanki. Uzyskane rezultaty wskazują, że recykling geosiatki może stanowić efektywny i racjonalny kierunek wspierający gospodarkę o obiegu zamkniętym oraz rozwój zrównoważonych technologii asfaltowych.

VEGETAL COVER CHANGE AND COMMERCIAL CHARCOAL PRODUCTION IN THE SOUTHERN REGION OF NIGER STATE, NIGERIA

ZMIANA POKRYCIA ROŚLINNEGO I KOMERCYJNA PRODUKCJA WĘGLA DRZEWNEGO W POŁUDNIOWYM REGIONIE STANU NIGER W NIGERII

Jibrin Katun Mohammed, Usman Abubakar Dzukogi
Federal Polytechnic Bida, Nigeria
Abdulafeez Adewale Olawale
Federal University of Technology, Minna, Nigeria

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Abstract

Vegetal cover change is a threat globally, a phenomenon with less attention concerning charcoal production. This study investigates vegetal cover loss and commercial charcoal production by analyzing three major charcoal depots in Niger south, Nigeria: Tatabu, Badeggi, and Batati. Utilizing a quantitative approach, primary data were collected through 663 questionnaires and secondary data via Landsat satellite imagery of 2010, 2015, and 2020 within a five-kilometer radius of the depots. Relative importance index (RII) was used to analyse primary data, while satellite imageries were processed using ArcGIS 10.8 software. Findings indicate a decrease in vegetative cover in Badeggi from 472.65 ha in 2010 to 269.92 ha in 2020. Key drivers of vegetation loss include deforestation (0.763 RII), farming (0.700 RII), and construction (0.690 RII). The region produces an average of 132 bags of charcoal weekly and ten truckloads monthly. The study emphasizes the urgent need for sustainable environmental management and alternative energy sources.

Streszczenie

Zmiana pokrycia roślinnego stanowi globalne zagrożenie, a zjawisku temu poświęca się mniej uwagi w kontekście produkcji węgla drzewnego. Niniejsze badanie analizuje utratę pokrycia roślinnego i komercyjną produkcję węgla drzewnego, analizując trzy główne składy węgla drzewnego w południowej części stanu Niger w Nigerii: Tatabu, Badeggi i Batati. Wykorzystując podejście ilościowe, zebrano dane pierwotne za pomocą 663 kwestionariuszy oraz dane wtórne za pomocą zdjęć satelitarnych Landsat z lat 2010, 2015 i 2020 w promieniu pięciu kilometrów od składów. Do analizy danych pierwotnych wykorzystano względny wskaźnik ważności (RII), a zdjęcia satelitarne przetworzono za pomocą oprogramowania ArcGIS 10.8. Wyniki wskazują na zmniejszenie się pokrywy roślinnej w Badeggi z 472,65 ha w 2010 r. do 269,92 ha w 2020 r. Głównymi czynnikami powodującymi utratę roślinności są wylesianie (0,763 RII), rolnictwo (0,700 RII) i budownictwo (0,690 RII). Region produkuje średnio 132 worki węgla drzewnego tygodniowo i dziesięć ciężarówek miesięcznie. Badanie podkreśla pilną potrzebę zrównoważonego zarządzania środowiskiem i alternatywnych źródeł energii.